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1 Introduction

The TOTEM experiment at the LHC is designed to measure the proton-proton elastic scattering, the inelastic and total cross-section and to study the diffractive physics in the forward region. This article summarizes the present status of the experiment and gives an overview of the latest results.

2 The experimental apparatus

The experimental apparatus [1], composed of three subdetectors (Roman Pots, T1 and T2 telescopes), is placed symmetrically on both sides of Interaction Point 5 (IP5), shared with the CMS experiment. All three subdetectors have trigger capability.

The Roman Pot stations, equipped with silicon detectors and placed at 147 and 220m from IP5, detect elastically and diffractively scattered protons with a small

\footnote{on behalf of TOTEM Collaboration}
scattering angle down to a few µrad. They host silicon detectors which are moved very close to the beam when it is in stable conditions. Each RP station is composed of two units in order to have a lever arm for a better local track reconstruction and a higher efficiency of trigger selection by track angle. Each unit (Figure 1, left) consists of three pots, two vertical and one horizontal completing the acceptance for diffractively scattered protons. Each pot contains a stack of 10 planes of silicon strip detectors (Figure 1, right). Each plane has 512 strips (pitch of 66 µm), oriented at +45° (5 planes) or at -45° (5 planes) w.r.t. the detector edge facing the beam, allowing a single hit resolution of ∼20µm. As the detection of protons elastically scattered at angles down to few µrads requires a detector active area as close to the beam as ∼1mm, a novel edgeless planar silicon detector technology has been developed in order to have an edge dead zone minimized to only ∼50µm.

The T1 and T2 telescopes, placed at about 8 and 14m from IP5 respectively, detect charged particles produced in the polar angular range of a few mrad to ∼100 mrad. The T1 telescope (3.1 < |η| < 4.7) consists of five planes formed by six trapezoidal Cathode Strip Chambers (CSC, Figure 2, left). These CSCs, with 10 mm thick gas gap and a gas mixture of Ar/CO₂/CF₄ (40%/50%/10%), give three measurements of the charged particle coordinates with a spatial resolution of ∼1mm: anode wires (pitch of 3mm) are parallel to the trapezoid base; cathode strips (pitch of 5mm) are rotated by ±60° with respect to the wires. The T2 telescope (5.3 < |η| < 6.5) is made of triple-GEM (Gas Electron Multipliers) chambers. Each half-arm, located at ∼13.5m from IP5, is made by the combination of ten aligned detector planes having an almost semicircular shape (Figure 2, right). The T2 GEMs are characterized by a triple-GEM structure and a gas mixture of Ar/CO₂ (70%/30%). The read-out board has two separate layers with different patterns: one with 256x2 concentric circular

Figure 2: Left: T1 telescope installed in the CMS endcap. Right: T2 telescope during the installation inside the CMS rotating shield.
strips (80µm wide, pitch of 400µm), allowing track radial coordinate reconstruction
with a resolution of ∼100µm; the other with a matrix of 24x65 pads (from 2x2mm² to
7x7mm² in size) providing level-1 trigger information and track azimuthal coordinate
reconstruction.

3 LHC special optics

The detection of elastically and diffractively scattered protons in the RP detectors is
strongly dependent on the accelerator optics used during the runs. After an elastic
interaction in IP5 with the transverse vertex position (x∗; y∗) and with scattering
angle projections (Θx∗; Θy∗), the displacement (x; y) of the proton trajectory from the
beam centre at the RP position is given by x = Lx Θx∗ + vx x∗ and y = Ly Θy∗ + vy y∗ with
Lx,y and vx,y depending on the optics. A special β∗=90m optics has been developed
and used during dedicated runs. This optics is characterized by vy ∼ 0 and Lx ∼ 0,
which allows the reconstruction of the vertical scattering angle Θy∗ from the proton
track position y and of the horizontal angle Θx∗ from the track angle Θx = dx/ds at
the RP: Θy∗ = y/Ly and Θx∗ = (dLx/ds)−1 · (Θx − dx/ds x∗), where s denotes the distance
from the interaction point and x∗ = x/vx since Lx ∼ 0.

4 Data taking and analysis

Data presented here have been taken at √s = 7TeV during runs in 2010 and in
2011. An integrated luminosity of 6.1nb−1 was collected in runs with the standard
β∗ = 3.5m optics, with the RP detectors approaching the beam to a distance as small
as 7 times the transverse beam size σbeam. With the special β∗ = 90m optics more
than 84µb−1 were collected with different RP approaches to the beam (10, 6.5, 5.5
and 4.8·σbeam).

For a detailed description of the event selection, background estimation, correc-
tions, statistical and systematic errors, the reader is referred to the original TOTEM
publications [2, 3, 4, 5, 6, 7].

5 Results

At the LHC energy of √s = 7TeV, under various beam and background conditions,
luminosities, and Roman Pot positions, TOTEM has measured the differential cross-
section for proton-proton elastic scattering as a function of the four-momentum transfer
squared t, the inelastic and the total cross-section.

The differential elastic cross-section dσel/dt was measured in the range 5·10−3 < |t| < 2.5GeV². In the low |t| range (5·10−3 < |t| < 0.2GeV²) the data can be
described by a single exponential fit with a slope $B = (19.9 \pm 0.3)\text{GeV}^2$ [5], which confirms the trend of a slope increase with $\sqrt{s}$ observed by previous experiments; this value is compatible with the fit performed with a different data set in the range $0.02 < |t| < 0.33\text{GeV}^2$ [2]. The position of the pronounced dip, $|t| = (0.53 \pm 0.01^{\text{stat}} \pm 0.01^{\text{syst}})\text{GeV}^2$, confirms the shrinkage of the forward elastic peak with $\sqrt{s}$, a trend already observed in elastic pp scattering at lower energies. Above the dip structure $d\sigma_{\text{el}}/dt$ becomes less steep and can be described with a power law $|t|^n$ with an exponent $n = -7.8 \pm 0.3^{\text{stat}} \pm 0.1^{\text{syst}}$ for $|t|$ values between $1.5\text{GeV}^2$ and $2.0\text{GeV}^2$.

The small error on the slope parameter $B$ allowed a precise extrapolation over the 9% non-visible elastic cross-section to $t = 0$ (optical point). With the luminosity from CMS, known with a $\sim 4\%$ uncertainty, the elastic cross-section was determined to be $(25.4 \pm 1.1)\text{mb}$ [5].

![Graph showing differential cross-section](image1.png)

**Figure 3:** Left: the measured differential cross-section $d\sigma_{\text{el}}/dt$ with its statistical (for all points) and systematic (for two example points) error bars [3]. Right: The measured pp elastic scattering differential cross-section $d\sigma_{\text{el}}/dt$ in the low $|t|$ range with the exponential fit. Between 0.35 and 0.4\text{GeV}^2 the overlap between data sets of [2] and [3] can be seen.

The inelastic cross-section has been directly measured by TOTEM using the inelastic telescopes and the luminosity from CMS. The preliminary value of this measurement is $\sigma_{\text{inel}} = (73.7 \pm 0.1^{\text{stat}} \pm 1.7^{\text{syst}} \pm 2.9^{\text{lumi}})\text{mb}$ [10].

The measurement of the total cross-section has been done by TOTEM in different ways (the still preliminary values are taken from [10]):

- using the optical theorem, depending on the measurement of the elastic scattering and on its extrapolation to the optical point, on $\rho$ from theory$^2$ and on

---

$^2\rho = 0.141 \pm 0.007$[8]
the luminosity from CMS

\[
\sigma_{tot}^2 = \frac{16\pi}{1 + \rho^2} \frac{1}{\mathcal{L}} \left. \frac{dN_{el}}{dt} \right|_{t=0}
\]

The measured value is \(\sigma_{tot} = (98.6\pm2.2)\text{mb}\). Moreover, in this case, the inelastic cross-section can be obtained by \(\sigma_{inel} = \sigma_{tot} - \sigma_{el}\):

- using the separate measurement of the elastic and inelastic cross-section \(\sigma_{tot} = \sigma_{el} + \sigma_{inel}\), depending on the luminosity from CMS. The measured value is \(\sigma_{tot} = (99.1\pm4.3)\text{mb}\);
- using the optical theorem, depending on the measurement of the elastic and inelastic rate, on the measurement of the elastic scattering extrapolation to the optical point, on \(\rho\) from theory and luminosity independent

\[
\sigma_{tot} = \frac{16\pi}{1 + \rho^2} \left. \frac{dN_{el}}{dt} \right|_{t=0}
\]

The measured value is \(\sigma_{tot} = (98.0\pm2.5)\text{mb}\).

Figure 4: Left: Compilation of measurements of \(\sigma_{tot}\), \(\sigma_{inel}\), and \(\sigma_{el}\) [8, 9]. Right: Charged particle pseudorapidity density distribution in the \(5.3 < |\eta| < 6.5\) range.

TOTEM has also measured the charged particle pseudorapidity density \(dN_{ch}/d\eta\) for \(5.3 < |\eta| < 6.4\) in events with at least one charged particle with \(p_T > 40\text{MeV}/c\) in this pseudorapidity range, extending the measurements performed by the other LHC experiments [4] into the forward region.

The measurement refers to more than 99% of non-diffractive events and to single and double diffractive events with diffractive masses above \(\sim 3.4\text{GeV}/c^2\), corresponding to about 95% of the total inelastic cross-section. Several MC generators have been compared to data; none of them has been found to fully describe the measurement (see Figure 4, right).
6 Summary

The TOTEM experiment at the LHC has measured the total, inelastic and differential elastic cross-section at the energy of $\sqrt{s} = 7$ TeV. The data were collected with the two inelastic telescopes and the Roman Pot detectors during several dedicated runs, partly with a special $\beta^* = 90$ m beam optics. The elastic scattering measurements cover a range of squared four momentum transfer $|t|$ from 0.005 to 2.5 GeV$^2$ and exhibit an approximately exponential behaviour for $|t| < 0.33$ GeV$^2$, followed by a significant diffractive minimum at $|t| = (0.53 \pm 0.01^{\text{stat}} \pm 0.01^{\text{syst}})$ GeV$^2$. For $|t| > 1.5$ GeV$^2$, a power-law decrease with an exponent of $-7.8 \pm 0.3^{\text{stat}} \pm 0.1^{\text{syst}}$ has been observed. The inelastic cross-section has been measured both directly and indirectly. The total cross-section has been measured with different methods providing consistent results. Furthermore, the charged particle pseudorapidity density $dN_{ch}/d\eta$ has been measured in the range $5.3 < |\eta| < 6.5$.

References


LHCb Status and Plans

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1 Introduction

LHCb is the dedicated flavour physics experiment at the LHC. While ATLAS and CMS search for the direct production of new states, LHCb is designed to see their indirect effect on charm and beauty decays, via virtual production in loop diagrams. Such an indirect approach can be very powerful: e.g. the discovery of $B^{0}-\bar{B}^{0}$ mixing [1] demonstrated that the top quark was unexpectedly heavy: $m(t) > 50 \text{ GeV}/c^2$, before it had been directly observed. Key topics for LHCb include the study of CP violation—is it due to a single phase in the quark mixing (CKM) matrix, as in the Standard Model?—and the study of rare decays: flavour-changing neutral current decays (e.g. $B^{0}_s \rightarrow \mu^+ \mu^-$) are strongly suppressed in the Standard Model, but may be enhanced by Supersymmetry or other new physics.

Since $b$-hadron production is strongly forward-peaked at the LHC, LHCb is a forward spectrometer covering the angular region from 10–300 mrad from the beam axis (but operating in collider mode), as shown in Fig. 1. The $b\bar{b}$ cross-section is large: it has been measured to be $284 \pm 53 \mu$b at the LHC (at $\sqrt{s} = 7 \text{ TeV}$) [2] which results in about 100,000 $b\bar{b}$ pairs being produced per second at LHCb ($\sim 10^4 \times$ the B factories). Charm production is a factor $\sim 20$ higher [3], so the LHC is an excellent environment for the precision study of flavour physics.

There are other advantages of flavour physics at the LHC. All $b$-hadron species are produced at high energy, and $B^{0}_s$ physics is rich and little explored until now. The enormous production rate has allowed LHCb to overtake the B factories even for $B^{0}$ and $B^{+}$ decays. For example, the recent measurement $\text{BR}(B^{+} \rightarrow \pi^{+} \mu^{+} \mu^{-}) = (2.4 \pm 0.6 \pm 0.2) \times 10^{-8}$ [4] is the rarest $B$ decay ever observed. The previous best limit (from Belle) was $< 6.9 \times 10^{-8}$ [5]. With the large boost at LHCb $B$ decay lengths are of order 1 cm, allowing excellent decay-time determination. Finally, the forward pseudorapidity coverage $2 < \eta < 5$ is complementary to the central detectors for other physics, including electroweak, QCD, and the search for exotics.

The LHCb detector is described in Ref. [6]. It features a precise silicon vertex detector (VELO) that approaches to within 8 mm of the beams, and a high-performance

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1 On behalf of the LHCb collaboration.
particle identification system based on RICH detectors. The trigger of the experiment is designed to be efficient for fully hadronic final states, as well as those containing leptons or photons, and the output data rate to storage is a few kHz.

2 LHCb status

LHCb has run successfully over the last three years, taking data with high efficiency (greater than 90%), and with all subdetectors working as designed. In 2011 an integrated luminosity of 1 fb$^{-1}$ was recorded, which has been used for a wide variety of physics analyses, with 58 published papers to date and an even larger number of preliminary results sent to conferences. In 2012 the detector continues to run well, at a luminosity that is levelled at $4 \times 10^{32}$ cm$^{-2}$s$^{-1}$.

The physics results are reviewed in many contributions to this conference, and just a few highlights are mentioned here. $B_s^0 - \bar{B}_s^0$ oscillations have been measured with the world’s best precision, see Fig. 2 (a). Radiative $B$ decays have been studied, Fig. 2 (b), and the ratio of $B_s^0 \rightarrow \phi \gamma$ and $B^0 \rightarrow K^{*} \gamma$ branching fractions determined, as well as the CP asymmetry for $K^{*} \gamma$. For the rare decay $B_s^0 \rightarrow \mu^+ \mu^-$ LHCb has set the most stringent limit on the branching ratio, $< 4.5 \times 10^{-9}$ at 95% CL. A few candidates are seen, as shown in Fig. 2 (c), compatible with the Standard Model expectation, but not enough to yield a significant observation. The limit on the branching ratio gives strong constraints on new physics models. The $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay is another mode that is very sensitive to new physics, and different angular distributions have been studied, including the forward-backward asymmetry shown in Fig. 2 (d), for which the zero-crossing point has been measured for the first time and found to be
Figure 2: (a) $B_s^0$ oscillations seen in the asymmetry as a function of decay time for the $D_s^-\pi^+$ channel. (b) Invariant mass distribution of $B_s^0 \rightarrow \phi\gamma$. (c) Invariant mass distribution of $B_s^0 \rightarrow \mu^+\mu^-$ candidates. (d) Forward-backward asymmetry of $B^0 \rightarrow K^*0\mu^+\mu^-$ decays, as a function of $q^2$.

in agreement with the Standard Model expectation.

CP asymmetries have been studied in the two-body decays of $B$ hadrons to charmless final states, as illustrated in Figs. 3 (a) and (b). The ~ 10% asymmetry between the CP-conjugated $B^0 \rightarrow K\pi$ decays is clear from the raw distributions, and remains after the small corrections for production and detector effects. In a related analysis the first $> 3\sigma$ evidence has been seen for CP violation in $B_s^0$ decays. A precise measurement has also been made of the CP phase of $B_s^0$ mixing ($\phi_s$), which is expected to be small in the Standard Model. In Fig. 3 (c) the very clean signal for $B_s^0 \rightarrow J/\psi\phi$ decay that is used for this study is shown, which has a mass resolution of about 8 MeV/$c^2$. In Fig. 3 (d) it can be seen that the result for $\phi_s$ is compatible with the Standard Model, and also gives the world’s best measurement of the decay width difference in the $B_s^0$ system, $\Delta\Gamma_s$. Important steps have been made towards the measurement of the most poorly known angle of the Unitarity Triangle, $\gamma$, through the observation of the suppressed modes in $B \rightarrow DK$ decays.

The above gives a taste of the results so far from LHCb, focussing on those key
Figure 3: (a) $K^+\pi^-$ invariant mass distribution showing signals from two-body $B$ decays, with the largest contribution from $B^0 \to K^+\pi^-$. (b) $K^-\pi^+$ invariant mass distribution, with the largest contribution from $\bar{B}^0 \to K^-\pi^+$ decays. (c) Invariant mass distribution of $J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ candidates. (d) Experimental constraints on the decay width difference $\Delta \Gamma_s$ and CP phase $\phi_s$ in $b \to c\tau\bar{s}$ decays [7].

measurements that had been identified before the experiment started taking data [8]. The results have already had a strong impact on models of physics beyond the Standard Model, as illustrated in Fig. 4 (a). In addition there have been many interesting results in spectroscopy, observing new excited states of $B$ mesons and $\Lambda_b$ baryons, new decay modes such as $B_c^+ \to J/\psi \pi^+\pi^+\pi^-$, and studying exotic states such as the $X(3872)$. Numerous electroweak and QCD measurements have also been performed. While the majority of the results have been in good agreement with Standard Model expectations, there have been a few surprises: evidence has been seen for CP violation in charm decays, and for an isospin asymmetry in $B \to K\mu^+\mu^-$ decays, which require further study with more data. Details of all these analyses can be found in the dedicated talks from LHCb at this conference, along with their references.
Figure 4: (a) Parameter space of various models for physics beyond the Standard Model, in the plane of BR($B^{0}_s \rightarrow \mu^+\mu^-)$ vs. the $B^{0}_s$ mixing phase $S_{\psi\phi} = \phi_s$, taken from [9]; the Standard Model point is shown with a star, and the constraints from LHCb are shown by the dashed box. (b) Trigger yield for different $B$ decays normalized to the trigger yield expected in nominal conditions at a luminosity of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$; the hadronic yields saturate, while the muon triggers continue to gain with increased luminosity.

3 Plans

By the end of the extended 2012 run, LHCb expects to have tripled its data sample, ready for detailed analysis during the first long shutdown of the LHC over 2013–14. In 2015 we expect to run at 13 TeV which will give significantly higher production cross-sections for heavy flavours (increasing roughly linearly with centre-of-mass energy). In the period 2015–17 we expect to further double the integrated luminosity, to a total of around 5–7 fb$^{-1}$. At this point the data-doubling time would become excessive, so it is planned to upgrade the experiment to run at higher luminosity.

The present detector could run at luminosities $\sim 10^{33}$ cm$^{-2}$s$^{-1}$ once the machine reaches its nominal number of bunches, corresponding to 25 ns spacing. However, it is currently limited to a read-out rate of 1 MHz. To trigger at an increased event rate requires a substantial change in the LHCb read-out architecture. The present first level trigger is implemented in hardware [6]. Trigger selections are made at the 40 MHz beam crossing rate using either the calorimeters or the Muon system. Criteria are based on the deposit of several GeV of transverse energy, $E_T$, by charged hadrons, muons, electrons or photons. While this provides high efficiencies on dimuon events, it typically removes half of the fully hadronic signal decays. In these hadronic decays the $E_T$ threshold required to reduce the rate of triggered events to an acceptable level is already a significant fraction of the $B$ meson mass. Any further increase in the rate requires an increase of this threshold, which then removes a substantial fraction of signal decays. The trigger yield therefore saturates for hadronic channels with increasing luminosity, as shown in Fig. 4 (b).
The most effective way of upgrading the trigger is to supply the full event information, including whether tracks originate from the displaced vertex that is characteristic of heavy flavour decays, at each level of the trigger. This requires reading out the whole detector at 40 MHz and then analysing each event in a trigger system implemented in software. A bigger CPU farm, more disk storage and more computing power will be needed to swallow a factor 5–10 more events at the output of the software trigger. The upgraded detector will be able to collect at least 5 fb$^{-1}$ per year, for a total of 50 fb$^{-1}$ over lifetime of the upgrade. The annual signal yields will be higher by a factor of around ten for muonic $B$ decays and twenty or more for heavy-flavour decays to hadronic final states, compared to those obtained by LHCb in 2011.

The detailed physics case for the LHCb upgrade was presented in Ref. [10]. Following endorsement of the physics case by the LHCC, the experiment was encouraged to prepare Technical Design Reports (TDRs), and a Framework TDR has been submitted in May 2012 [11] giving an overview of the schedule, cost and participating institutes. After the current period of R&D it is planned to submit TDRs for the subsystems next year, to be ready for installation of the upgraded detector during the second long shutdown of the LHC in 2018. An exciting future lies ahead for the experiment, searching for signs of physics beyond the Standard Model in the flavour sector and beyond.

References

Identification of jets, $\tau$ leptons, and missing transverse energy at CMS

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1 Introduction

The CMS is one of the general purpose high energy physics detectors operating at CERN, collecting pp collision data delivered by the Large Hadron Collider. Its detailed description can be found elsewhere [1].

Data recorded by the CMS detector are successfully used to perform a wide range of physics analyses including both measurements of the standard model (SM) processes and searches for the Higgs boson and beyond SM phenomena. A crucial ingredient to the success of the CMS physics program is an excellent performance of the reconstruction and identification algorithms of final state physics objects. CMS uses the particle-flow (PF) technique [2, 4] to reconstruct all final-state particles (PF candidates) produced in the collision event using information from all CMS sub-detectors. The PF candidates are further classified as charged hadrons, neutral hadrons, electrons, muons, or photons and are used with different algorithms to identify final state physics objects: jets, $\tau$ leptons, etc. In this article I describe the identification of jets, $b$ jets, $\tau$ leptons, and an imbalance of the transverse energy, often referred to as missing transverse energy ($E_T$) or MET. The performance of the object identification is measured both in data and in the Monte Carlo (MC) simulation. The MC samples are passed through a detailed simulation of the CMS detector based on GEANT [3] and both data and MC sample are subject to the same reconstruction chain and selection criteria.

2 Jets

Jets are the experimental signatures of quarks and gluons produced in high energy processes, such as hard scattering of partons in pp collisions. Jets are reconstructed using PF candidates with the anti-$kT$ algorithm [5] with a spatial separation parameter of $R = 0.5$. Jet reconstruction performance is evaluated in MC: at first, generated jets in the event are identified using generator-level information in the same anti-$kT$
algorithm; then, to estimate the reconstruction efficiency one checks if the reconstructed jet is spatially matched to the generator-level jet using a separation in $\eta - \phi$ plane $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$.

The ability to measure energy of jets is of crucial importance for many physics analyses at CMS. Jet energy calibration is performed in order to relate energy measured in the detector jet to the energy of the true particle jet. The total correction is a multiplicative factor and is a product of different components: the offset correction ($C_{\text{offset}}$), the MC calibration factor ($C_{\text{MC}}$) and the residual calibrations, ($C_{\text{rel}}$) and ($C_{\text{abs}}$) for the relative and absolute energy scales, respectively:

$$C = C_{\text{offset}} \cdot C_{\text{MC}}(p_T', \eta) \cdot C_{\text{rel}}(\eta) \cdot C_{\text{abs}}(p_T''),$$

(1)

where $p_T'$ is the transverse momentum of the jet after applying the offset correction and $p_T''$ is the $p_T$ of the jet after all previous corrections.

The offset corrections are used to subtract the average contribution from particles from other proton-proton collisions in the same beam crossing (pileup). Two different methods are used to estimate offset corrections at CMS: jet area method [6] and average offset method, yielding very similar performance as a function of pileup as shown on Fig. 1 (left). The MC calibration factor is to correct the non-uniformity and non-linearity of energy response in pseudorapidity and jet transverse momentum, respectively. This factor is estimated from MC simulation of multi-jet events by requiring the energy of the “generator jets” to match that of the reconstructed jets. Finally, the residual corrections account for the small differences between data and simulation. The dijet $p_T$ balance technique [7] is used to measure the energy of a jet at any $\eta$ relative to the other jet identified in the central region with $|\eta| < 1.3$. The relative jet energy response measured in data is compared to one obtained from the simulation and the correction is derived to correct for the observed small differences. The absolute jet energy response is measured in the reference region of $|\eta| < 1.3$ using $\gamma^*/Z+$jet events in data and MC simulation where a jet energy scale is derived by exploiting the balance in transverse momentum between a boson and a jet in the final state.

Uncertainties from different systematic sources that affect the jet energy scale as a function of $p_T$ and $\eta$ are given in Fig. 1.

### 3 b jets

Jets arising from b quark hadronization and decay are present in a wide range of physics processes, such as the decay of top quarks, Higgs bosons, and are expected in a wide range of physics beyond the SM, such as supersymmetry. The ability to accurately identify b jets is vital in reducing the otherwise overwhelming background from gluon (g) jets, light-flavour quarks (u, d, s) and from c quark fragmentation.
Characteristic features of b quarks are the relatively large mass, high track multiplicity, and high $p_T$ of decay products with respect to b-flight direction, and long lifetime of the heavy flavour hadrons. These features are used to develop algorithms that allow distinguishing b jets from those produced by light-flavor quarks and gluons.

Important variables that hold large discriminating power to distinguish decay products of a b hadron from prompt tracks are the impact parameter (IP) of a track with respect to the primary vertex and secondary decay vertex and kinematic variables associated with this vertex. The IP is calculated in three dimensions, taking advantage of the excellent resolution of the pixel detector along the $z$ axis. The variables associated to the secondary vertex are the flight distance and direction, based on the vector between primary and secondary vertex, and various properties of the system of associated secondary tracks such as the multiplicity, the mass or the energy. These variables are used to build simple discriminator variables, such as the Track Counting and Simple Secondary Vertex algorithms [8]. Besides these, more complex methods are developed that are based on a likelihood estimation using either an IP significance of several tracks in a jet or combining secondary vertices with track-based lifetime information. These yield more complicated identification techniques, such as Jet Probability (JP), Jet B Probability, or Combined Secondary Vertex taggers [8]. Performance of these identification algorithms obtained from MC simulation are shown in Fig. 2.

Performance of these taggers is also measured in-situ using various samples and methods. Due to a large b quark mass, the muon momentum component transverse to the jet axis ($p_T^{rel}$) or IP of the muon track is larger for muons from b hadron decays than that for muons in light-flavour jets. Modeling of $p_T^{rel}$ and IP in MC simulation to represent distributions expected from b jets is used as a template and that is
Figure 2: Performance curves obtained from the MC simulation for the algorithms described in the text: light flavour efficiencies as a function of the b efficiency.

compared to the distribution observed in multijet data events. The distribution of \( p_T^{rel} \) is used to measure efficiency for low/average-\( p_T \) jets, while that of IP allows to measure efficiency for high-\( p_T \) jets. The measurements from different methods are combined based on weighted mean taking into account the correlation between uncertainties.

A large sample of pair-produced top quark events is also used to measure b-tagging efficiency using several methods. The profile likelihood ratio (PLR) method is used to measure b-tagging efficiency using dilepton final state of \( t\bar{t} \) decay. The method uses 2-dimensional distribution of the jet multiplicity versus the b-tagged jet multiplicity. The Flavor Tag Consistency method (FtCM) requires consistency between the observed and expected number of tags in the lepton+jet events from \( t\bar{t} \) process. Here as well, the results from different methods are combined using weighted mean [9].

4 Hadronically decaying \( \tau \) leptons

The products of the hadronically decaying \( \tau \) lepton (\( \tau_{had} \)) are one or three charged mesons (mostly \( \pi^+ \) and \( \pi^- \)), up to three neutral pions, and tau neutrino. Thus, its signature is similar to that expected from jets. The main reconstruction algorithm for \( \tau_{had} \) used at CMS is Hadron plus Strips (HPS) algorithm [10]. It searches for PF jets consistent with \( \tau \) lepton decaying to hadrons. The algorithm employs an optimized \( \pi^0 \) reconstruction method that accounts for a wider energy deposition profile of two spatially-close photons from \( \pi^0 \rightarrow \gamma \gamma \) decay.

The efficiency of \( \tau_{had} \) reconstruction and identification is measured in data using a sample of \( Z \rightarrow \tau\tau \) events, where one of the \( \tau \) leptons decay hadronically, and the
other one as $\tau \rightarrow \mu \nu_\mu \nu_\tau$. The events are preselected using a set of requirements to suppress the backgrounds from $Z \rightarrow \mu \mu$, $W+$jets, and multijet events, but without applying the $\tau_{\text{had}}$ identification algorithms. The $\mu \tau_{\text{jet}}$ invariant mass distributions for those events which pass or fail the $\tau_{\text{had}}$ identification are fit using signal and background templates estimated in Monte Carlo simulation. The efficiency is calculated as: $\varepsilon = N_{Z\rightarrow\mu\mu}^{\text{pass}} / (N_{Z\rightarrow\mu\mu}^{\text{pass}} + N_{Z\rightarrow\mu\mu}^{\text{fail}})$, where $N_{\text{pass}}$ ($N_{\text{fail}}$) is the number of events, after subtracting background contributions, that pass (fail) the $\tau_{\text{had}}$ identification criteria. The jet to $\tau_{\text{had}}$ misidentification rate is measured on a sample of either multijet or $W+$jets events. The measured misidentification rate as a function of efficiency is shown in Fig. 3.

![Figure 3: The measured jet to $\tau_{\text{had}}$ misidentification rate as a function of MC estimated efficiency for all working points for $\mu$-enriched multijet and $W+$jet data samples. Performance of another algorithm (TaNC) is also shown.](image)

5 Missing Transverse Energy

The missing transverse energy is associated with production of particles that escape detection: neutrinos as well as a number of exotic particles predicted by extensions of the SM. Thus, MET is of crucial importance for a number of physics analyses. The reconstruction of $E_T$ is very sensitive to the particle momentum measurements, detector malfunctions, particles impinging on poorly instrumented regions of the detector, beam-halo particles, and cosmic-ray particles.

The $E_T$ is computed using all PF candidates in event [11]. The effects due to energy scale correction for jets and other physics objects are taken into account. The missing transverse energy resolution is studied in $Z \rightarrow \mu \mu$ events that is a source of clean final state with two energetic, isolated muons and no intrinsic missing transverse
energy. Events containing signatures of instrumental noise are rejected. In well-measured event transverse momentum of a boson and hadronic activity should be balanced:

\[ \vec{p}_T + \vec{u}_T + \vec{E}_T = 0 \]  

(2)

where, \( p_T \) and \( u_T \) are transverse momentum of the boson and hadronic recoil, defined as the vector sum of the transverse momenta of all particles except the vector boson, respectively. The projections of \( u_T \) onto axis, parallel and perpendicular to the boson momentum direction, are noted as \( u_\parallel \) and \( u_\perp \), respectively. The former variable is used to obtain the energy correction to the MET in data. The MET resolution is assessed by measuring the RMS spread of \( u_\parallel \) and \( u_\perp \) about their mean values, after correcting for the energy scale. The MET resolution as a function of number of pileup vertices is shown in Fig. 4. The resolution worsens in later data of 2011 due to larger pileup contribution.

![Figure 4: The width of \( u_\parallel \) and \( u_\perp \) distributions in data and MC simulation as a function of the number of primary vertices for 2011 different data-taking period.](image)

6 Conclusion

In summary, CMS collaboration has developed a number of sophisticated and well-performing algorithms to identify jets, b jets, \( \tau \) leptons and missing transverse energy. The performance of these objects is measured using pp collision data and the MC simulation is found to describe the performance in data well. Great performance of the object identification offers unique opportunity to explore a tremendous physics program at CMS.
References


Neutral particles energy spectra for 900 GeV and 7 TeV p-p collisions, measured by the LHCf experiment

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1 Abstract

LHCf is an experiment designed to study the production in the very forward direction of neutral particles produced in collisions at the LHC. Its results are and will be used to calibrate the hadron interaction models of the Monte Carlo codes which allow the interpretation of energy spectrum and composition of high-energy cosmic rays as measured by air-shower ground detectors. The experiment has already completed data taking in proton-proton collisions at $\sqrt{s} = 900$ GeV and at $\sqrt{s} = 7$ TeV during 2009 and 2010. At the beginning of 2013 the experiment will take data again with p-Pb collisions, and then the detectors will be upgraded for the $\sqrt{s} = 14$ TeV collisions in 2014.

2 Introduction

The physics case for LHCf lies in the energy spectra and composition of cosmic rays. The AGASA [1] and HiRes [2] experiments showed a marked discrepancy in results 10 years ago over the energy spectrum at extremely high energies (the ankle region) as shown at the left in Figure 1. Recent results the Pierre Auger Collaboration [3], HiRes (final), and Telescope Array Collaboration [4] however seem to indicate the presence of a GZK cutoff. In fact the uncertainty caused by the poor knowledge of the characteristics of the interaction of particles with the Earths atmosphere at such high energies remains an important source of systematic error in the determination of energy and also of chemical composition of primary particles (right part of Figure 1).

The aim of the LHCf experiment [5, 6] is to provide experimental results useful for testing and calibrating hadronic interaction models used in Monte Carlo (MC)

¹ on behalf of the LHCf collaboration
simulation of extensive air showers, by measuring the energy spectra and the transverse momentum of neutral particles in a very high pseudo-rapidity region (\( \eta > 8.4 \), ‘forward’ region) at the Large Hadron Collider (LHC). The LHC provides the unique opportunity of studying the energy dependence of hadron interaction processes up to equivalent fixed-target energy of \( 10^{17} \) eV (at its design center-of-mass energy \( \sqrt{s} = 14 \) TeV), which corresponds to the region between the knee and the GZK cut-off of the cosmic ray spectrum.

Figure 1: Energy spectra of cosmic rays as measured by the AGASA and the HiRes experiments (left). On the right, the energy spectra of cosmic rays as measured by the Auger collaboration, compared to different model expectations. Depending on the model chosen the favoured composition goes from proton to iron.

## 3 Detector

The LHCf experiment is based on two similar detectors, i.e. two electromagnetic sampling calorimeters, made of plastic scintillator and tungsten layers, complemented by a tracking system. Each detector, respectively called Arm1 and Arm2, consists of two independent calorimeter towers enclosed in a box which contains also part of the front-end electronics (see Figure 2. Detailed information about these detectors can be found in references [5, 6]. During data taking the detectors are positioned in such a way that one of the calorimeter towers, the smallest one, lies directly along the beam line at zero degrees. The LHCf standard run configuration, established for the past running and foreseen also for the future 14 TeV pp run, requires the installation of both detectors inside the reserved slots of the two TAN absorbers located 140 m on opposite sides of Interaction Point 1 (IP1) (as shown in Figure 3. This not only allows a comparison of the results between the two detectors which is very useful for systematic error checking, but also allows the study of double diffractive events.
4 Data taking and results

LHCf took data with stable beams at 900 GeV from December 6th to December 15th 2009 and from May 2nd to May 27th 2010. It then took data at 7 TeV from March 30th to July 19th 2010. Data was taken at 0 and 100 µrad crossing angle for different vertical detector positions. Table 1 summarises the acquired triggers and the type of events acquired. Details on event selection and analysis are provided in [7]. Basically the energy of photons is determined from the signals produced in

<table>
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<th>Showers</th>
<th>γ</th>
<th>Hadrons</th>
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<td>46,800</td>
<td>4,100</td>
<td>11,527</td>
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<tr>
<td>ARM2 (900 GeV)</td>
<td>66,700</td>
<td>6,158</td>
<td>26,094</td>
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<td>ARM1 (7 TeV)</td>
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<td>56,846,874</td>
<td>111,971,115</td>
<td>344,526</td>
</tr>
<tr>
<td>ARM2 (7 TeV)</td>
<td>160,587,306</td>
<td>52,993,810</td>
<td>104,381,748</td>
<td>676,157</td>
</tr>
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Table 1: Number of events acquired and then selected as photons or hadrons (neutrons).
the scintillators, after applying corrections for the non-uniformity of light collection and for particles leaking in and out of the edges of the calorimeter towers. In order to correct for these effects and to reject events with more than one shower inside the same tower (multi-hit events) the transverse impact position of showers provided by the position sensitive detectors is used. Events produced by neutral hadrons are selected by simple identification criteria based on the longitudinal development of the shower. Figure 4 shows the single photon spectra measured by LHCf in the two pseudo-rapidity regions for 7 TeV and 900 GeV p-p collisions (roughly corresponding to the small calorimeter tower and the larger one respectively), compared with results

Figure 4: Single photon energy spectra measured by LHCf (black dots) for $\eta > 10.94$ (top left) and $8.81 < \eta < 8.99$ (top right) in 7 TeV proton-proton collisions, and for $\eta > 10.15$ (bottom left) and $8.77 < \eta < 9.46$ (bottom right) in 900 GeV proton-proton collisions. The MC results predictions for DPMJET III 3.04 (red), QGSJET II-03 (blue), SIBYLL 2.1 (green), EPOS 1.99 (magenta) and PYTHIA 8.145 (yellow) are shown. Error bars show the statistical error and the grey shaded areas the systematic error for experimental data. Figures from [8, 9].
predicted by MC simulations using different models, namely DPMJET III-3.04 [10], QGSJET II-03 [11], SIBYLL 2.1 [12], EPOS 1.9 [13] and PYTHIA 8.145 [14]. Statical errors and systematic uncertainties are also plotted. A careful study of systematic uncertainties has been done and conservative estimates have been taken into account. Further details can be found in [8, 9]. A clear discrepancy is present between the experimental results and the predictions of the models in particular at high energies.

The LHCf experiment has recently finished the analysis of the transverse momentum spectra for \( \pi^0 \) produced in 7 TeV proton collisions at LHC [16]. The integrated luminosities corresponding to the data used in this analysis are 2.53 nb\(^{-1}\) (Arm1) and 1.90 nb\(^{-1}\) (Arm2).

![Figure 5: Combined \( p_T \) spectra of the Arm1 and Arm2 detectors [16] (black dots) and the total uncertainties (shaded triangles) compared with the predicted spectra by hadronic interaction models.](image)

The \( \pi^0 \) are reconstructed in LHCf through the identification of their decays in two photons. Events are selected by requiring that each tower has only one well isolated photon. Because of the limited detector geometrical acceptance only photons from \( \pi^0 \) decays with an opening angle of \( \theta < 0.4 \) mrad can be detected. Energy, \( p_T \) and rapidity of the \( \pi^0 \) are reconstructed through the measurement of the photon energy and incident position in each calorimeter tower. Figure 5 shows the \( p_T \) spectra
predicted by DPMJET 3.04, QGSJETII-03, SIBYLL 2.1, EPOS 1.99, and PYTHIA 8.145 (default parameter set) to the combined ARM1 and ARM2 $p_T$ spectra (black dots), for different rapidity bins. Error bars take into account both statistical and systematic uncertainties. Among hadronic interaction models tested in this analysis, EPOS 1.99 shows the best overall agreement with the LHCf data. DPMJET 3.04 and PYTHIA 8.145 and SIBYLL 2.1 in general have harder spectra than the LHCf data. Finally, QGSJET II-03 predicts $\pi^0$ spectra that are softer than LHCf data and other models.

5 Conclusions and future activities

LHCf will measure very forward particle emission in the LHC p-Pb collisions at the beginning of 2013. The measurement is expected to constrain the nuclear effect for forward particle emission relevant to the CR-Air interactions, useful for model calibration [8]. Further improvements in data analysis for the 2009-2010 runs will provide the measurement of the neutral hadron spectra.

Also the LHCf collaboration is upgrading of the detector to improve the radiation resistance for the 14 TeV p-p run, currently foreseen in 2014. To this purpose the scintillating part of the detector is being replaced with GSO plates [16]. Planned improvements in the front-end electronics of the silicon position sensitive layers of ARM2 detectors to reduce the saturation effects, as well as an optimisation of the layout in the silicon layers will allow the use of the silicon strips also for calorimetry and not only for shower profile determination.

We acknowledge and are grateful to the LHC machine people who, through their constant and unrelenting effort, have allowed LHCf to achieve these results.

References


1 Introduction

The extreme conditions of high energy density and high temperature achieved in Pb–Pb collisions at LHC energies are expected to realize a deconfined plasma of quarks and gluons (the so-called Quark-Gluon Plasma, QGP [1]), from which a phase transition to ordinary colourless hadronic matter takes place as a consequence of subsequent expansion and cooling down. ALICE (A Large Ion Collider Experiment, [2]) is the LHC experiment dedicated to the investigation of the nature and the properties of the QGP using heavy-ion collisions. Especially, it is designed and built to cope with the high track density environment expected in Pb–Pb collisions. ALICE also can provide unique information on low-$p_T$ pp physics (thanks to the low material budget and low magnetic field of 0.5 T), which makes the experiment complementary to CMS and ATLAS.

ALICE addresses many observables, spanning from the global characteristics of the events (such as multiplicity densities and rapidity distributions), to more specific QGP signals (like direct photons, charmonium and bottomonium). One of the basic requirement in order to carry out such measurements is an excellent particle identification (PID) performance. Making use of all known PID techniques, the ALICE detector is capable to identify hadrons and leptons over a very wide momentum range covering three orders of magnitudes, from $\sim 100\,\text{MeV}/c$ to $\sim 100\,\text{GeV}/c$.

In the following sections, the ALICE detector will be briefly described (see Sec. 2). The PID techniques used by the experiment will be presented in Sec. 3. Finally, a few examples of PID applications in physics analyses will be presented (Sec. 4). The conclusions will be drawn in Section 5.
Figure 1: Left panel: schematic view of the ALICE detector. Right panel: ITS $dE/dx$ resolution as a function of $p_T$ from data (filled markers) and Monte Carlo simulations (hollow markers). The performance is shown for the two different configurations, when either only three layers give a signal (red), or all of them (blue).

the global tracking due to the spacial acceptance and the intrinsic $p_T$ cutoff of the outer detectors, and to particle decay.

The ALICE Time Projection Chamber (TPC), following the ITS in radial direction, is the main ALICE tracking detector. Its tracking efficiency reaches $\sim 80\%$ in $|\eta| < 0.8$ with a momentum resolution $\sigma(p_T)/p_T \sim 5\%$, which gets down to $\sim 2.5\%$ up to $p_T = 10$ GeV/$c$ (and increasing at higher transverse momenta) when combined with the ITS. Each track in the TPC is reconstructed using up to a maximum of 159 space points, with a resolution of 0.8 mm in the xy plane, and 1.2 mm in the z direction.

After TPC comes the Transition Radiation Detector (TRD), mainly dedicated to the electron identification. The TRD is followed by the Time Of Flight detector (TOF), at a radius of 3.7 m from the interaction point.

In the central $\eta$ region, ALICE has several detectors, referred to as single-arm detectors, which have a limited acceptance. Namely, they are a Cherenkov RICH detector (the HMPID), a homogeneous photon spectrometer (PHOS), and a sampling electromagnetic calorimeter (EMCAL). At forward rapidities, a Photon Multiplicity Detector (PMD) and a muon spectrometer (MUON) are placed.

Some more detectors complete the ALICE setup, but they won’t be described in these proceedings since they do not contribute to the particle identification of the experiment. For more details about them and about the other ALICE detectors in general, see [2].

3 ALICE PID

Out of the 16 detectors in ALICE, 6 provide particle identification information, using all the PID techniques known nowadays, implementing them at their state of art. Below, the different ALICE PID procedure will be presented. It is worth to mention that on top of PID
technologies, ALICE identifies also cascades, V0 and kinks thanks to its excellent capability for tracking and secondary vertex determination.

3.1 PID in the central barrel

The central barrel detectors (i.e. those with full \(\phi\) coverage) perform particle identification using the specific energy loss of a charged particle traversing a medium, the transition radiation emitted by charged particles when crossing the boundary between two materials, and the time of flight that it takes to a charged particle to reach a detector’s sensitive volume from the interaction point.

\(dE/dx\) measurements are provided by the last four layers of the ITS detector, i.e. the SDD and the SSD, thanks to their analog readout. A truncated mean is applied to the measurements, that is, an average of the lowest two is taken if all the four layers gave a signal, or a weighted average is taken if only three are available. The ITS PID is performed in the low \(p_T\) region, up to \(\sim 1\) GeV/\(c\), and pions reconstructed in standalone mode can be identified down to \(\sim 100\) MeV/\(c\). The right panel of Fig. 1 shows the \(dE/dx\) resolution achieved by the ITS detector which stays around 10-15% over the whole \(p_T\) range.

The ALICE TPC detector adds PID information using specific energy loss measurements as well. Also in this case, a truncated mean is applied over the maximum number of 159 cluster information. The performance is excellent, with a resolution of \(\sim 5\%\) calculated for isolated tracks, in the cases when 159 space points were available. In addition to the identification of charged hadrons up to \(p_T \sim 1 – 2\) GeV/\(c\), the TPC wide dynamic range (up to 26 MIP) allows to identify light nuclei, as shown in the left panel of Fig. 2. Moreover, while in the \(1/\beta^2\) Bethe-Bloch region of the \(dE/dx\) distribution particle identification for individual tracks is possible, in the region of relativistic rise a statistical approach is utilized, allowing the TPC to identify charged hadrons up to \(p_T\) of a few tens of GeV/\(c\).

Electron identification in ALICE is carried out by the TRD in the momentum region \(p > 1\) GeV/\(c\), with a pion rejection factor of 100. The PID relies on a 1-dimensional likelihood approach, which makes it possible to distinguish between pions and electrons due to the different shapes of the signals they release in the detector\(^1\).

Charged hadrons in the intermediate momentum range (i.e. up to a few GeV/\(c\)) are identified in ALICE by the TOF detector. In this case, the mass (and as a consequence the identity) of a particle is obtained by combining the measurement of its time of flight (from TOF) and its momentum (from ITS and TPC). The reference time of the event is given by a combination of the the event time information from the ALICE T0 detector, and the one estimated from the particle arrival times measured by TOF. The right panel of Fig. 2 shows the TOF resolution for the identification of pions (the most abundant particle specie) in terms of the difference between the measured time of flight, and the expected one calculated from the track length and momentum assuming that the particle is a pion. As one can see, the detector performance is outstanding, with < 90 ps of resolution.

\(^1\)The signal from electrons in a TRD detector is characterized by a further peak at late times due to the presence of transition radiation photons, which is absent in the case of pions.
3.2 PID with single-arm detectors

Hadron identification at high momenta (up to 3–5 GeV/c depending on the specie) is performed by the HMPID detector. This is a single-arm proximity focusing RICH, which determines the $\beta$ of a particle from the measurement of the Cherenkov angle. This information is then combined with the momentum measured by the TPC and ITS to assign an identity to the particle. The left panel of Fig. 3 shows the Cherenkov angle measured by the HMPID as a function of $p$. As one can see, the $\pi$, K and p bands are clearly distinguishable.

The two ALICE electromagnetic calorimeters, PHOS and EMCAL, have partial $\eta$ and $\phi$ coverage as well. They measure $\gamma$ up to 100 and 250 GeV respectively. The EMCAL is also used in ALICE to help hadron rejection when identifying electrons, thanks to the $E/p$ distribution characteristically peaked at 1 only for electrons due to their small mass.

At forward rapidities where the multiplicities are too high to use calorimetry, photons are identified in ALICE also using the PMD, through the pre-shower method.

On the opposite side of the experiment, a MUON spectrometer reconstructs and identifies muons in the momentum range $p > 4$ GeV. Hadron rejection is possible requiring matching between the tracks reconstructed by the tracking chambers with one track segment in the triggering chambers. Moreover, geometrical and topological cuts are applied in order to reduce contamination from fake tracks, and Monte Carlo simulations are used to estimate muon contributions from hadron decays. The right panel of Fig. 3 shows the invariant mass distribution of $\mu$ pairs ($1 < p_T < 4$ GeV/$c$) reconstructed and identified by the MUON detector after background subtraction. The various contributions to the spectrum are shown.

Figure 2: Left panel: Energy loss measured by the TPC as a function of rigidity for negative tracks. The inset shows the distribution of $m^2/z^2$ for the light nuclei candidates obtained with the TOF detector. Right panel: Difference between the measured and the expected time of flight in the pion hypothesis. Superimposed, the gaussian fit of the distribution.
Figure 3: Left panel: Cherenkov angle measured by the HMPID as a function of $p$. Right panel: Invariant mass distribution of muon pairs measured by the MUON detector.

4 Physics Results with PID

Many of the ALICE physics results rely on Particle Identification. Since a comprehensive review is not possible in these proceedings, only a few examples will be presented. For more information about the ALICE results, see [3].

Hadron identification is one of the key elements in the femtoscopy studies. These are aimed at the measurement of the size and shape of the emitting source especially important in Pb–Pb collisions, by utilizing the Bose-Einstein correlations between identical particles. When pion pairs are used, the particle identification response of the TPC is used. Studies are also made for charged kaons, and in this case the analysis depends on both TPC and TOF PID. Recently, results using neutral kaons have also become available despite the smaller statistics, in this case, the topological PID is exploited for the $K_0$ identification.

The knowledge of the particle composition of the low $p_T$ hadrons at mid-rapidity is important in order to understand the hadronization mechanisms. ALICE combines the responses of its different PID detectors in order to build the identified charged hadrons spectra as shown in the left panel of Fig. 4 for the case of positive pions, kaons and protons. Here, the ITS, TPC and TOF PID information\(^2\) are used allowing to extend the PID reach of the experiment. The fit with the Lévy function are superimposed.

The right panel of Fig. 4 shows the inclusive electron spectrum measured by ALICE in pp collisions at 7 TeV. Here, the results from three different analysis based on the use of different combination of detectors are superimposed. Up to 3 GeV/c, the TPC and TOF are used for the identification of electrons; in the range $1 < p_T < 8$ GeV/c, the TRD is included in the analysis. Finally in the $p_T$ range between 3 and 7 GeV/c the EMCAL is used together with the TPC. From the figure one can see their remarkable agreement in the overlapping ranges, and will infer the complementarity of the ALICE PID techniques.

\(^2\)The inclusion in the analysis of the HMPID is ongoing.
Figure 4: Left panel: Identified pions, kaons and protons using the combination of the information from ITS, TPC and TOF. The Lévy fit are superimposed. Right panel: Inclusive electron spectrum measured by three ALICE analysis using different detectors.

5 Conclusions

The ALICE experiment at the LHC is endowed with many different PID detectors. Thanks to the different momentum range that they cover, the ALICE PID capability is extended to a broad momentum interval. The use of the most up-to-date techniques and technologies makes ALICE PID capabilities unique. Many analysis reckon on PID results, both in pp and Pb–Pb collisions. The outstanding PID results demonstrates that ALICE is fully complying with its wide and varied physics program.

References


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Measurement of the $t$-channel single top-quark production with the ATLAS detector

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1 Introduction

At the LHC, single top-quark production can occur in three processes. The dominant process, the $t$-channel exchange of a virtual $W$ boson, has a predicted top-quark production cross section of 41.9 pb and top-antiquark cross section of 22.7 pb [1]. The difference between the top-quark and -antiquark cross sections is directly related to the difference of the up-quark and the down-quark density functions (PDF) of the proton. This report presents measurements of the cross-sections of single top-quark and single top-antiquark production, $\sigma_t(t)$ and $\sigma_t(t)$ in the $t$-channel, and a measurement of the cross-section ratio $R_t \equiv \sigma_t(t)/\sigma_t(t)$ [3] at a center-of-mass energy of $\sqrt{s} = 7$ TeV with 4.7 fb$^{-1}$ of data recorded by the ATLAS detector [2] in 2011. The measurements of $\sigma_t(t)$, $\sigma_t(t)$ and $R_t$ are sensitive to the PDFs of the $u$-quark and the $d$-quark in the momentum fraction ($x$) regime of $0.02 < x < 0.5$.

2 Measurement of the $t$-channel cross-section ratio

The single top signal includes a $b$ quark and a $W$ boson, that decays leptonically, from the top decay as well as additional jets. The main backgrounds to the single-top quark final state are multijet events, $W$ boson production in association with jets, and top pair production ($tt$), that are reduced by the event selection. Lepton candidates, $e$ or $\mu$, are required to be well reconstructed and isolated and to have $p_T > 25$ GeV and $|\eta| < 2.5$. Only jets with $p_T > 25$ GeV and $|\eta| < 4.5$ are considered. Jets containing bottom quarks are tagged in the region $|\eta| < 2.5$ using a neural network technique. The final event selection requires exactly one charged lepton, two jets or three jets, and missing transverse energy $E_T^{\text{miss}} > 30$ GeV. The multijet background contribution is reduced by requiring the $W$ transverse mass $m_T(W) > 30$ GeV.

The multijet background is estimated using a data-driven method and performing a binned maximum likelihood fit to the $E_T^{\text{miss}}$ distribution. The kinematic distributions for the $W$+jets background are taken from Monte Carlo samples, while the
overall normalisation and the flavour composition are derived from data when extracting the result of the analysis. The $t\bar{t}$ background and other smaller backgrounds are normalised to their theory predictions.

![Figure 1: Measurement of $R_t$ with its statistical (yellow band) and total (green band) uncertainty compared to the calculated values for different NLO PDF sets [3].](image)

The analysis is performed in four independent channels: $l^+$ and $l^-$ for two and three jets. In each channel a neural network combines a maximum of 19 variables into one discriminant. The variables with the most discriminating power are the reconstructed top-quark mass $m_{t\ell\nu}$, and the pseudorapidity of the untagged jet $|\eta(\text{u-jet})|$. The effects of systematic uncertainties on the measurement, that affect the normalisation of the individual backgrounds, the signal acceptance and the shape of the individual predictions, are taken into account with pseudo-experiments. Thus, uncertainties on the object modeling, the Monte Carlo generators, the PDFs, the background normalisation to data, and integrated luminosity are considered in the measurement.

To extract the signal content of the selected sample, we perform a simultaneous maximum likelihood fit to all four NN output distributions. The measured $t$-channel single top-quark production cross section is $\sigma_t(t) = 53.2 \pm 1.7\,\text{(stat.)} \pm 10.6\,\text{(syst.)}\,\text{pb}$, while the top-antiquark production cross section is $\sigma_t(\bar{t}) = 29.5 \pm 1.5\,\text{(stat.)} \pm 7.3\,\text{(syst.)}\,\text{pb}$. This results into a measured cross-section ratio of $R_t = 1.81 \pm 0.10\,\text{(stat.)}^{+0.21}_{-0.20}\,\text{(syst.)}$. The measured value of $R_t$ is compared to the predictions obtained with different PDF sets in Figure 1.

References


Fourth generation searches at ATLAS

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In the following, four analyses with searches for heavy quarks of a 4th generation are presented. The analysed data (1 fb$^{-1}$) were taken with the ATLAS detector [1] at the LHC at $\sqrt{s} = 7$ TeV. All analyses assume QCD pair-production of these Dirac fermions as a simple extension of the three generations Standard Model (SM), where the up-type quark is noted as $t'$ and the down-type quark as $b'$.

4th generation quarks could play an interesting role in electroweak symmetry breaking [2]. A SM with four generations has also the property to generate gauge coupling unification at a scale of order $10^{15} - 10^{16}$ GeV [3]. There are also discussions in the literature if a fourth generation of quarks could play a central role in baryogenesis [4].

In the presented analyses, events are selected passing single electron or muon triggers. Electrons are selected with a transverse energy of $E_T > 25$ GeV, tight quality selection criteria, calorimeter isolation, and must be within $|\eta| < 2.47$ ($\eta = -\ln \tan \theta/2$), excluding $1.37 < |\eta| < 1.52$. Muons are selected with a transverse momentum $P_T > 20$ GeV, $|\eta| < 2.5$, isolation and a veto on cosmic muons. Muons overlapping with jets are removed. Jets are reconstructed with an anti-$k_T$ algorithm and are required to have $P_T > 25$ GeV (unless otherwise stated) and $|\eta| < 2.5$. Jets overlapping with electrons are removed. $H_T$ is defined as the scalar sum of jets and leptons $P_T$. The dilepton analyses apply cuts on the invariant mass $m_{\text{inv}}$ of the leptons ($ee/\mu\mu$) of $m_{\text{inv}} > 15$ GeV and $m_{\text{inv}} \notin [81, 101]$ GeV.

$m_T = \sqrt{2E_T^{\text{Miss}}P_T^\ell \left(1 - \cos \left(\Delta \Phi \left(E_T^{\text{Miss}}, P_T^\ell\right)\right)\right)}$ describes the transverse mass of lepton $\ell$ and neutrino in the single lepton analyses.

In [5] $b'$ quarks are searched for in single lepton final states ($b' \rightarrow tW$, branching ratio BR=100%), where the events are required to have at least six jets, missing transverse energy $E_T^{\text{Miss}} > 35$ GeV and $m_T > 25$ GeV ($e$ events), $E_T^{\text{Miss}} > 20$ GeV and $E_T^{\text{Miss}} + m_T > 60$ GeV ($\mu$ events) and high-$P_T$ $W$ decays into two jets are identified. The signal is extracted by a binned maximum-likelihood fit of nine bins in $(N_W, N_{\text{jets}})$, where $N_W = 0, 1, \geq 2$ describes the number of reconstructed $W$ bosons and $N_{\text{jets}} = 6, 7, \geq 8$ the number of jets. No excess is found and a limit of $m_{b'} > 480$ GeV (Fig. 1) is set.

In [6] $b'$ quarks are searched for in same-sign dilepton final states ($b' \rightarrow tW$, BR=100%). The events are required to have at least two jets ($P_T > 20$ GeV), $H_T > 350$ GeV and $E_T^{\text{Miss}} > 40$ GeV. The signal is extracted by a single-bin counting experiment. No excess is observed and a limit of $m_{b'} > 450$ GeV is set.
In [7] t’ quarks are searched for in single lepton final states, \((t' \rightarrow bW, \text{BR}=100\%)\) where the events are required to have at least three jets (one with \(P_T > 60\text{ GeV}\)), at least one b-jet, \(E_T^{\text{Miss}} + m_T > 60\text{ GeV}\), \(E_T^{\text{Miss}} > 35\text{ GeV (e events)}\) and \(E_T^{\text{Miss}} > 20\text{ GeV (\(\mu\) events)}\). The reconstructed \(t’\) mass \(m_{\text{reco}}\) is used as discriminant in the signal extraction. No excess is found and a limit of \(m_{t'} > 404\text{ GeV}\) is set.

In [8] heavy 4th generation quarks \(Q\) (benchmark model: \(t'\)) are searched for in opposite-sign dilepton final states \((Q \rightarrow qW)\), where the events are required to have at least two jets, \(H_T > 130\text{ GeV (e\(\mu\) events)}\) and \(E_T^{\text{Miss}} > 60\text{ GeV (ee/\(\mu\mu\) events)}\). The signal is extracted by a fit of \(m_{\text{coll}}\), which is the reconstructed heavy quark mass assuming the neutrinos from \(Q \rightarrow qW \rightarrow q\ell\nu\) are approximately collinear to the charged leptons. No significant excess over expected background is observed and a limit of \(m_Q > 350\text{ GeV}\) is set.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{Left: Discriminant. Right: Limit on \(b'\) mass in single lepton final states [5].}
\end{figure}

References

Search for Supersymmetric particles using final states with one lepton, jets and missing transverse momentum with ATLAS detector

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Supersymmetry (SUSY) is one of the promising theories which propose a solution to the hierarchy problem of the Standard Model (SM) and a natural candidate for dark matter. We search for a SUSY signature in the final state with one isolated lepton, multijets, and large missing transverse momentum ($E_T^{miss}$). The full dataset (4.7 fb$^{-1}$) recorded by the ATLAS [1] detector at $\sqrt{s} = 7$ TeV in 2011 is used in the analysis.

As a pre-selection, exactly one isolated electron (muon) with $p_T > 25$ (20) GeV, transverse mass $m_T > 100$ GeV, and $E_T^{miss} > 250$ GeV are required. Events with additional leptons are vetoed. To cover both squark-pair production and gluino-pair production, two signal regions (3-jet SR and 4-jet SR) are defined after the pre-selection. The 4-jet SR has at least four jets with $p_T > 80$ GeV and $E_T^{miss}/m_{eff} > 0.2$ and $m_{eff} > 800$ GeV, where $m_{eff}$ is the scalar sum of the transverse momenta of the lepton, $E_T^{miss}$ and jets. The 3-jet SR is required to have a leading jet with $p_T > 100$ GeV, at least two additional jets with $p_T > 25$ GeV, $E_T^{miss}/m_{eff} > 0.3$ and $m_{eff} > 1200$ GeV; Events in which the second, third and fourth jets have $E_T > 80$ GeV are removed from the 3-jet SR as these events are in the 4-jet sample.

Further improvement in sensitivity is achieved by splitting the SRs into bins in $m_{eff}$, thereby the shape differences of signal and backgrounds are taken into account.

The dominant backgrounds in both of the SRs are W+jets and $t\bar{t}$, which are estimated by Monte Carlo simulation. They are normalized in two dedicated Control Regions (CRs), where the following kinematic selections are applied to enhance the components: $m_T = 40 - 80$ GeV, $E_T^{miss} = 30 - 120$ GeV, $m_{eff} > 400$ GeV, and at least three jets with $p_T > 25$ GeV are required, where the leading jet should have $p_T > 80$ GeV. W+jets and $t\bar{t}$ components are then separated by the existence of $b$-jet in the leading 3jets. If there is at least 1 $b$-tagged jet, the event is classified into $t\bar{t}$ CR, and if there is no $b$-tagged jet, then the event goes to W+jets CR.

The dominant uncertainty in the SR prediction comes from the shape variation caused by the energy scale uncertainty of jets. Multijets background is estimated in a data-driven way.

\[^{1}m_T = \sqrt{2p_T^{lep} E_T^{miss} (1 - \cos \Phi(lep, E_T^{miss}))}\]
As shown in Figure 1, three events are observed in 3jet-SR, where the SM predicts 5.7±4.0 events, while six events are found in 4jet-SR, which is consistent with our expectation of 8.3±3.1. Since no significant excess is observed in both of the SRs, 95% CL exclusion limit is calculated in the MSUGRA/CMSSM model (Figure 2). Squark mass has been excluded up to 1.2 TeV.

Figure 1: m_{eff} distributions in 3jet-SR(left) and 4jet-SR(right) [2].

Figure 2: Expected and observed 95% CL exclusion limits [2].

References


Parameters of the Neutrino sector in tau decays

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1 Introduction

The smallness of the neutrino masses can be well understood within the see-saw mechanism (type I). After spontaneous symmetry breaking of the Standard Model gauge group one obtains a $(n_L + n_R) \times (n_L + n_R)$ Majorana mass matrix $M_\nu$ for neutrinos. The mixing between the $n_R$ ”right-handed” singlet fermions and the neutral parts of the $n_L$ lepton doublets gives masses for the neutrinos which are of the size expected from neutrino oscillations.

The diagonalization of the mass matrix gives rise to a split spectrum consisting of heavy and light states of neutrinos given by $U^T M_\nu U = \text{diag}(m_{\text{light}}^{i}, m_{\text{heavy}}^{i})$. For the case $n_R = 1$ we diagonalize $M_\nu$ with a rotation matrix determined by two angles, two masses, and Majorana phases. For the case $n_R = 2$ we diagonalize the mass matrix with a unitary matrix determined by complex parameters, four masses, and Majorana phases. In both cases we take $n_L = 3$.

We calculate the one-loop radiative corrections to the mass parameters which produce mass terms for the neutral leptons. In both cases we numerically analyse light neutrino masses as functions of the heavy neutrino masses.

2 Discussion

At the tree level the mass terms for the neutrinos can be written in a compact form as a mass term with a $(n_L + n_R) \times (n_L + n_R)$ symmetric mass matrix $M_\nu = \left( \begin{array}{cc} 0 & M_D^T \\ M_D & M_R \end{array} \right)$, where $M_D$ is $n_L \times n_R$ Dirac neutrino mass matrix and $M_R$ is a diagonal matrix. $M_\nu$ can be diagonalized as $U^T M_\nu U = \hat{m} = \text{diag}(m_1, m_2, \ldots, m_{n_L+n_R})$, where the $m_i$ are real and non-negative. In order to implement the seesaw mechanism [1] we assume that the elements of $M_D$ are of order $m_D$ and those of $M_R$ are of order $m_R$, with $m_D \ll m_R$. Then, the neutrino masses $m_i$ with $i = 1, 2, \ldots, n_L$ are of order $m_D^2/m_R$, while those with $i = n_L + 1, \ldots, n_L + n_R$ are of order $m_R$. 

1
One-loop corrections to the mass matrix, i.e. the self energies, are determined by the neutrino interactions with the Z boson, the neutral Goldstone boson $G^0$, and the Higgs boson $h^0$ [2]. Each diagram contains a divergent piece but when summing up the three contributions the result turns out to be finite [3].

First we consider the minimal extension of the standard model adding only one right-handed field $\nu_R$ to three left-handed fields contained in $\nu_L$. We use the parametrization of $M_D = m_D \vec{a}^T$ with $|\vec{a}| = 1$. Working at tree level, we can construct the diagonalization matrix $U$ from two diagonal matrices of phases and three rotation matrices $U = \hat{U}_\phi(\phi_i)U_{12}(\alpha_1)U_{23}(\alpha_2)U_{34}(\beta)\hat{U}_i$, where the angle $\beta$ is determined by the masses of light and heavy neutrinos. The values of $\phi_i$ and $\alpha_i$ can be chosen to cover variations in $M_D$. The radiative corrections give mass to the second lightest neutrino. The third lightest neutrino remains massless.

If we add two singlet fields $\nu_R$ to three left-handed fields $\nu_L$, the radiative corrections give masses to all three light neutrinos. Now we parametrize $M_D = \begin{pmatrix} m_{D_2} \vec{a}^T \\ m_{D_1} \vec{b}^T \end{pmatrix}$ with two vectors, which $|\vec{a}| = 1$ and $|\vec{b}| = 1$. The diagonalization matrix for tree level $U = U_{12}(\alpha_1, \alpha_2)U_{eq\nu}(\beta_i)\hat{U}_\phi(\phi_i)$ is composed of a rotation matrix, an eigenmatrix of $M_\nu M_\nu^T$ and a diagonal phase matrix, respectively.

The full results with discussions are presented in [4]. For the case $n_R = 1$ we can match the differences of the calculated light neutrino masses to $\Delta m^2_{\odot}$ and $\Delta m^2_{\text{atm}}$ only for a mass of the heavy singlet of order $10^{17}$ GeV.

In the case $n_R = 2$ we obtain three non vanishing masses of light neutrinos for normal hierarchy. The numerical analysis shows that the values of light neutrino masses (especially of the lightest mass) depend on the choice of the heavy neutrino masses. The radiative corrections generate the lightest neutrino mass and have a big impact on the second lightest neutrino mass.

In future we plan to apply our parametrization to study the $\tau$ polarization coming from the decay of a $W$ boson in the data of the CMS experiment at LHC and thus determine restrictions to the parameters of the neutrino sector.

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References


Search for Supersymmetry in Final States with a Single Lepton, B-jets and Missing Transverse Energy at the CMS Experiment

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1 Introduction

Searches for new physics in states with third generation quarks at the Large Hadron Collider are motivated by various extensions of the Standard Model (SM). Among these, supersymmetric models are regarded as attractive as they resolve the hierarchy problem and may yield the unification of the electroweak and strong interactions. Supersymmetry (SUSY) (see e.g. [1]) predicts that for each Standard Model particle there exists a partner particle (sparticle) with identical gauge quantum numbers, but a spin differing by 1/2. Assuming $R$-parity conservation, sparticles are produced in pairs and their decay chains terminate with the lightest supersymmetric particle (LSP), which is stable. In proton-proton collisions predominantly colored sparticles will be produced. In scenarios with light top and bottom squarks this may result in an excess of events with a large b-jet multiplicity.

The analysis outlined in the following is based on data recorded at the CMS experiment in proton-proton collisions at a center of mass energy of $\sqrt{s} = 7$ TeV during 2011, corresponding to an integrated luminosity of 4.96 fb$^{-1}$. The complete CMS publication and a description of the CMS detector can be found elsewhere [2, 3].

2 Event Selection and Background Estimation

Events with exactly one isolated muon or electron with a transverse momentum of $p_T > 20$ GeV and at least four jets with $p_T > 40$ GeV reconstructed with the anti-$k_T$ algorithm with a distance parameter of 0.5 are selected. In addition the missing transverse energy ($E_T^{\text{miss}}$) is required to be larger than 60 GeV and $H_T$, which is defined as the scalar sum of the $p_T$ of the selected jets, to be larger than 375 GeV. Jets are identified as b-jets if they have at least two tracks with an impact parameter significance greater than 3.3 [4]. The decay of colored sparticles is expected to result in a large hadronic activity (as measured by $H_T$) and a significant amount of $E_T^{\text{miss}}$. 
which can be quantified by $Y_{MET} \equiv \frac{E_{T}^{miss}}{\sqrt{H_T}}$. As for the main background, $t\bar{t}$ events, $H_T$ and $Y_{MET}$ are nearly uncorrelated, the number of background events in a signal region at large values of $E_{T}^{miss}$ and $Y_{MET}$ is estimated from data in background enriched control regions at low values of $E_{T}^{miss}$ or $Y_{MET}$ using a factorization method.

3 Results and Interpretation

No excess of events has been observed. The obtained results are used to set limits upon the parameters of different SUSY models using the CLs technique [5]. Limits for the Constrained Minimal Supersymmetric Standard Model (cMSSM) with $\tan \beta = 10$, $A_0 = 0$, and $\mu > 0$ and a heavy flavor simplified model after the additional requirement of at least one b-jet and at least three b-jets, respectively, are shown in Fig. 1. The simplified model covers the pair production of gluon partner particles that decay into a $t\bar{t}$ pair and the LSP.

Figure 1: The 95% CL limits for the cMSSM and a heavy flavor simplified model.

References

Search for a Light Higgs Boson at BABAR

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1 Introduction

A light CP-odd Higgs Boson ($A^0$) is predicted in extensions to the Standard Model such as Next-to-Minimal Supersymmetry (NMSSM) [1]. Such Higgs with a mass less than two bottom quarks is not excluded from LEP constraints. We search for $\Upsilon \rightarrow \gamma A^0; A^0 \rightarrow$ muons, tauons, invisible, hadrons or photons at BABAR. We have a sample of 122M $\Upsilon(3S)$, 99M $\Upsilon(2S)$, and 23M $\Upsilon(1S)$.

2 Results

BABAR could not find evidence of such Higgs. We exclude some parameters space of NMSSM as shown in Figure 1 for Higgs goes to muons [2] and tauons [3]. The dots come from Dermisek’s theory paper [1] and boxes are parameters space excluded by BABAR data. Other analyses are still in progress.

References


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Figure 1: NMSSM parameters space excluded by BABAR data for Higgs goes to muons (upper) or tauons (lower). Dots are branching fraction predictions. Boxes are our ranges of exclusion at different masses. The horizontal positions of different coloured boxes are separated for clarity. Blue is for Higgs mass less than two tauons, red is for Higgs mass less than $7.5\text{GeV/c}^2$, green is for Higgs mass less than $8.8\text{GeV/c}^2$, and black is for Higgs mass less than $9.2\text{GeV/c}^2$. 


Search for Contact Interaction in dilepton events from pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

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1 Introduction

A wide range of new physics phenomena such as quark/lepton compositeness, extra dimensions and new gauge bosons can produce modifications to the dilepton mass spectra predicted by the standard model (SM). The expected form of these deviations is often either a resonance or an excess in the number of events in the spectra at high mass. ATLAS [1] has searched for such an excess in dilepton events produced in $\sqrt{s} = 7$ TeV proton-proton collisions at the LHC, interpreting the data in the context of contact interactions (CI) assuming left-left isoscalar model (LLIM) [2],[3],[4].

Under LLIM scheme, the differential cross section for the process $q\bar{q} \rightarrow \ell^+\ell^-$ can be written as

$$\frac{d\sigma}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} - \eta_{LL} \frac{F_I(m_{\ell\ell})}{\Lambda^2} + \frac{F_C(m_{\ell\ell})}{\Lambda^4}, \quad (1)$$

where $m_{\ell\ell}$ is the final-state dilepton mass and $\eta_{LL}$ is LLIM parameter defining interference type (destructive or constructive). $\Lambda$ is the contact interaction scale. The expression above includes a SM Drell-Yan (DY) term, as well as DY-CI interference ($F_I$) and pure contact interaction ($F_C$) terms calculated with a coupling $g^2 = 4\pi$ (see Ref. [4] for the full form of this expression). The analysis uses early 2011 run data amounting to 1.08 and 1.21 fb$^{-1}$ of pp collisions recorded by the ATLAS detector for final states with electron and muon pairs, respectively.

2 Results

Events were selected by requiring that they pass the single electron (muon) trigger with a transverse momentum $p_T$ threshold of 20 (22) GeV. This analysis follows the same event selection as the search for new heavy resonances described in Ref. [5].
Figure 1: Dielectron (left) and dimuon (right) invariant mass distributions for data (points) and Monte Carlo simulation (histograms) [6]. The open histograms correspond to the distributions expected in the presence of CI with different values of $\Lambda$ for both constructive (solid) and destructive (dashed) interference.

Figure 1 displays the dielectron and dimuon mass spectra for all selected events with invariant mass greater than 70 GeV along with the SM (including mass dependent NNLO k-factors) and expected CI contributions for four values of $\Lambda$ for both constructive ($\Lambda^-$) and destructive ($\Lambda^+$) interference.

The observed limits [6] (at 95% CL) with a flat prior of $1/\Lambda^2$ are $\Lambda^- > 10.1$ TeV ($\Lambda^+ > 9.4$ TeV) in the electron channel and $\Lambda^- > 8.0$ TeV ($\Lambda^+ > 7.0$ TeV) in the muon channel for constructive (destructive) interference and are obtained using Bayesian Analysis Toolkit (BAT) [7]. The resulting combined limits are $\Lambda^- > 10.2$ TeV and $\Lambda^+ > 8.8$ TeV for the same prior.

References

Search for new physics with a Z boson, jets, and 
\( E_T^{\text{miss}} \) at CMS (arXiv:1204.3774)

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1 Introduction

We search for physics beyond the standard model in events containing a leptonically 
decaying Z boson \((Z \to \ell^+\ell^-, \ell = e, \mu)\), jets, and missing transverse energy \((E_T^{\text{miss}})\). 
The search is performed using 4.98 fb\(^{-1}\) of \(\sqrt{s} = 7\) TeV data collected by the CMS 
experiment at the LHC in 2011. \cite{1}

After selecting \(Z \to \ell^+\ell^- (\ell = e, \mu)\), the main backgrounds include Z plus jets 
where the \(E_T^{\text{miss}}\) comes from jet mismeasurement, dileptonic \(t\bar{t}\) where the dileptons 
happen to fall in the Z mass window, and diboson processes.

The Z plus jets background is predicted using the \(E_T^{\text{miss}}\) templates method, flavor 
symmetric backgrounds (such as \(t\bar{t}\)) are predicted from opposite flavor \((e\mu)\) events, 
and the diboson background \((VZ)\) is taken from MC simulation.

2 \(E_T^{\text{miss}}\) Templates Method

This data-driven technique uses \(\gamma\) plus jets events as a control sample to predict the 
\(E_T^{\text{miss}}\) in Z plus jets, and is predicated on the fact that fake \(E_T^{\text{miss}}\) from jet mismeasurement 
can be parameterized in terms of the \(N_{\text{jets}}\) and scalar sum of jet \(p_T\) \((H_T)\). The 
\(E_T^{\text{miss}}\) templates are \(E_T^{\text{miss}}\) plots in \(\gamma\) plus jets events binned in \(N_{\text{jets}}\) and \(H_T\), normalized 
to unity. The prediction of the \(E_T^{\text{miss}}\) distribution in Z plus jets is formed by summing 
the templates which correspond to the \(N_{\text{jets}}\) and \(H_T\) in each Z plus jets event.

3 Results

The signal regions are formed by applying \(E_T^{\text{miss}}\) cuts as shown in the table, and most 
expected sensitivity comes from \(E_T^{\text{miss}} > 100, 200, \) and 300 GeV. Lower \(E_T^{\text{miss}}\) cuts are 
shown as a validation of the background predictions. The results shown here are for 
\(N_{\text{jets}} \geq 2\); see the paper (arXiv:1204.3774) for \(N_{\text{jets}} \geq 3\) results.
The background estimations described above are compared with observed yields and used to derive model independent upper limits (UL) on new physics contributions. Uncertainties include both statistical and systematic contributions. For the observed yield (data), the first (second) number in parentheses is the yield in the \(ee\) \((\mu\mu)\) final state. Background predictions agree with data: no evidence for new physics.

We show yields for two example cMSSM model points (LM4 and LM8), both of which are ruled out.

![Figure 1: Data and background predictions as a function of \(E_{\text{miss}}\).](image)

**References**

Measurement of the Polarization Amplitudes and Triple Product Asymmetries in the $B^0_s \to \phi\phi$ Decay at LHCb

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The $B^0_s \to \phi\phi$ decay is an example of a flavour changing neutral current (FCNC) interaction and as such, may only proceed via penguin diagrams in the Standard Model. CP violation in the $B^0_s \to \phi\phi$ decay may be accessed with a time-integrated untagged method using $T$-violating triple product asymmetries (further information on this rich subject may be found in [1, 2, 3, 4]). The rest of this document details the study of the triple product asymmetries ($A_U$ and $A_V$), polarization amplitudes ($|A_0|^2$, $|A_\parallel|^2$ and $|A_\perp|^2$) and strong phase difference in the $B^0_s \to (\phi \to K\bar{K})$ decay using 1.0 fb$^{-1}$ of proton-proton collision data collected at centre-of-mass (COM) energy $\sqrt{s} = 7$ TeV with the LHCb detector.

1 Experimental Method and Results

A total of 801 ± 29 signal candidates are observed through a cut based selection optimized with the use of the $\mu$Plot method [5] to distinguish signal from background.

The measurement of the polarization amplitudes ($|A_0|^2$, $|A_\parallel|^2$, $|A_\perp|^2$) and strong phase difference ($\cos \delta_\parallel$) is performed using a time-integrated, untagged probability density function (PDF) under the assumption that the time acceptance is uniform and that the CP-violating weak phase is zero. A maximum log-likelihood fit is then performed to the three helicity angles (see Reference [6] for more information). The lifetimes of the heavy and light $B^0_s$ mass eigenstates are constrained to be within the errors of the LHCb measured values [7] taking in to account correlations. S-wave contributions are ignored in the fit. Data-driven methods indicate the S-wave contribution to be $(1 \pm 1)\%$, therefore systematic uncertainties are based on a 2% S-wave contribution. The angular acceptance is determined from simulated events. The limited number of simulated events determines the systematic uncertainty due to the angular acceptance. The time acceptance is understood from Monte Carlo events and simplified simulations are used to assign a systematic uncertainty from the assumption that it is uniform. The polarization amplitudes and strong phase difference are measured to be
\[ |A_0|^2 = 0.365 \pm 0.022 \text{ (stat)} \pm 0.012 \text{ (syst)}, \]
\[ |A_\perp|^2 = 0.291 \pm 0.024 \text{ (stat)} \pm 0.010 \text{ (syst)}, \]
\[ |A_\parallel|^2 = 0.344 \pm 0.024 \text{ (stat)} \pm 0.014 \text{ (syst)}, \]
\[ \cos(\delta_0) = -0.844 \pm 0.068 \text{ (stat)} \pm 0.029 \text{ (syst)}. \]

Triple product asymmetries are based on \( T \)-odd observables \( U \) and \( V \) (defined in Reference [6]). Events are separated into datasets according to whether \( U(V) > 0 \) and a simultaneous fit is then performed to obtain the asymmetries \((A_U, A_V)\) using the \( KKKK \) invariant mass as the discriminating observable.

The main systematic uncertainties arise from the choice of signal and background model; the effect of ignoring the time acceptance and the angular acceptance of the \( B^0_s \to \phi\phi \) decay. The systematic uncertainties on the triple product asymmetries due to acceptance effects are estimated using simplified MC studies.

Simultaneous fits to the \( U(V) \) datasets yield triple product asymmetries of
\[ A_U = -0.055 \pm 0.036 \text{ (stat)} \pm 0.018 \text{ (syst)}, \]
\[ A_V = 0.010 \pm 0.036 \text{ (stat)} \pm 0.018 \text{ (syst)}. \]

## 2 Summary

We provide the most accurate measurements of the physics parameters in the \( B^0_s \to \phi\phi \) penguin decay, which are in agreement with those reported from QCD factorization methods [8, 9]. The most precise measurements of \( CP \) violation in the \( B^0_s \to \phi\phi \) decay through triple product asymmetries are reported and are found to be in agreement with SM expectations of \( CP \) conservation in the \( B^0_s \to \phi\phi \) decay.

## References

Measuring the b-jet tagging efficiency using top anti-top events with ATLAS data

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The identification of jets originating from b-quarks is relevant for many physics analyses with the ATLAS detector [1]. Algorithms that allow to identify such jets are thus of great importance and it is crucial to understand their performance with data-driven measurements of efficiencies and fake rates.

Since the decay of a t$\bar{t}$ pair has a very clear signature and because the top quark almost exclusively decays to a W boson and a b-quark, a sample of top anti-top events is ideal for calibrating the various b-tagging algorithms used in ATLAS analyses. The calibration results are presented in the form of data-to-simulation scale factors

$$\kappa_{\varepsilon_{b}}^{\text{data/sim.}} = \frac{\varepsilon_{b}^{\text{data}}}{\varepsilon_{b}^{\text{sim.}}} \quad (1)$$

in which the measured b-tagging efficiency in data is divided by the b-tagging efficiency in simulated events. Currently three different t$\bar{t}$ calibration methods are in use, where both the lepton+jets and the dileptonic decay channels are considered [2].

Using the kinematic selection method the b-tagging efficiency can be estimated by

$$\varepsilon_{b} = \frac{1}{f_{b\text{-jets}}} \cdot \left( f_{b\text{-tag}} - \varepsilon_{c} f_{c\text{-jets}} - \varepsilon_{l} f_{l\text{-jets}} - \varepsilon_{\text{fake}} f_{\text{fake}} \right), \quad (2)$$

where $f_{b\text{-jets}}$, $f_{c\text{-jets}}$ and $f_{l\text{-jets}}$ are the fractions of b-, c- and light-flavour jets within the selected sample, while $f_{\text{fake}}$ is the fraction of jets coming from the fake lepton background. The mistag efficiencies $\varepsilon_{c}$ for c- and $\varepsilon_{l}$ for light-flavour jets as well as the fractions of the various jet flavours are calculated using all the selected events in simulation, while the tagging efficiency of the jets coming from the fake lepton background $\varepsilon_{\text{fake}}$ and the fraction of b-tagged jets $f_{b\text{-tag}}$ are obtained from data.

While the b-jet purity with the kinematic dileptonic selection reaches 40-80 %, the lepton+jets selection includes a requirement that at least one jet in each event is b-tagged, to enhance the signal purity. If the leading jet (the second leading jet) in the lepton+jets analysis passes that b-tagging requirement, the b-tagging efficiency is measured on the three subleading jets (the leading jet). In the dilepton channel the b-tagging efficiency is instead extracted from the two leading jets.
In case of the tag counting method a Likelihood fit is performed to estimate the b-tagging efficiency by assuming that the expected number of events containing \( n \) b-tagged jets is given by

\[
<N_n> = \sum_{i,j,k} \left\{ \left( \sigma_t \cdot \mathcal{A}_{t\bar{t}} \cdot \mathcal{L} \cdot F_{ijk} \right) + \left( N_{bkg} \cdot F_{bkg}^{ijk} \right) \right\} \times \sum_{i'+j'+k'=n} \left( \begin{array}{c} i' \\ j' \\ k' \end{array} \right) \varepsilon_b^{i'} (1 - \varepsilon_b)^{i - i'} \cdot \left( \begin{array}{c} j' \\ j \end{array} \right) \varepsilon_c^{j'} (1 - \varepsilon_c)^{j - j'} \cdot \left( \begin{array}{c} k' \\ k \end{array} \right) \varepsilon_l^{k'} (1 - \varepsilon_l)^{k - k'} \right\} \tag{3}
\]

where \( i, j \) and \( k \) are the number of b-, c- and light-flavour jets per event before applying b-tagging, while \( i', j' \) and \( k' \) represent the number of those jets after b-tagging. \( F_{ijk} \) is the fraction of events (before tagging) containing \( i \) b-jets, \( j \) c-jets and \( k \) light-flavour jets. \( BR \) is the branching ratio, \( \mathcal{A}_{t\bar{t}} \) is the selection acceptance and \( \mathcal{L} \) is the integrated luminosity. The b-tagging efficiency can then be determined by fitting this expected \( n \)-tag distribution to that observed in data.

The b-tagging calibration results for the kinematic selection and tag counting methods are shown in Figure 1.

Figure 1: b-tagging efficiencies in data and simulation (left), the corresponding scaling factors \( \kappa^{\text{data/sim.}}_{\varepsilon_b} \) (middle) both measured with the kinematic selection method and the 2-dimensional contour of the b-tagging efficiency and the \( t\bar{t} \) cross section from the tag counting method (right). All plots show results for the SV0 tagging algorithm at an operating point corresponding to 50 % signal efficiency in simulated \( t\bar{t} \) events [2].

**References**


Search for supersymmetry in events with four or more leptons and missing transverse momentum in $p - p$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

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1 Introduction

A search for supersymmetric particles in events with four or more leptons (electrons or muons) in the final state is presented [1]. This search is sensitive to various supersymmetric models including pair-production of strongly interacting SUSY particles with R-parity violating (RPV) decays of $\tilde{\tau}_1$ Lightest Supersymmetric Particle (LSP) [2, 3]. Moderate missing transverse momentum is expected in the final state due to the presence of neutrinos originating in the decay of the LSP. The analysis is performed using 2.06 fb$^{-1}$ of proton-proton collision data at $\sqrt{s} = 7$ TeV delivered by the LHC and recorded by the ATLAS detector [4] in 2011.

2 Event Selection, Results and Interpretation

Events are selected using a single-electron or single-muon trigger. Isolated electrons (muons) with transverse momentum greater than 10 GeV and pseudorapidity $|\eta| < 2.47$ ($|\eta| < 2.4$) are considered. Two signal regions are defined (SR1 and SR2), both selecting events with at least four leptons and missing transverse momentum greater than 50 GeV. An additional veto on events containing a Z-boson candidate is applied in SR2. At least one of the selected leptons has to be in the efficiency plateau ($p_T > 25$ GeV and $p_T > 20$ GeV for electrons and muons respectively) and match a lepton firing the trigger.

The dominant backgrounds arise from the production of di-boson pairs (ZZ, WZ), $t\bar{t}$ pairs, $t\bar{t}+Z$ production, and $Z$+jets production. In the selected sample the purely hadronic Standard Model (SM) backgrounds are negligible. The background estimation is performed using Monte Carlo (MC) simulation and is validated using $t\bar{t}$-rich and ZZ-rich control regions in data.

In SR1, four events are observed, while 1.7±0.9 events are expected from SM processes. Zero events are observed in SR2, with 0.7±0.8 expected events. The
systematic uncertainties are dominated by the jet energy scale and resolution, the electron energy resolution and the number of MC events generated. The agreement between observed and expected event yields is expressed as a $p$-value assessed using a profile likelihood method, and is found to be 0.10 for SR1 and >0.5 for SR2. Upper limits can be set to the visible cross-sections for new phenomena. The observed (expected) upper limits are 3.5 (2.1) fb and 1.5 (1.5) fb for SR1 and SR2 respectively.

The results in SR2 are used to set limits for the mSUGRA/CMSSM scenario with $m_0=0$, $\mu > 0$, and one R-parity lepton flavor violating parameter $\lambda_{121}=0.032$ at $m_{GUT}$, where the $\tilde{\tau}_1$ is the LSP [2]. In this scenario, the RPV coupling is small enough that the SUSY particle pair production dominates, and large enough that the $\tilde{\tau}_1$ LSP decays promptly. Values of $m_{1/2} < 800$ GeV are excluded at 95% Confidence Level (C.L.) if $\tan \beta < 40$ and $m_{\tilde{\tau}_1} > 80$ GeV. Figure 1(left) illustrates the $\tilde{\tau}_1$ RPV decay into leptons and Fig. 1(right) shows the excluded region in the $\tan \beta$-$m_{1/2}$ plane.

Figure 1: Left: Illustration of the four body $\tilde{\tau}_1$ decay in the R-parity violating mSUGRA/CMSSM model. Right: Observed excluded region (blue area) at 95% C.L. as a function of $m_{1/2}$ and $\tan \beta$ in SR2. The expected exclusion is indicated by dashed lines [2].

References

Search for Charged Higgs Bosons Decaying via $H^+ \rightarrow \tau \nu$ in 7 TeV pp Collisions with the ATLAS Detector

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Charged Higgs bosons ($H^+, H^-$) are predicted by several non-minimal Higgs scenarios, such as the Minimal Supersymmetric Standard Model (MSSM), and their discovery would be clear evidence for new physics beyond the Standard Model. If the mass of the charged Higgs boson, $m_{H^+}$, is less than the top quark mass, the main production mode at the LHC is via top quark decays, $t \rightarrow H^+ b$ in $t \bar{t}$ production. For values of $\tan \beta > 2$, the decay mode $H^+ \rightarrow \tau \nu$ is dominant in the MSSM. Using 4.6 fb$^{-1}$ taken by the ATLAS detector [1] at $\sqrt{s} = 7$ TeV in 2011, three different final states have been investigated [2], taking into account various combinations of leptonically or hadronically decaying $\tau$ leptons (arising from the charged Higgs boson decay) and $W$ boson decays (resulting from the second top quark decay). The three final states are the lepton+jets, the $\tau$+lepton and the $\tau$+jets channel.

In the lepton+jets channel, leptonically decaying $\tau$ leptons arising from the $H^+$ decay and hadronically decaying $W$ bosons are considered. The background contribution from misidentified or non-isolated leptons is estimated in a data-driven way using a matrix method. All other background contributions are estimated using simulation, with the normalization of the $t \bar{t}$ background being taken from data. A transverse mass [3] of the charged Higgs boson is used as final discriminating variable.

In the $\tau$+lepton channel, events containing hadronically decaying $\tau$ leptons originating from the $H^+$ decay and leptonically decaying $W$ bosons are considered. The background contribution from misidentified or non-isolated leptons is estimated in the same way as for the lepton+jets channel. Events containing electrons and jets misidentified as $\tau$ leptons are estimated using their misidentification probabilities measured from data. Only the background contribution with true $\tau$ leptons is estimated using simulation. Missing transverse momentum, $E_T^{\text{miss}}$, is used as a final discriminating variable.

In the $\tau$+jets channel, both the $\tau$ lepton arising from the charged Higgs boson decay and the $W$ boson decay hadronically. In this final state, all background contributions are estimated using data-driven methods. Electrons and jets misidentified as $\tau$ jets are estimated in the same way as in the $\tau$+lepton channel. Multijet background events are estimated using a template fit in $E_T^{\text{miss}}$. The background contribution including true $\tau$ jets is estimated with an embedding method. A transverse mass
calculated from $E_T^{\text{miss}}$, the transverse momentum of the $\tau$ jet and the angle between these two is used as final discriminating variable.

Data and background estimation agree well in all three channels, thus no evidence for charged Higgs bosons is found. Exclusion limits at a 95% confidence level [4] are set on the branching ratio $B(t \rightarrow H^+ b)$ assuming $B(H^+ \rightarrow \tau \nu) = 1$. For charged Higgs boson masses between 90 and 160 GeV the limits range from 5% to 1% (Fig. 1, left). These limits are interpreted in the $m_h^{\text{max}}$ scenario of the MSSM [5]. For $90 < m_{H^+} < 150$ GeV, values of $\tan \beta$ between 1 and 2 and as much as between 1 and 6 are excluded and values of $\tan \beta$ above 26 to 12 are excluded (Fig. 1, right).

![Figure 1: Exclusion limit on the branching ratio $B(t \rightarrow H^+ b)$ assuming $B(H^+ \rightarrow \tau \nu) = 1$ for all three final states combined (left) and interpretation in the $m_{H^+}-\tan \beta$-plane of the $m_h^{\text{max}}$ scenario of the MSSM (right)[2].](image)

**References**


$B^{0}_{(s)} \rightarrow \mu^{+}\mu^{-}$ searches at LHCb

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1 Introduction

The rare decays $B^{0}_{s} \rightarrow \mu^{+}\mu^{-}$ and $B^{0} \rightarrow \mu^{+}\mu^{-}$ are benchmark channels to constrain models beyond the Standard Model (SM) with a larger Higgs sector. In the SM these processes are highly suppressed as they occur through loop processes. Together with an associated helicity suppression renders the branching fraction of these decays to be $[2]$:

$\mathcal{B}(B^{0}_{(s)} \rightarrow \mu^{+}\mu^{-}) = 3.2 \pm 0.2 \times 10^{-9}$ and $\mathcal{B}(B^{0} \rightarrow \mu^{+}\mu^{-}) = 0.10 \pm 0.01 \times 10^{-10}$.

Any deviation from these well predicted branching fractions can lead to indications of physics beyond the SM. For instance, they can be significantly enhanced within Minimal Supersymmetric extensions of the SM (MSSM) due to contributions from new processes or new heavy particles. In these scenarios, $\mathcal{B}(B^{0}_{s} \rightarrow \mu^{+}\mu^{-})$ is proportional to $\tan^{6} \beta$ [3], where $\tan \beta$ is the ratio of the vacuum expectation values of the two Higgs fields.

2 Branching fraction measurements of $B^{0}_{(s)} \rightarrow \mu^{+}\mu^{-}$ at the LHCb

The LHCb experiment [1] has collected 1.0 fb$^{-1}$ of data during the 2011 at a center-of-mass energy of $\sqrt{s} = 7$ TeV.

The $B^{0}_{(s)} \rightarrow \mu^{+}\mu^{-}$ analysis starts with a loose and efficient selection of the $B^{0}_{(s)} \rightarrow \mu^{+}\mu^{-}$ candidates and control channels ($B^{0}_{(s)} \rightarrow h^{+}h^{-}$ decays, where $h$ can be either a pion or a kaon, $B^{+} \rightarrow J/\psi(\rightarrow \mu^{+}\mu^{-})K^{+}$ and $B^{0}_{s} \rightarrow J/\psi(\rightarrow \mu^{+}\mu^{-})\phi(\rightarrow K^{+}K^{-})$ decays). The main goal of this selection process is to reduce the background to manageable levels, while keeping the same efficiency in all aforementioned channels.

After the selection, $B^{0}_{s} \rightarrow \mu^{+}\mu^{-}$ candidates are classified according to their invariant mass and the output of a multivariate classifier (figure 1 on the left) combining geometrical and kinematic information. This classification is performed in a binned 2D parameter space. The signal expectation in each bin is calculated using data events such as $B^{0}_{(s)} \rightarrow h^{+}h^{-}$ and $B^{+} \rightarrow J/\psi(\rightarrow \mu^{+}\mu^{-})K^{+}$ decays. The number of background is obtained after an interpolation from the invariant mass sidebands.
The distribution of observed events (figure 1 on the right) is finally compared with the signal plus background and background only hypothesis using the CL$_S$ method [4].

The upper limits [5] on the branching fractions are:

\[ B(B_{(s)}^0 \rightarrow \mu^+\mu^-) < 4.5 \times 10^{-9}, \]  \hspace{1cm} (1)

\[ B(B^0 \rightarrow \mu^+\mu^-) < 1.0 \times 10^{-10}. \]  \hspace{1cm} (2)

Figure 1: On the left, the output of the multivariate classifier for signal $B_{(s)}^0 \rightarrow \mu^+\mu^-$ events (black dots) and background (empty blue dots). On the right, distribution of the selected di-muon events in the $B_s^0 \rightarrow \mu^+\mu^-$ mass window with BDT (classifier) requirement above 0.5, combinatorial background (light gray) and SM $B_s^0 \rightarrow \mu^+\mu^-$ (gray).

The aforementioned limits are the most restrictive limits on these branching fractions obtained to date.

References

Measuring the $b$-jet tagging efficiency using samples of jets containing muons with ATLAS data

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1 Introduction

The identification of jets originating from the decay of $b$-hadrons is used in many physics channels like top quark and Higgs boson physics.

We describe several algorithms used in the ATLAS experiment [1] to identify $b$-jets produced in pp collisions at 7 TeV center of mass energy. These algorithms exploit the properties of tracks from $b$-hadron decays and the existence of secondary vertices in jets to identify them. An example for such an algorithm is the MV1 algorithm, a neural-net-based combination of three SV1, IP3D and JetFitter algorithms [2].

In order for these algorithms to be used in the simulation they must be calibrated by measuring their efficiency in data. One calibration approach is to exploit the fact that muons emerging from $b$-hadrons carry a relatively high transverse momentum with respect to the axis of the $b$-jet. That variable $p_T^{rel}$ is sensitive to the flavour of the original quark and works independently of a specific $b$-tagging algorithm. Such calibrations are carried out in the so called $p_T^{rel}$ and system8 methods.

2 Calibration Methods and Results

In the $p_T^{rel}$ method template fits to the distribution of the muon $p_T^{rel}$ are performed before and after the tagging criterion to obtain the number of $b$-jets before and after the decision. The efficiency is then the number of $b$-jets after the tagging requirement divided by the original number of $b$-jets. The templates for $b$- and $c$-jets are taken from simulation while the template for light-quark jets is taken from data with the additional requirement that no jet in the event is tagged by a very efficient $b$-tagging algorithm. The resulting light-quark jet sample has a about (2−6)% contamination of $b$-jets which needs to be corrected for.

The system8 method uses three criteria to split the jet sample into 8 different sub-samples to build a system of eight equations. One of the three criteria is the $b$-tagging algorithm which is to be calibrated. Another one is a cut on the $p_T^{rel}$ of the
muon inside the jet. The third criterion is the presence of an opposite side $b$-tagged jet. In this method the $b$-tagging efficiency is one of the parameters in the set of equations. A key feature of the method is that the only reliance on simulation it has comes from the correlation between the different criteria.

![Diagram of b-tagging efficiency for MV1 algorithm in simulation and measurement with both methods.](image)

Figure 1: The $b$-tagging efficiency for the MV1 algorithm at an efficiency of 70% in simulation and measured by the $p_T^{rel}$ (left) and the system8 (right) methods.

Both methods calibrate jets which are based on an anti-$k_T$ algorithm with a cone size of 0.4 using topological clusters in the ATLAS calorimeters. Muons are reconstructed by a statistical combination of the tracks from the muon spectrometer and the inner detector. Additionally the muon is required to have a transverse momentum of at least $p_T > 4 \text{ GeV}$ and to be within the cone of a jet.

As the $b$-tagging efficiency depends on the transverse momentum of the jet, the measurement is carried out in several bins of $p_T$, varying from 20 GeV to 200 GeV. Figure 1 shows the efficiency for the MV1 $b$-tagging algorithm in simulation and the measurement with both methods. The parameters of the algorithm were chosen such that it has 70% $b$-tagging efficiency in a sample of $t \bar{t}$ simulated events. Both methods show good agreement between data and simulation with a slightly lower efficiency in data than in simulation. The ratio of the efficiency in data and simulation is used as a scale factor to correct the simulation performance.

References

Searches for long-lived, Exotic particles at ATLAS

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1 Introduction

Three recent searches for massive, exotic, long-lived particles are presented for 2011 LHC data using the ATLAS detector [1]. No new physics has been found but limits have been set, and tools for future searches have been developed. Improvements are under way using timing, ionization, and displaced vertices in several ATLAS sub-detectors for searches with full 2011 data and 2012 data.

2 Disappearing-track signature

In models of anomaly-mediated supersymmetry breaking (AMSB), the lightest chargino ($\tilde{\chi}^\pm_1$) is predicted to have a long lifetime due to a small mass difference between the $\tilde{\chi}^\pm_1$ and the neutralino $\tilde{\chi}^0_1$ to which it decays. The $\tilde{\chi}^0_1$ leaves the detector allowing a trigger on a high-$p_T$ jet and missing $E_T$. Candidates are identified as high-$p_T$ tracks with few hits in the outer part of tracker, as the low-$p_T$ π from the $\tilde{\chi}^\pm_1 \rightarrow \tilde{\chi}^0_1 \pi^\pm$ decay sequence is not reconstructed. Backgrounds come primarily from hadronic interactions and mismeasured tracks. They are studied using control samples of non-disappearing tracks and low missing $E_T$, respectively. The $p_T$ distributions are modeled for the control samples as well as the AMSB signal samples. A maximum likelihood fit of $p_T$ distributions to data shows no signal contribution in 4.7 $fb^{-1}$ of $pp$ collisions. Model-independent limits for a new physics process with an isolated, disappearing track and limits on the signal cross-section as a function of $\tilde{\chi}^\pm_1$ lifetime are extracted [2].

3 Hidden Valley

One Standard Model (SM) extension is a hidden sector ($v$-sector) with a light Higgs communicator. The Higgs’ high mass and weak couplings create a barrier which hides the $v$-sector and makes production of $v$-particles rare at low energies. Some $v$-particles may decay to SM particles, and their production may be observable through displaced vertices. A range of $\pi_v$ lifetimes gives decay signatures in all parts of the ATLAS detector. Decays to two $b$-jets near the muon system (from 4.5-11 m) have been used by searching for two vertices of > 3 muon segments not pointing back to
the interaction point. A special trigger has been designed to improve efficiency by an order of magnitude near the muon system. No events meeting the analysis selection are observed in 1.94 \( fb^{-1} \) of \( pp \) collisions [3]. Exclusion limits are shown in Fig. 1(a).

4 R-hadrons

R-hadrons are hadronic states containing a heavy exotic long-lived parton. They have \( \beta < 1 \), resulting in high ionization, but can become neutral through hadronic interactions inside ATLAS. The Pixel detector provides ionization information close to the interaction point using minimum bias events to calibrate a \( dE/dx \) measurement. This \( dE/dx \) is used to determine a \( \beta \) via Bethe-Bloch and then a mass using momentum. The conversion is calibrated using protons and extrapolating to R-hadrons. Candidates are isolated, high \( p_T \) tracks, and 333 are observed in 2.1 \( fb^{-1} \) of \( pp \) collisions as is consistent with data-driven background estimation [4]. The result can be interpreted as excluding gluino R-hadrons with \( m < 810 \) GeV as shown in Fig. 1(b).

![Diagram](image-url)

Figure 1: (a) Observed 95% CL (multiples of the SM cross-section for Higgs production with 100% branching ratio to \( \pi \nu \)'s) for \( h^0 \rightarrow \pi \nu \pi \nu \) vs. the \( \pi \nu \) proper decay length [3]. (b) Cross section as a function of mass for gluino R-hadrons [4].

References

Quark contact interactions at the LHC

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1 Introduction

The standard four-quark operator that is taken into account for deriving constrains on quark contact interaction scale involves left-currents [1]

\[ \mathcal{L} = \frac{2\pi A}{\Lambda^2} \psi_L^i \gamma^\mu \psi_L^j \bar{\psi}_R^j \gamma^\mu \bar{\psi}_R^i \] (1)

where \( \Lambda \) is the characteristic energy scale of the new interaction and \( A = \pm 1 \). Current constraints on contact interactions given by ATLAS and CMS [2, 3] assume the existence of only one kind of contact term, namely that in eq. (1). The aim of this work is to provide an analysis that extends the search for the bounds to more than one operator. A great variety of four fermion operators can arise in many low-energy effective theories. We do not want to track down every possible operator, so in this work we consider just a minimal model. The bounds on the interaction scales are derived at the level of Monte Carlo simulation, studying the dijet production in proton-proton collisions at the LHC, for a representative integrated luminosity of 200 \( \text{pb}^{-1} \) at \( \sqrt{s} = 7 \text{ TeV} \).

2 The minimal model

We consider the case of a single fermion family with quarks with the same mass. Following the general idea that stronger interactions are more symmetric than weaker ones, we want to be more restrictive and impose \( SU(2)_L \times SU(2)_R \) symmetry and parity. The complete set of such invariant four-fermion operators is given by four independent terms:

\[
\mathcal{L}_{\psi^4} = \begin{array}{c}
\frac{2\pi}{\Lambda^2} \left( \bar{\psi}_L^i \gamma^\mu \psi_L^j \bar{\psi}_R^j \gamma^\mu \psi_L^i \right) + \frac{2\pi}{\Lambda^2} \left( \bar{\psi}_L^i \gamma^\mu \psi_R^j \bar{\psi}_R^j \gamma^\mu \psi_L^i \right) \\
+ \frac{2\pi}{\Lambda^2} \left( \bar{\psi}_L^i \gamma^\mu \psi_L^j \bar{\psi}_R^j \gamma^\mu \psi_L^i \right) + \frac{2\pi}{\Lambda^2} \left( \bar{\psi}_R^i \gamma^\mu \psi_R^j \bar{\psi}_R^j \gamma^\mu \psi_R^i \right)
\end{array}
\] (2)

where \( i, j \) and \( a, b \) are \( SU(2) \) and color indices.
3 Event generation and analysis

Dijet production in proton-proton collisions \((pp \rightarrow jj + X)\) is the best channel to search for quark contact interactions. The variable \(\chi = \exp(2|y^*|)\) is the quantity used for the angular distribution study, where \(y^* = (y_1 - y_2)/2\) is the CM rapidity. In terms of the \(\chi\) variable, the dijet \(1/NdN/d\chi\) distribution obtained from the leading QCD subprocesses is almost flat, while in the case of contact interactions, which are more isotropic, the total dijet angular distribution can be considerably modified in the low \(\chi\) region [2]. The measure of the isotropy in the dijet distribution is given by the variable \(F_\chi\). It measures the fraction of dijets produced centrally versus the total number of observed dijets in a specified dijet mass range:

\[
F_\chi = \frac{N_{ev}(\chi < 3.32)}{N_{ev}(\chi < 30)}
\]  

MADGRAPHv4 has been used to simulate LHC dijet production in pp collisions at \(\sqrt{s} = 7\) TeV. Monte Carlo samples corresponding to 1 fb\(^{-1}\) are generated for pure QCD and for QCD modified by the new four fermion interactions where different points of the \((\Lambda_1, \Lambda_2, \Lambda_3, \Lambda_4)\) parameter space are considered. In addition, a sample corresponding to 200 pb\(^{-1}\) of QCD data has been generated to be used as a pseudo-data sample. Hadronization and showering are implemented by PYTHIA v6.4, which is included in MADEVENT. Then the generated events are then passed through PGS in which the parameters are set to reproduce the ATLAS detector performance. We have applied the following cuts at generator level: \(M_{jj} > 100\) GeV, \(p_{Tj1}, p_{Tj2} > 30\) GeV, \(|\eta_j| < 2.8, |y^*| < 1.70\). At the level of analysis we select events with at least two jets requiring \(p_{Tj1} > 60\) GeV and \(p_{Tj2} > 30\) GeV, veto on an additional jet with \(p_T > 15\) GeV and \(|y_B| < 1.10\), where \(y_B = (y_1 + y_2)/2\). Then, pseudo-experiments have been made for the chosen points of the \(\Lambda\)-parameters space in order to construct one-sided \(F_\chi\) 95\% confidence level (CL) which is used to set the lower bounds on the contact interaction scales.

4 Results

The first part of the study takes into account only two operators of eq. (1), the ones corresponding to \(\Lambda_1\) and \(\Lambda_3\). In this case \(\Lambda_2, \Lambda_4 = \infty\). The result of this analysis is shown by the first \(F_\chi\) contour plot of Fig. 1. The values of \(\Lambda_1\) and \(\Lambda_3\) which satisfy the 95 % CL bound are represented by the area inside the curve. Lower bounds on the contact interaction scales are \(\Lambda_1 = 2.4\) TeV and \(\Lambda_3 = 5.1\) TeV. The standard one-operator analysis would give a limit \(\Lambda_3 \sim 5.6\) TeV, we find a weaker bound because of interference effects. The second plot in Fig. 1 shows the \(F_\chi\) 95 % CL contour in the case where all four fermion operators of eq. (1) are switched on. We assume two
common scales $\Lambda_S = \Lambda_1 = \Lambda_2$ and $\Lambda_V = \Lambda_3 = \Lambda_4$. Lower bounds on these common contact interaction scales are $\Lambda_S = 4.8$ TeV and $\Lambda_V = 6.5$ TeV.

Figure 1: $F_\chi$ 95% CL contour plot. The area inside the curves represent the values of the contact interaction scales compatible with the pseudo-data measured quantity.

I am grateful to F. Bazzocchi, U. De Sanctis and M. Fabbrichesi as co-authors of the paper [4] from which this poster has been extracted.

References


Observation of CP Violation in $B^\pm \rightarrow DK^\pm$ Decays at LHCb

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The unitarity of the Cabibbo Kobayashi Maskawa (CKM) quark mixing matrix can be represented by a closed, ‘unitarity triangle’ (UT). Of the three CKM phases in the UT, the least well known is $\gamma$, currently measured to be $(66 \pm 12)^\circ$ in direct measurements [1]. The Large Hadron Collider beauty (LHCb) experiment is the only dedicated flavour physics experiment at the LHC and has as one of its primary objectives the precise measurement of this Standard Model (SM) parameter.

1 Measuring $\gamma$ in $B^\pm \rightarrow [hh']_D K^\pm$ at LHCb

Sensitivity to $\gamma$ arises as a result of interference between the amplitudes for $B^\pm \rightarrow D^0 K^\pm$ and $B^\pm \rightarrow \bar{D}^0 K^\pm$ decay processes where the intermediate neutral $D$ meson decays to a common final state $F$, labelled by $[F]_D$. The complex phase between the two $B^\pm$ decay amplitudes is the sum or difference of the strong and weak phases, $\delta_B$ and $\gamma$ respectively. Two classes of $D$ meson final states were considered in the analysis [2], non-CP eigenstates ($D^0 \rightarrow K^+\pi^-$, an ‘ADS’ final state [3], described in this paper) and CP eigenstates ($D^0 \rightarrow K^+K^-, \pi^+\pi^- \text{ ‘GLW’ final states [4], discussed in the proceedings for my talk ‘CP Violation in Hadronic B Decays at LHCb’}$).

The observables are, for the ADS case, $R_{ADS} = \frac{\Gamma(B^\pm \rightarrow [\pi^-K^+]_D K^\pm) + \Gamma(B^+ \rightarrow [\pi^+K^-]_D K^\pm)}{\Gamma(B^\pm \rightarrow [\pi^+K^+]_D K^\pm) + \Gamma(B^+ \rightarrow [\pi^-K^-]_D K^\pm)}$ and $A_{ADS} = \frac{\Gamma(B^- \rightarrow [\pi^-K^+]_D K^-) + \Gamma(B^+ \rightarrow [\pi^+K^-]_D K^+)}{\Gamma(B^- \rightarrow [\pi^-K^-]_D K^-) + \Gamma(B^+ \rightarrow [\pi^+K^+]_D K^+)}$ which in turn depend on $\gamma$ e.g. $A_{ADS} = 2r_Br_D \sin(\gamma) \sin(\delta_D + \delta_B)$ where $r_B, \delta_B$, and $r_D, \delta_D$ are hadronic parameters of the $B^\pm$ and $D$ decays.

The 2011 LHCb data set ($1 \text{ fb}^{-1}$) was used and decay modes were selected for analysis: the ‘ADS mode’ $B^\pm \rightarrow [\pi^\pm K^\mp]_D K^\pm$ and the ‘favoured’ mode $B^\pm \rightarrow [K^\pm\pi^\mp]_D K^\pm$ where the interference, and therefore sensitivity to the CP violating phase $\gamma$, is negligible. A boosted decision tree was used, having been trained using simulated signal data and background candidates from the 2010 LHCb data sidebands. Due to the detector’s good impact parameter ($20\mu m$ for tracks with high $p_T$) and momentum resolution ($(0.4 - 0.6)\%$ in the range of $5 - 100\text{ GeV}/c$), the most effective variables were flight distances of the $B^\pm$ and $D$ mesons, impact parameters, $p_T$ cuts on the daughter tracks and vertex quality requirements. The Ring Imaging Cherenkov (RICH) detectors were used to distinguish pions and kaons in the final state.
2 Results and conclusion

The invariant mass spectra of the ADS mode $B^\pm \to (\pi^\pm K^{\mp})_D K^\pm$ are shown in Figure 1 along with the $B^\pm \to (\pi^\pm K^{\mp})_D \pi^\pm$ mode used to control elements of the signal fit. The visible charge asymmetry in the $B^\pm \to D K^\pm$ signals results in: $R_{ADS(K)} = 0.0152 \pm 0.0020 \pm 0.0004$ and $A_{ADS(K)} = -0.52 \pm 0.15 \pm 0.02$. The ADS mode is observed for the first time with $\sim 10\sigma$ statistical significance and displays evidence of an asymmetry at $4.0\sigma$. Combined with the GLW results, CP violation is observed with $5.8\sigma$ significance.

![Figure 1: $B^\pm$ invariant mass spectrum from ADS modes with $B^\pm \to DK^\pm$ signal (solid red line) and $B^\pm \to D\pi^\pm$ control (solid green line) [2].](image)

I am grateful to the Institute of Physics (IOP) and Merton College, Oxford for their financial support.

References


The LHCb Upgrade

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The flavour sector offers a very rich programme to search for physics beyond the Standard Model in a complementary way to the direct particle searches carried out at ATLAS and CMS. The recent LHCb results in the beauty and charm sectors have shown the potential of flavour Physics at LHC and the excellent performance of the detector. Thanks to its forward geometry, LHCb covers a complementary pseudorapidity range to the one of ATLAS and CMS. An upgrade of the LHCb detector is foreseen during the long shutdown expected in 2018 [1]. The current preliminary schedule of LHC and the expected integrated luminosity in LHCb are shown in Fig. 1. In the upgrade phase LHCb intends to collect about 50 fb$^{-1}$ [2]. These data would allow to fully exploit the flavour physics potential and extend the programme to a general-purpose detector for the forward region. More details on the physics programme and the motivation can be found in [3, 4].

The current LHCb trigger is made of two stages, the Level-0 (L0) and the High Level Trigger (HLT). The L0 reduces the data rate from 40 MHz to 1 MHz. It is based on custom electronics receiving dedicated information from the calorimeters and from the muon chambers. The HLT is a software trigger running on a dedicated CPU farm. It receives the full detector information at 1 MHz and it reduces the rate down to a few kHz. Thanks to the full event reconstruction done at HLT, this trigger allows to select inclusive or exclusive heavy-quark decays, with a selection close the offline one.

In the upgrade [2], the full detector readout at 40 MHz will allow to have a fully flexible software trigger with a data rate up to 20 kHz at the storage. This will allow to increase the annual signal yield by about a factor 10 for the leptonic channels and by a factor 20 for hadronic channels. These yields will offer a statistical sample able to reach experimental sensitivities for many observables comparable or even better than their theoretical uncertainties. These data would also allow to exploit a wide physics programme beyond the beauty and charm sectors, e.g.: lepton flavour violation (Majorana neutrino, LFV in $\tau$ decays); electroweak physics ($\sin 2\theta_{\text{eff}}$, $M_W$); exotic searches (hidden valleys); QCD (central exclusive production).
The vertex detector (VELO) is a silicon strip detector with $r$ and $\phi$ geometry. For the upgrade, two options are under study: a pixel detector (pixel size of 55 $\mu m \times 55 \mu m$) based on the Timepix chip [5] and a silicon strip detector with a smaller pitch and strip length than the current detector. The tracker detector (TT) upstream of the magnet is a silicon strip detector. In the upgrade the same technology will be used with a wider acceptance and larger granularity. The tracker detectors (IT and OT) downstream of the magnet are composed by a silicon-strip detector in the inner region and a straw tubes detector in the outer region. In the upgrade the straw coverage will be reduced and the inner detector will be replaced with a scintillating fiber tracker or a larger silicon tracker.

The particle identification system is composed by two RICH detectors, a hadron and electromagnetic-calorimeter and by a set of muon chambers. The RICH photon detector will be replaced by a multi-anode photomultiplier to allow readout at 40 MHz. The front-end electronics of the calorimeters will be replaced, while the muon systems will almost remain unchanged.

In the LHCb upgrade, the tracking performance should remain at the same current performance level. This includes a high momentum resolution of $\Delta p/p = 0.4\% - 0.6\%$, high tracking efficiency (~96% for $p > 5$ GeV) with a low ghost rate (~15% without any selection). As well, the full event reconstruction in the trigger will continue to have a fast processing time of about 30 ms.

The LHCb upgrade is under preparation: an expected integrated luminosity of 50 $fb^{-1}$ will allow to have unprecedented precision in the flavour physics measurements and to extend the current physics programme.
References

Combining $b$-tagging calibrations in ATLAS

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Identifying jets of particles from $b$-quarks is important for a number of the physics goals at the ATLAS experiment [1]. A number of $b$-tagging algorithms have been developed by ATLAS [2] at the LHC. The algorithms’ performance is calibrated on data [3]. Calibration measures the scale factor of data performance to Monte Carlo (MC) performance. Two methods, $p_T^{rel}$ and System 8, are currently used to measure the efficiency of the $b$-tagging algorithms on $b$-jets; both use a large multi-jet sample with an associated muon collected with a range of single-jet triggers. Both methods use the relative $p_T$ of a muon in a jet as a way to measure $b$-jet purity in the calibration sample: the $p_T^{rel}$ distribution from a heavy $B$-hadron semileptonic decay is quite different than for muons from other sources. In both cases the $b$-jet scale factors are determined in $\eta$ and $p_T$ bins, as the $b$-tagging algorithms’ performance is strongly dependent on these parameters.

To improve the accuracy of the scale factors, we combine the calibration results from the two methods by maximizing the following likelihood:

$$L = \prod_{i=1}^{2} p_i = G(\kappa_1 | \hat{\kappa} \times (1 + \delta\kappa_1^{syst} \lambda_{\text{syst}1} + \delta\kappa_1^{syst} \lambda_{\text{syst}2}), \delta\kappa_1^{\text{stat}}) \times$$

$$G(\kappa_2 | \hat{\kappa} \times (1 + \delta\kappa_2^{syst} \lambda_{\text{syst}1} + \delta\kappa_2^{syst} \lambda_{\text{syst}2}), \delta\kappa_2^{\text{stat}}) \times (1)$$

The function $G(x|a, w)$, as written in Eqn. 1, represents a Gaussian centered at $a$ with width $w$. $\kappa_1$ is the value of the scale factor as measured by one of the calibration analyses and $\kappa_2$ the other. $\hat{\kappa}$ is the true value of the scale factor in a given $p_T, \eta$ bin - and is what is being fit for (there is a term for each $p_T$ and $\eta$ bin). $\delta\kappa_1^{\text{stat}}$ is the statistical error associated with the $\kappa_1$ measurement and is expected to be uncorrelated with all other measurements. Finally, $(1 + \delta\kappa_1^{syst} \lambda_{\text{syst}1} + \delta\kappa_1^{syst} \lambda_{\text{syst}2})$ are the systematic errors associated with this measurement. There is an additional Gaussian $G(\lambda_{\text{syst}1}|0, 1)$ to constrain each systematic error. The strength of the effect of each systematic error in each bin is accounted for by $\delta\kappa_i^{\text{syst}}$. Figure 1 shows the combination results for the Secondary Vertex (SV) tagger, a tagging algorithm that reconstructs a vertex from tracks significantly displaced from the primary vertex [2].
Figure 1: The results of the fit for combining scale factor results from the $p_T^{rel}$ and System 8 calibration methods. The points show the individual results and the colored bands show the results in each bin. Both statistical (dark) and statistical+systematic (light) errors are shown. Results are shown for the Secondary Vertex Tagger tuned to give 50% efficiency in a top sample (SV050). Taken from [3].

The fits are done using the RooFit library, part of ROOT. The fitting infrastructure is designed to incorporate asymmetric errors and additional calibrations in the future.

Both the $p_T^{rel}$ and System 8 methods are statistically correlated because they are based on the same jet sample. A study was done to determine the extent of the statistical correlation using a toy Monte Carlo. The numbers of events used in System 8 along with the flavor composition and the $b$-tagging efficiency were taken from data fits. The expected $p_T^{rel}$ inputs were taken by fitting data with MC templates. A toy MC is used to sample these numbers and distributions. The efficiency is re-calculated using $p_T^{rel}$ and System 8 for each sample. The correlations are then accounted for in the global fit. The method tracks the individual contributions of each systematic error to the final combination so the analyzers can properly treat common correlated errors in their analyses and the $b$-tagging calibration.

References


Measuring the $b$-jet tagging efficiency on $c$-jets containing $D^{*+}$ mesons with ATLAS data

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1 Introduction

The identification of jets originating from $b$-quarks ($b$-tagging) is a crucial tool for the ATLAS [1] physics program at the LHC, both for precision measurements and in searches for new particles. One important ingredient when using $b$-tagging in physics analyses is the determination of the probability to mistakenly $b$-tag a jet originating from a $c$-quark ($c$-tag efficiency). The optimal sample for measurements of the $c$-tag efficiency would be a clean sample of jets originating from $c$-quarks. The sample of jets associated to reconstructed $D^{*+}$ mesons (through the decay chain $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$) is quite close to this ideal case since most $D^{*+}$ mesons originate from $c$-quark hadronization. The $c$-tag efficiency has been measured by comparing the reduction in the yield of $D^{*+}$ mesons before and after the $b$-tagging requirement of the associated jet. The contamination from $D^{*+}$ mesons that originate from $b$-hadron decays has been taken into account using a fit to the $D^0$ pseudo-proper time distribution.

2 Flavour composition and $c$-tag efficiency

The data sample has been collected by ATLAS during 2011, using events selected by single jet triggers, and corresponds to a total integrated luminosity $L \approx 5$ fb$^{-1}$. Signal and background regions are defined as the region within $3\sigma$ of the $\Delta m$ peak center and the region above 150 MeV respectively (Fig. 1a).

The discriminating variable to identify beauty and charm components is the $D^0$ pseudo-proper time: $t(D^0) = \text{sign}(L_{xy} \cdot p_T(D^0)) \cdot m_{D^0} \cdot \frac{L_{xy}(D^0)}{p_T(D^0)}$. The beauty component $F_b(t)$ is modelled as the convolution of two exponential functions with the resolution function, while the charm component $F_c(t)$ is modelled as a single exponential function convolved with the resolution. The beauty component $f_b$ is fitted as: $F(t) = f_b \cdot F_b(t) + (1 - f_b) \cdot F_c(t)$. The fit is done on background subtracted data (Fig. 1b), obtained by subtracting the background $t(D^0)$ distribution, normalized to the fitted background fraction in the $\Delta m$ signal region, from the signal $t(D^0)$ distribution.
The $c$-tag efficiency can be obtained as: $\epsilon_c = \frac{\epsilon_{D^0} - f_b}{1 - f_b} \epsilon_b$, where $f_b$ is the fitted beauty fraction, $\epsilon_{D^0}$ accounts for the $D^0$ mesons yield reduction when applying the $b$-tagging selection, and $\epsilon_b$ is the $b$-tagging efficiency measured by independent analyses [2]. Results are presented for the MV1 tagging algorithm at 70% efficiency (Fig. 2). A complete list of results and systematic uncertainties is available in [3]. Scale factors ($SF = \frac{\epsilon_{\text{data}}}{\epsilon_{\text{sim}}}$) are consistent with unity for all the taggers and operating points with uncertainties varying, depending on the jet $p_T$, from 10% to 40%.

Figure 2: The $c$-tag efficiency in data and simulation (left) and the data-to-simulation scale factor (right) [3].

References


A Search for $t\bar{t}$ Resonances in the Dilepton Channel in 2.05 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS experiment

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1 Introduction

Many models of physics beyond the Standard Model (BSM) predict the existence of new resonances that decay predominantly into top quark pairs[1]. This note provides a description of the search [2] for a KK-gluon resonance in the Randall-Sundrum model[3], decaying to $t\bar{t}$ pairs in the dilepton channel by the ATLAS experiment [4][2] at the CERN Large Hadron Collider.

2 Event Selection

The data analyzed were collected between March and August 2011, corresponding to a total integrated luminosity of $\mathcal{L} = 2.05$ fb$^{-1}$. The selection of $t\bar{t}$ events makes use of reconstructed electrons, muons, jets and $E_T^{miss}$, passing standard ATLAS event and object selection cuts as listed in [2]; $E_T^{miss}$ is the missing transverse momentum from the escaping neutrinos from the leptonic $W$ boson decay. The final event selection is driven by the topology of the top decay. Events must have two or more jets and have exactly two oppositely charged leptons (electrons or muons) with a dilepton invariant mass greater than 10 GeV.

For the $ee$ and $\mu\mu$ final states the signal region is defined by $E_T^{miss} > 40$ GeV and $|m_Z - m_{\ell\ell}| > 10$ GeV, to reduce the large $Z$+jets background. For the $e-\mu$ channel the scalar sum of the transverse momenta of the selected leptons and jets is required to be greater than 130 GeV. A control region for the $ee$ and $\mu\mu$ channels is defined by inverting the $Z$ mass cut.

The main background to the KK-gluon signal production is the irreducible Standard Model $t\bar{t}$ production. Background sources also include: $Z$+jets, single top production, diboson production and ”fake” i.e. QCD multijet and $W$+jets processes where one or two jets are misidentified as leptons. All background distributions are derived from Monte Carlo (MC) and normalised to the ATLAS luminosity, except for
the fakes, which are obtained from data, and the the Z+jets background (for ee and \(\mu\mu\) decays) which is normalised to data. The signal MC is generated using MadGraph interfaced to Pythia.

3 Analysis and Results

Due to the missing neutrinos in the event, we choose the effective mass, \(H_T + E_T^{\text{miss}}\), as the discriminating variable for this analysis; \(H_T\) is defined as the scalar sum of the transverse momenta of the two identified leptons and of the two leading jets in the event. For the statistical analysis we construct a binned likelihood function based on Poisson statistics for signal and background for each bin of the effective mass distribution. Sources of systematic uncertainty are included as nuisance parameters in the likelihood function.

The largest systematic variations on the background shape and yield prediction is from the jet energy scale (2.5%) and the choice of Parton Distribution Function (3.7%). For the signal the greatest is the modelling of the initial and final state radiation (5.1%) and the jet energy scale (3.0%). Both rate and shape dependences were computed. The largest rate only systematics are the luminosity (3.7%) and cross-section uncertainties for \(t\bar{t}\), which were included as overall rate changes.

A p-value based on a likelihood ratio technique was found to be consistent with the SM only hypothesis. A lower limit at 95% C.L. on the mass of the KK-gluon in the Randall-Sundrum model was set at 1.08 TeV (1.07 TeV expected) with masses below 500 GeV not taken into consideration.

References


Search for Long-Lived Massive Particles at CMS

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Long-lived massive particles are predicted by several theories of beyond the Standard Model physics, such as the minimal supersymmetric standard model, split supersymmetry, and gauge-mediated supersymmetry breaking. The first two models predict hadron-like particles, stops and gluinos, respectively, and the last predicts a lepton-like particle, the stau. The particles considered here carry electric charge in the case of the lepton-like particles, and the hadron-like particles will hadronize to form a color-singlet “R-hadron” state. In both cases, due to their large masses, these particles travel at low values of \( \beta \), resulting in increased \( dE/dx \) over a minimum ionizing particle and prolonged time of flight. Here we consider the case in which their lifetimes are long enough to traverse the entire CMS detector (7.4 m) before decaying. A search for these particles was conducted with the CMS detector using data from the Large Hadron Collider collected in pp collisions at \( \sqrt{s} = 7 \) TeV in 2011 [1].

A complete description of the CMS detector can be found elsewhere [2]. Here we note the silicon inner tracking system, used to measure the \( dE/dx \), and the muon system consisting of drift tubes and resistive plate chambers in the barrel region, used to measure the time of flight. Combining either of these measurements with the particle’s momentum, measured in the tracker, yields a mass measurement.

Two different triggers are used: a single muon trigger, and a missing transverse energy trigger to add efficiency for R-hadrons becoming neutral due to nuclear interactions in the detector. Selection variables used include the transverse momentum \( P_T \), the \( dE/dx \) compatibility with minimum ionizing particles \( I_{as} \), and \( 1/\beta \) calculated from the time of flight. The distributions of these variables for background and several models is shown in Figure 1. Two different analyses were conducted: one using the tracker only and the other adding the time-of-flight information from the muon system.

The analysis was conducted as follows. To predict the background, an ABCD or sideband method was used, taking advantage of the uncorrelated \( P_T \), \( I_{as} \), and \( 1/\beta \) measurements. This estimates the amount of background in the signal region D. A mass cut is applied to the data at the nominal model reconstructed mass minus twice the expected mass resolution, and its affect on the background estimate in the D
region is accounted for. Then the statistical analysis is performed using the estimated background and the observed number of events.

As there is no evidence of signal, 95% confidence level upper limits are set using CLs. The results are shown in Figure 2. Using theoretical calculations of HSCP cross sections, the calculated mass lower limits are: 314 GeV and 223 GeV for the GMSB stau and pair produced stau; 1098 GeV and 928 GeV for the gluino, using the cloud and charge suppression nuclear interaction models; 737 GeV and 626 GeV for the stop, using the cloud and charge suppression nuclear interaction models.

Figure 2: Upper limits on the cross section for various models. Left: Tracker-only analysis. Right: Tracker+time-of-flight analysis.

References


Supersymmetry Searches in Final States with Three Leptons and Missing Transverse Momentum at ATLAS

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1 Introduction

Supersymmetry (SUSY) is an extension of the Standard Model (SM) which postulates that each SM field has a corresponding superpartner field whose spin differs by a half unit. SUSY provides elegant solutions to several open problems in the SM; these include the hierarchy problem, the identity of dark matter, and grand unification.

Signatures with multiple charged leptons can arise at the LHC through cascade decays of charginos ($\tilde{\chi}_i^\pm$) and neutralinos ($\tilde{\chi}_j^0$). These weak gauginos can either be produced directly or can result from decays of squarks and gluinos. The analysis presented here [1] consists of a search for direct production of weak gauginos in final states with three leptons and missing transverse momentum (MET) at $\sqrt{s} = 7$ TeV with integrated luminosity 2.06 fb$^{-1}$ collected by the ATLAS [2] detector at the LHC.

Two classes of supersymmetric models were considered. In the first of these, the phenomenological minimal supersymmetric Standard Model (pMSSM), a series of simplifying assumptions reduces the 105 parameters of the $R$-parity conserving MSSM to 19. These assumptions include CP conservation (to remove phases) and degenerate 1st and 2nd generation sfermion masses. This analysis made further assumptions, e.g. $\tan\beta = 6$ to ensure that the leptonic branching fraction is the same for each flavor, to reduce the number of parameters to 3: the $U(1)$ gaugino mass $M_1$, the $SU(2)$ gaugino mass $M_2$, and the Higgsino mass $|\mu|$.

The other class of SUSY models considered are the so-called simplified models. These are models which have been constructed with the minimal particle content necessary to produce multilepton SUSY-like events in $pp$ collisions. They are parametrized directly in terms of the sparticle masses. This analysis focused on direct production of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$.

2 Results and Interpretation

In addition to standard ATLAS event quality cuts, the baseline event selection requires 3 leptons ($e$, $\mu$) with transverse momentum $p_T > 10$ GeV, MET $> 50$ GeV,
and at least one same flavor, opposite charge (SFOC) lepton pair. Two signal regions (SR) have been considered. SR1 is defined by requiring that the invariant mass of the SFOC pair be further than 10 GeV from the $Z$ mass, and vetoing jets identified as originating from $b$ quarks. Conversely, SR2 is defined by requiring the SFOC mass to be within 10 GeV of the $Z$ mass.

SM background (BG) processes which produce the desired detector signature have been modeled with Monte Carlo (MC) simulated samples. BG processes which produce the desired signature via “fake” leptons (i.e. leptons in jets or from photon conversions) have been modeled with a data-driven matrix method. Good agreement was found between SM predictions and data in two orthogonal validation regions ($Z$+jets-dominated and $t\bar{t}$-dominated). The dominant background contributions in SR1 (SR2) were from $WZ$ and $t\bar{t}$ ($WZ$) production.

In SR1 (SR2), 32 (95) events were seen in data. The total SM prediction was $26 \pm 5$ (72 $\pm 12$) events. The BG-only $p$-value was found to be 19% (6%). The observed excesses are not significant, so 95% confidence level (CL) limits have been set on the parameter spaces of both SUSY scenarios. These limits have been computed using the modified frequentist $CL_s$ prescription [3] and are shown in Figure 1. An upper bound of 9.9 fb (23.8 fb) at 95% CL has been placed on the visible cross section in SR1 (SR2).

![Figure 1: 95% CL limits on the parameter spaces of pMSSM (left) and simplified model (right) scenarios. Both limits are set in SR1. [1]](image)

References


Study of the ATLAS muon identification efficiency in the presence of high pile-up

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The muon reconstruction and isolation efficiency of the ATLAS detector [1] at the Large Hadron Collider have been measured using the data collected in 2011. An unbiased sample of muons is selected, using tag-and-probe on the $J/\psi$ and $Z$ resonances, to measure these efficiencies. The tag-and-probe method selects events with one well reconstructed muon, the tag, and one loose opposite charge muon, the probe, that form an invariant mass near the mass of the resonance. The specific selections on the probes are tuned to provide a high purity sample of muons that will not bias the efficiency being measured. In both reconstruction efficiency measurements, a combined (CB) muon\(^1\) is chosen as tag. For the muon reconstruction efficiency, measured at low transverse momentum ($p_T$) using the $J/\psi$ sample [2] and at high $p_T$ using the $Z$ sample [3], a calo-tagged\(^2\) inner detector track was used as probe. For the isolation efficiency, a CB muon was used as probe.

Figure 1: Combined muon data/MC efficiency scale factor comparison between the $J/\psi$ and $Z$ measurements for $p_T$ range of $10 \text{ GeV} < p_T \leq 15 \text{ GeV}$ for the $J/\psi$ measurement and $15 \text{ GeV} < p_T \leq 20 \text{ GeV}$ for the $Z$ measurement [4].

\(^1\)A combined muon is the statistical combination of an inner detector track with a track in the muon spectrometer.

\(^2\)Calo-tagging selects inner detector tracks whose energy deposition in the calorimeter is consistent with that of a minimum ionizing particle.
Figure 1 shows the scale factors, calculated by dividing the efficiency in data by the efficiency in Monte Carlo, comparing the $Z$ and $J/\psi$ measurements versus the pseudo-rapidity $\eta$. The results show good agreement between the $J/\psi$ and $Z$ measurements. The track and calorimetric isolation efficiency versus the number of reconstructed vertices per event is seen in Figure 2. The pile-up corrected calorimeter isolation efficiency displays a small dip in efficiency at high pile-up. The track isolation efficiency, on the other hand, remains constant at even the highest levels of pile-up.

![Figure 1 and 2](image.png)

Figure 2: Track isolation (left) and pile-up corrected calorimeter isolation (right) efficiencies versus the number of reconstructed vertices [5].

References


$^{3}$Where $\eta = -\ln \left(\tan \left(\frac{\theta}{2}\right)\right)$ and $\theta$ is the polar angle of the particle from the beam line.

$^{4}$Relative isolation is when the sum of the track momentum or calorimeter energy deposition around the given particle in a specific cone does not exceed a certain threshold. For this analysis, track isolation is defined by $\sum p_T (\Delta R < 0.3)/p_T < 0.15$ and calorimeter isolation is defined by $\sum E_T (\Delta R < 0.3)/p_T < 0.14$

$^{5}$The term pile-up refers to multiple interactions per bunch crossing. Accordingly, high pile-up events are those with many reconstructed vertices.
Flavour Tagging at LHCb

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1 Introduction

LHCb is a heavy flavour experiment, mainly focused on beauty and charm physics, which performs precision measurements of CP violation and rare decays. The results shown here correspond to data samples up to 1 fb$^{-1}$ of proton proton collisions at $\sqrt{s} = 7$ TeV collected in 2011. As $b\bar{b}$ pairs are produced in the same forward (or backward) region, the LHCb detector [1] is fully instrumented in the forward direction, covering a pseudorapidity range $2 < \eta < 5$. The requirements for CP measurements in the B sector are: a flexible and efficient trigger, a good particle identification and an excellent tracking and vertexing, conditions that the detector fulfills.

Many LHCb measurements require the knowledge of the initial flavour ($b$ or $\bar{b}$) of the reconstructed $B^0_{d, s}$ mesons, such as $B^0 - \bar{B}^0$ oscillations and time dependent CP asymmetries. The process of flavour identification is known as flavour tagging [2, 3, 4] and this will be detailed in the following sections. Some examples of LHCb published results that use flavour tagging are: measurement of the $B_s$ oscillation frequency $\Delta m_s$ in $B^0_s \rightarrow D_s \pi$ [5, 6]; CP violating mixing phase, $\phi_s$ [7, 8, 9, 10] and direct and mixing induced CP violation in $B \rightarrow hh$ [11].

2 Flavour tagging

Different type of taggers (algorithms) are used for the B flavour determination in LHCb. A schematic view of the possible sources of information are shown in Fig. 1. The one known as Same Side (SS) tagger exploits the particle produced at the fragmentation process of the signal B: a pion in the case of $B^0$ or $B^+$ signal (or from a $B^{**}$ decay) and a kaon for $B^0_s$. The rest of taggers are those called Opposite Side (OS) taggers. These exploit the decay products of the other b-hadron produced in the event: a lepton (electron or muon) from semileptonic B decays; a kaon from a $b \rightarrow c \rightarrow s$ chain and an overall charge of the secondary vertex. In any case, the charge of the tagger tags the flavour of the signal B.
Due to the possibility to select a wrong track to tag the event, the tagging performance is not perfect. Moreover, as the opposite B can be neutral and oscillate, OS tagging algorithms have an intrinsic dilution. In order to evaluate the performance, we define a tagging efficiency, $\epsilon_{\text{tag}}$, which is the fraction of events with a tagging decision; a wrong tag fraction, $\omega$, or mistag rate, which is the fraction of events with a wrong tagging decision and an effective efficiency, $\epsilon_{\text{eff}}$, or tagging power, which indicates the statistical precision of the sample, given by $\epsilon_{\text{tag}}(1 - 2\omega)^2$.

The flavour tagging performance can be evaluated in data using flavour-specific decay channels, known as control channels, as the decays: $B^+ \to J/\psi K^+$, $B^0 \to D^{*-} \mu^+ \nu$, $B^0 \to J/\psi K^*0$ and $B^0_s \to D_s^-\pi^+$. For $B^+$ the mistag can be estimated just comparing the flavour tagging decision with the observed (true) flavour. In case of neutral B, $\omega$ can be determined from a fit to the time dependent mixing asymmetry, whose amplitude is proportional to the dilution factor $(1 - 2\omega)$. Fig. 2 shows the mixing asymmetry fits for $B^0 \to D^{*-} \mu^+ \nu$ and $B^0 \to J/\psi K^*0$ using OS tagged events.

Figure 1: Schematic view of the different sources of information available to tag the initial flavour of a signal B candidate.
Figure 2: Raw mixing asymmetry of $B^0 \rightarrow D^{*-}\mu^+\nu$ (left) and $B^0 \rightarrow J/\psi K^{*0}$ (right) when using the combination of all OS taggers for 0.37 $fb^{-1}$. Black points are data and red line is the result of the fit. The lower plots show the pull of the residuals with respect to the fit.

3 Optimization and calibration

Flavour tagging algorithms were initially designed studying simulated events [2]. For each tagger, the tagging particle is selected requiring several cuts on kinematic and geometrical observables (such as $IP/\sigma, p, p_T$) and particle identification discriminators. In the case of SS taggers, also proximity to the signal B is required. If several candidates for the same tagger exist, the one with highest $p_T$ is selected. An optimization of the selection cuts with real data has been performed using several control channels, in order to maximize the tagging power [3, 4]. For OS the main control channel used is $B^+ \rightarrow J/\psi K^+$ and the other channels are used as a cross check.

The taggers make individual decisions about the flavour with varying accuracy, which is evaluated by means of a Neural Net (NNet). The NNet uses as input some properties of the tagger and of the event ($B p_T$, number of interactions, ...), providing an estimate of the mistag probability ($\eta$) for each event. As this NNet was trained on MC samples, a calibration has to be performed on real data. The predicted mistag is calibrated with a linear fit using the measured $\omega$ in a control channel: $\omega = p_0 + p_1(\eta - <\eta>)$.

In case more than one tagger give a response, the final decision and predicted mistag are obtained combining the individual decisions and calibrated predicted mistag ($\eta_c$). Due to the correlation among taggers (mainly between secondary vertex
charge and other OS taggers) the OS predicted mistag needs to be calibrated in data.

The OS calibration is performed with $B^+ \to J/\psi K^+$ and validated using other control channels [10] (as $B^0 \to J/\psi K^{*0}$ and $B^0 \to D^-\pi^+$), as shown in Fig. 3. This calibrated per-event mistag can be used directly in the time-dependent CP fits.

![LHCb preliminary graph](image)

**Figure 3**: Measured OS mistag as a function of the predicted mistag probability, $\eta_c$, for $B^+ \to J/\psi K^+$ (left) and $B^0 \to J/\psi K^{*0}$ (right) with 1 fb$^{-1}$ data sample. The solid red line corresponds to a linear fit. In the right plot the calibration obtained from the $B^+ \to J/\psi K^+$ sample is superimposed as a blue shaded area, corresponding to a ±1σ variation.

### 4 Performances

After the optimization and calibration performed with the control channels, Table 1 shows the tagging power using OS taggers and the event-per-event mistags in some control channels with 0.37 fb$^{-1}$ [4] and Table 2 the performance in some CP-channels with 1.0 fb$^{-1}$ 2011 data [8, 9, 10]. Some differences in performance among channels are expected due to different trigger and selection requirements.

The SSπ tagger was already used together with OS taggers in 2010 measurements as $\Delta m_d$ with $B^0 \to D^\ast -\pi^+$ [12] and $\sin(2\beta)$ with $B^0 \to J/\psi K^0_s$ [13]. The tagging power for SSπ is around 1%.

The performance of SSK was initially optimized using prompt $D^+_s \to \phi \pi^+$, due to the low event yield of the main control channel $B^0_s \to D^-\pi^+$. The SSK has been used in the $\Delta m_s$ measurement with $B^0_s \to D^-\pi^+$ [6], where a clear oscillation is seen with only this tagger, as seen in Fig. 4 and obtaining a tagging power of (1.3 ± 0.4)%.
corresponding $\epsilon_{eff}$ is $(4.3 \pm 1.0)\%$ when using both OS and SSK. A new optimization and calibration has been performed with $B^0_s \rightarrow D^- \pi^+$ and the whole 2011 data sample, $1\ fb^{-1}$, to be used for next updates.

![Graph](image)

Figure 4: Mixing asymmetry for $B^0_s \rightarrow D^- \pi^+$ candidates as a function of decay time, modulo ($\frac{2\pi}{\Delta m_s}$), for a fit using only the SSK tagger (left) and the combination of OS and SS taggers (right).

## 5 Summary

Flavour tagging is a fundamental ingredient for B physics measurements in LHCb. An optimization and calibration of the OS and SS\pi tagging algorithms have been performed with $B^+ \rightarrow J/\psi K^+$ data and validated with other control channels. The SSK optimization and calibration with $B^0_s \rightarrow D^- \pi^+$ required the whole 1 $fb^{-1}$ and is going to be used in next updated measurements.

OS taggers have been already used in several published LHCb results, with an effective efficiency that goes from 2.1\% to 3.5\%, depending on the decay. SS taggers have also been used in a few measurements. The SS\pi effective efficiency is approximately 1\% and the SSK effective efficiency is 1.3\% (with a preliminary optimization).

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\epsilon_{tag}(1 - 2\omega)^2(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow J/\psi K^+$</td>
<td>$2.10 \pm 0.08 \pm 0.24$</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi K^{*0}$</td>
<td>$2.09 \pm 0.09 \pm 0.24$</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^{*-} \mu^+ \mu$</td>
<td>$2.53 \pm 0.10 \pm 0.27$</td>
</tr>
</tbody>
</table>

Table 1: OS effective efficiency for some control channels measured with $0.37\ fb^{-1}$. 
Table 2: OS effective efficiency for some CP-channels, used for several measurements of $\phi_s$ in LHCb with 1 fb$^{-1}$.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\epsilon_{tag}(1 - 2\omega)^2(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \to J/\psi\phi$</td>
<td>$2.29 \pm 0.07 \pm 0.26$</td>
</tr>
<tr>
<td>$B_s^0 \to J/\psi f_0(980)$</td>
<td>$2.12 \pm 0.26$</td>
</tr>
<tr>
<td>$B_s^0 \to J/\psi\pi\pi$</td>
<td>$2.43 \pm 0.08 \pm 0.26$</td>
</tr>
</tbody>
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References


Electron and Photon Performance Measurements with the ATLAS Detector

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Abstract

At LHC, excellent particle reconstruction and identification is needed for electrons and photons. The measurement of the electron and photon performance and the determination of the electromagnetic energy scale are presented using proton-proton collision data collected in 2010/2011. The electron and photon identification and isolation requirements are described and their efficiency rates are discussed.

1 Introduction

The precise measurement of the electron and photon performance with the ATLAS detector at the LHC is vital not only for the measurement of Standard Model processes but also for searches including the Higgs boson. These processes produce particles with energy range from a few GeV to a few TeV. To distinguish isolated electrons and photons from background objects such as hadron jets, excellent electron and photon identification is needed. In order to achieve this, a combination of the ATLAS subdetectors [1] is exploited: the inner detector (ID) is used to separate electrons and photons and to measure the tracks associated to electrons and converted photons; the electromagnetic calorimeter (EMC) measures the energy and position of the electromagnetic showers; the hadronic calorimeter is used to measure the leakage of the electromagnetic shower behind the electromagnetic calorimeter.

2 Improved Electron Reconstruction Using Gaussian Sum Filter-based model for bremsstrahlung

The behaviour of high-energy electrons in the ATLAS ID is dominated by radiative energy losses (bremsstrahlung) when interacting with the material. These losses can be significant and can give rise to deviations from the original charged particles path,
resulting in alterations of the curvature of the electrons trajectory in the magnetic field. The ATLAS electron reconstruction has been improved to take into account such radiative losses by using track refitting with the Gaussian Sum Filter (GSF) algorithm in order to improve the estimated electron track parameters [2]. Figure 1 shows the improvement on the track parameters for high and low $p_T$ electrons, in simulation and data respectively.

Figure 1: *Left plot:* The dependence on the pseudorapidity $\eta$ of the width of the transverse impact parameter significance for GSF (open red) and standard (solid black) truth-matched Monte-Carlo electrons from Z-boson decays. *Right plot:* The $e^+e^-$ invariant mass distributions for prompt $J/\psi$ 2011 collision data samples [2].

### 3 Energy Scale and Resolution

An in-situ calibration is used in ATLAS to fine tune the electromagnetic energy scale provided by the EMC on data. The well-known mass of the Z boson and its decay in $e^+e^-$ pairs are used to improve the knowledge of the electron energy scale and the linearity of the electromagnetic calorimeter. In addition, the $J/\psi$ process as well as the $W \rightarrow e\nu$ (the latter relying on an $E/p$ measurement) are also used to cross-check the obtained results. For the $Z \rightarrow ee$ channel, two electrons with transverse energy $E_T > 20$ GeV are required to satisfy an invariant dielectron mass in the range 80-100 GeV, in the pseudorapidity region $|\eta| < 4.9$.

To determine the energy scale, the electron energy is parametrised as $E_{\text{meas}} = E_{\text{true}} (1 + \alpha_i)$ for a given region $i$, where $E_{\text{meas}}$ is the energy measured by the calorimeter after a simulation based energy scale correction, $E_{\text{true}}$ is the true electron energy and $\alpha_i$ the residual miscalibration. The energy scale correction factors $\alpha$ are determined using a log-likelihood fit and constraining the dielectron mass to the Z boson lineshape. Figure 2 shows the $\alpha$ correction factors as a function of the pseudorapidity for the region $|\eta| < 4.9$ and its stability over time. The main systematic uncertainties on the electron energy scale (at the level of 1% each) are coming from the knowledge
of the material budget in the simulation setup, from the uncertainty in the description of the low \( E_T \) electrons, and from the presampler energy scale [3].

\[
\begin{array}{c}
\text{Relative energy scale} \\
0.995 \\
0.996 \\
0.997 \\
0.998 \\
0.999 \\
1 \\
1.001 \\
1.002 \\
1.003 \\
1.004 \\
1.005 \\
\text{RMS: 0.054\%} \\
\text{RMS: 0.052\%}
\end{array}
\]

\[
\begin{array}{c}
\text{E}/p_{\nu} \rightarrow W \\
\text{ee inv. mass} \\
\int dt/dL = 7 \text{ TeV}, s, \text{ Data 2010}, \\
ee \rightarrow Z \\int \approx 40 \text{ pb}
\end{array}
\]

\[
\begin{array}{c}
\text{Figure 2: } \text{Left plot: The energy-scale correction factor } \alpha \text{ as a function of the pseudo-rapidity of the electron cluster derived from fits to } Z \rightarrow ee \text{ data. The uncertainties of the } Z \rightarrow ee \text{ measurement are statistical only. The boundaries of the different detector parts are indicated by dotted lines [3].} \\
\text{Right plot: Energy scale obtained by the } Z \rightarrow ee (\text{black points}) \text{ and } W \rightarrow e\nu (\text{red points}) \text{ method presented as a function of time. The values obtained by these two methods are normalised to one. Each point represents a recorded amount of data of around 100 pb}^{-1}. \text{ The quoted RMS is the sum of statistical fluctuations and time dependence, providing an upper bound on the energy response uniformity with time [4].}
\end{array}
\]

4 Electron and Photon Identification

The electron and photon identification provides good separation of isolated electrons and photons from background objects (non-isolated electrons, background electrons from photon conversions and Dalitz decays, hadron jets, non-prompt photons from the decay of neutral hadrons in jets, ...). The requirements of the electron and photon identification for the central region \(|\eta| < 2.5\) include lateral and longitudinal shower shape variables using information from the different layers of the electromagnetic calorimeter and energy leakage in the hadronic calorimeter. In addition, for the electrons track quality variables and cluster-track matching information are also used.

There are three levels of electron identification called loose, medium and tight each with more stringent requirements. For photons two identification levels are defined: loose and tight.

In the forward region (2.5 < \(|\eta| < 4.9\)) where there are no tracking detectors present, the identification relies solely on cluster moments and shower shapes. These provide efficient discrimination against hadrons due to the good transverse and longitudinal segmentation of the calorimeters, though it is not possible to distinguish
between electrons and photons. Two identification levels are defined in this case: forward loose and forward tight.

### 4.1 Electron Identification Measurements

The measurements of the electron identification efficiencies are performed using the Tag-and-Probe method. This method uses $W$, $Z$ and $J/\psi$ decays in electrons to derive data-driven efficiency measurements. It is based on the definition of a probe-like object, used to make the performance measurement, within a properly tagged sample of events. In the following, a well-identified electron is used as the tag in the $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ measurements and high missing transverse momentum is used in the $W \rightarrow e\nu$ measurements.

For these measurements, the contamination of the probe sample by background requires the use of some background estimation technique (usually a side-band or a template fit method on the dielectron mass for $Z$ and $J/\psi$ measurements or the isolation distribution for the $W$ measurements). The number of electron candidates is then independently estimated both at the probe level and at the level where the probe passes the cut of interest. The efficiency is equivalent to the fraction of probe candidates passing the cut of interest.

The efficiency measurements for the medium and tight identification performed using the $W \rightarrow e\nu$ Tag and Probe method are shown in Figure 3 as a function of the pseudorapidity and integrated for electrons with transverse energy $20 < E_T < 50$ GeV. With this method, the $E_T$ region between 15-20 GeV is also explored. Compatible results are obtained with the $Z \rightarrow ee$ Tag and probe method used in the $E_T$ region 20-50 GeV and the $J/\psi$ measurement used for low-$E_T$ electrons ($4 < E_T < 20$ GeV). For the $Z$ and $J/\psi$ measurements, the statistical uncertainty is comparable to the systematics. The main sources of systematic uncertainties are the background subtraction method, the discriminating variable used and the level of the background contamination.

The dependence of the electron identification efficiencies for all three identification levels on the number of reconstructed vertices during the 2011 data taking is shown in Figure 4. The number of reconstructed vertices is a way to assess the in-time pileup. Alterations to the identification requirements have been made in preparation for the 2012 data taking in order to provide a more robust behaviour against pileup.

### 4.2 Photon Identification

Unlike the electron case, the method presented here in order to measure the identification efficiency for photons is not completely data-driven. The photon identification efficiencies are measured in simulation samples and are then corrected for differences observed between simulation and data. An important requirement used in photon
analyses is the isolation of the photon candidate defined as the transverse energy deposit within a cone around the calorimetric photon cluster.

The first plot in Figure 5 shows the tight photon identification efficiencies measured as a function of the reconstructed transverse energy in three different pseudorapidity bins. The identification efficiency increases for higher $E_T$ from the level of 65% for the $E_T$ region 15-20 GeV to 95% for photons with transverse energy $60 < E_T < 100$ GeV [6]. The second plot shows the photon isolation distribution for the leading photon as measured for a diphoton analysis. The variable $E_{Tiso}$ is calculated by summing the cells of the electromagnetic and hadronic calorimeters in

Figure 4: Identification efficiencies as a function of the number of reconstructed vertices during the 2011 data taking (open circles) and as expected for the 2012 data (dark circles) after reoptimisation of the identification requirements [5].
Figure 5: *Left plot:* Tight identification efficiency as a function of the reconstructed photon transverse energy for prompt isolated photons in three different pseudorapidity regions. The efficiency is calculated with respect to reconstructed true photons satisfying $E_{T}^{\text{iso}} < 3$ GeV. The yellow bands include the systematic uncertainties [6].

*Right plot:* Isolation distribution for the leading photon in diphoton events. The solid points represent the data, the black solid line indicates the fit result and the dash-dotted curves show the diphoton decomposition [7].

a cone of angular radius $R < 0.4$ around the photon candidate. The $E_{T}^{\text{iso}}$ is corrected to take into account the energy leakage outside the photon cluster and the ambient energy density measured in the event [7].

References


Overview of soft QCD and diffractive physics at LHC

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1 Introduction

The soft QCD processes dominate the hadronic cross section at the LHC energy. The study of the particle production at low $p_T$ is one of the basic measurements at any hadron collider, providing a wide set of observables useful to model the event generators. Unidentified hadron multiplicity is sensitive to multi parton interactions while identified hadrons allow to test the modeling of strange and heavier quarks production in the event generators. A significant fraction of the inelastic cross section comes from diffractive processes, whose prediction is affected by large uncertainties. The study of the single, double and central diffraction provide a constrain to the Monte Carlo simulations and is therefore a mandatory step to understand the charged particle production at LHC.

2 Inclusive measurements

The study of the inclusive charged particle production was the first physics result obtained at LHC. The proton-proton interactions at $\sqrt{s}=900$ GeV, detected by ALICE during the early phase of the accelerator commissioning, showed results consistent with earlier measurements obtained in proton-antiproton interactions at the same energy[1]. The charged pseudorapidity density, the multiplicity and the $p_T$ distributions, and the dependence of the $<p_T>$ from the charged multiplicity were investigated in detail at LHC. From an experimental point of view the nice agreement in these measurements obtained by ALICE[2],ATLAS[3] and CMS[4] demonstrated the excellent detector performance and showed the experiments capability to control the systematics. The event generators aiming to simulate these data(PHOJET[5],PYTHIA 6[6] and PYTHIA 8[7]) can reproduce the measured distributions only qualitatively. ALICE[2] studied the charged particle pseudorapidity density for inelastic collisions having at least one charged particle at $|\eta| < 1$. The charged particle pseudorapidity density, compared to the one measured at $\sqrt{s}=900$ GeV, increases by $(23.3 \pm 0.4 (sta)+^{1.1}_{-0.7}(sys))$ at $\sqrt{s}=2.36$ TeV and by $(57.6 \pm 0.4 (sta)+^{3.6}_{-1.8}(sys))\%$ at $\sqrt{s}=7$ TeV, while the Monte Carlo with the highest values (PYTHIA tune ATLAS-CSC) provides 17.6% and 47.6% respectively[2]. The multiplicity distribution measured by ALICE at $\sqrt{s}=7$ TeV is not reproduced by PHOJET and by several PYTHIA6 tunes: ATLAS-CSC is the closest but this tune underestimates the average $p_T$ as a function of the event charged multiplicity ($n_{ch}$) at $\sqrt{s}=900$ GeV[2]. CMS found similar results at $|\eta| < 2.4$[4]: PHYTIA
8 reproduces the multiplicity distribution at \( \sqrt{s} = 7 \text{ TeV} \) but overestimates the same distribution at \( \sqrt{s} = 900 \text{ GeV} \). Moreover the agreement with PYTHIA 8 does not hold if a cut \( p_T > 500 \text{ MeV/c} \) is applied, showing the softer part of the hadronic production is the most difficult to be reproduced. PHOJET shows an opposite trend: it reproduces the multiplicity distribution measured by ALICE[2] and CMS at \( \sqrt{s} = 900 \text{ GeV} \), but underestimates the same distribution at \( \sqrt{s} = 7 \text{ TeV} \). CMS showed that the average \( p_T \) is reproduced at \( \sqrt{s} = 900 \text{ GeV} \) and \( \sqrt{s} = 2.36 \text{ TeV} \) by PHITIA 8, but this model overestimates it at \( \sqrt{s} = 7 \text{ TeV} \). ATLAS[3] measured the charged particle multiplicity distribution at \( |\eta| < 2.5 \), requiring \( p_T > 100 \text{ MeV} \) and \( n_{ch} \geq 2 \); by applying these cuts PYTHIA 8 underestimates the data both at \( \sqrt{s} = 900 \text{ GeV} \) and \( \sqrt{s} = 7 \text{ TeV} \) by 10-15%. It is worth noting, changing the above cuts to \( p_T > 500 \text{ MeV} \) and \( n_{ch} \geq 6 \), PYTHIA tune ATLAS AMBT1 reproduce nicely the data both at \( \sqrt{s} = 900 \text{ GeV} \) and \( \sqrt{s} = 7 \text{ TeV} \). Recently the charged multiplicity \( (n_{ch} > 1) \) was measured by LHCb in the \( \eta \) interval \( 2 < \eta < 4.5 \) [8] and by TOTEM at \( 5.3 < \eta < 6.5 \) [9]. In these \( \eta \) regions the event generators (default or tuned) underestimate the charged particle multiplicity too. As a conclusion of this first part we note each model/tuning can reproduce a limited number of observables at few center of mass energies.

### 3 Exclusive measurements

CMS measured the spectra and the \( p_T \) of identified charged particle at \( \sqrt{s} = 900 \text{ GeV}, 2.36 \text{ TeV} \) and \( 7 \text{ TeV} \) [10]. The experimental results obtained at midrapidity \((|y| < 1)\) have been compared with the expectation provided by several event generator. The average \( p_T \) as a function of the track multiplicity is properly reproduced by PYTHIA 8 tune 4C and PYTHIA 6 tune Z2 for pion and kaons at any center of mass energy, but none of the above models/tunes provides an acceptable description of the protons. ALICE shows[11] the ratio \( \pi/K \) as a function of the \( p_T \) is missed by PHOJET, PYTHIA tunes Perugia 0 and D6T at \( \sqrt{s} = 900 \text{ GeV} \) for \( p_T > 1.2 \text{ GeV/c} \). The CMS measurement shows PYTHIA 8 tune 4C is inadequate to reproduce this ratio as a function of the track multiplicity at any center of mass energy. The same event generator underestimate the \( K^0 \) and the \( \Lambda \) production in CMS at \( \sqrt{s} = 900 \text{ GeV} \) and \( \sqrt{s} = 7 \text{ TeV} \): the discrepancy increases with the particle mass [10]. Things get worse when focusing on multi-strange hadrons. The ALICE collaboration measured the production of mesons and baryons containing two or three strange quarks in proton-proton collisions at the LHC at \( \sqrt{s} = 7 \text{ TeV} \). The ratio \( N_{\Phi}/(N_{\rho} + N_{\omega}) \) measured by ALICE in the forward region \((2.5 < y < 4)\) in the muon channel agrees nicely with the LHCb measurement \((2.44 < y < 4.06)\) obtained in the \( K^+K^- \) channel. The predictions underestimate this ratio up to a factor 2[11], with the exception of the ATLAS CSC tune (PHOJET) giving a reasonable estimate for \( p_T > 1.5 \text{ GeV/c}(3 \text{ GeV/c}) \). The study of the \( \Xi \) and of the \( \Omega \) provides an useful tool to check the strangeness production in proton-proton collisions, since these two baryons differ only by a valence quark, with the u-quark replaced by a s-quark in the \( \Omega \). ALICE showed[11] PYTHIA 6 tunes Z1, Z2 and Perugia 0 are up to an order of magnitude below the \( \Omega \) measured spectra and yield and the ratio \( \Omega/\Xi \) is also underestimated by a factor up to \( \simeq 4 \)[11]. The Perugia 2011 gives better results, but underestimates by a factor 4(2) the \( \Omega/\Xi \) yield (Fig. 1). Simulating the strange hadrons is a
difficult task: in PYTHIA the strangeness production is controlled by several parameters, as the suppression of the s quark pair production in the field compared with the u-pair or d-pair production, the extra suppression of strange diquark production compared with the normal suppression of strange quarks, etc. It is worth noting the Perugia 2011 tune makes use of the CTEQ5L parton distribution function, and has a significant increase in multi-strange baryon yields with respect to other tunings/models. Nevertheless the production of strangeness in ALICE is not adequately described by this tune too. An effort to increase the strangeness production has been attempted by the Z1C tuning, increasing the above parameters: as a result the Λ/K ratio increases but the K/π ratio has to be improved at \( p_T > 1\text{GeV/c} \), where the ratio is still underestimated.

4 Inelastic cross section

The inelastic cross-section is the sum of several contributions: the single diffractive(SD), the double diffractive(DD), the central diffractive(CD) and the non diffractive (ND) cross section. Diffraction study is challenging: most of the proton excitation remains into the beam pipe and low pile-up runs are required. In addition the transition from ND to DD events is smooth; experimental observables requires Monte Carlo corrections to be linked with physics quantities. ATLAS relied on the calorimeters to study the distribution of the forward gap \( \Delta \eta^F \)[12], defined as the larger of the \( \eta \) regions extending to the limits of the ATLAS sensitivity (\( \eta = \pm 4.9 \)), in which no final state particles are produced above a given \( p_T \) threshold. ND events correspond to \( \Delta \eta^F \approx 0 \), while SD events have large \( \Delta \eta^F \). PYTHIA 8 reproduces the \( \Delta \eta^F \) distribution at low and high \( \Delta \eta^F \), while the central region (3 \( \leq \Delta \eta^F \leq 6 \)) is overestimated. On the contrary this region is nicely reproduced by PHOJET, missing the low and the high \( \Delta \eta^F \) region. None of the models can reproduce the rise at
This region can be matched by decreasing the pomeron intercept from $\alpha \simeq 1.085$ to $\simeq 1.058$, but the price to be paid is an underestimate of the central region ($3 \leq \Delta \eta^F \leq 6$). The fraction of diffractive events in the Monte Carlo has to be constrained from the data: ATLAS used the fraction of events ($R_{ss}$) giving a signal only in one of the two Minimum Bias Trigger Scintillator detector (single-sided events)[13]. The MC generators predict that less than 1% of the ND process pass the single-sided event selection, whereas 27–41% of the SD and DD processes pass the single-sided selection. $R_{ss}$ was computed for different Monte Carlo codes by varying the fraction of the diffractive cross section with respect to the total inelastic cross section ($f_D$). The experimental value $R_{ss}=(10.02 \pm 0.03(stat)^{+0.1}_{-0.4}(sys)$) is reproduced assuming a diffractive fraction $f_D=(26.9\pm2.5)\%$. The model closest to the central value is PYTHIA 8 with the Donnachie-Landshof(DL) model with $\epsilon=0.085$ and $d=0.25 \text{GeV}^{-2}$, where $\epsilon + 1$ is the intercept of the pomeron trajectory and $d$ is the pomeron trajectory slope. This code was selected by ATLAS as reference model. The cross section for values of the fractional momentum loss of the scattered proton $\xi = M^2_\pi/s > 5 \cdot 10^{-6}$ is $\sigma_{inel}(\xi > 5 \cdot 10^{-6})=(60.3 \pm 0.05(stat) \pm 0.5(sys) \pm 2.1(lumi)) \text{mb}$. To extrapolate the above cross section to the full cross section ($\xi > m^2_p/s$), the fractional contribution to the inelastic cross-section of events passing the cut $\xi > 5 \cdot 10^{-6}$ is determined from the models. The reference model, PYTHIA 8 + DL, gives 87.3%, while other models considered give fractions ranging from 96% (PHOJET) to 86% (DL with $\epsilon=0.10$). The inelastic cross section at $\sqrt{s} = 7 \text{TeV}$ for $\xi > m^2_p/s$ measured by ATLAS is $\sigma_{inel}=(69.1 \pm 2.4(exp.) \pm 6.9(model)) \text{mb}$, where the experimental error includes both the statistical and the systematic error. Similar procedures were used by ALICE and CMS, finding respectively $\sigma_{inel}=(73.2^{+2.0}_{-4.6}(model) \pm 2.6(lumi)) \text{mb}[15]$ and $\sigma_{inel}=(64.5\pm1.1(exp.)\pm1.5(model)\pm2.6(lumi)) \text{mb}[14]$. ALICE used the distribution of the largest pseudorapidity gap in the event and the ratio of events with a single arm to those with two arms to constrain the fraction of the SD and the DD cross section[14]. The result obtained was $\sigma_{SD}/\sigma_{inel}=(0.21^{+0.04}_{-0.07})$ and $\sigma_{DD}/\sigma_{inel}=(0.12^{+0.05}_{-0.04})$. The cross sections measured by ALICE, ATLAS and CMS agree within the quoted uncertainties, the first one being slightly larger. TOTEM[16] used the elastic cross section and the optical theorem. The result is $\sigma_{inel}=(73.4\pm0.1(stat)\pm1.9(sys)\pm2.9(lumi)) \text{mb}$, in good agreement with the measurements quoted above, specially the ALICE one.

5 Hard diffraction dijet production

Diffractive dijet production is characterised by the presence of a high-momentum proton which escapes undetected, and by a system $X$, which contains high-$p_T$ jets and is separated from the proton by a large rapidity gap(LRG). One proton emits a pomeron with fractional momentum $\xi$ and then the pomeron interacts with the other proton. This process has been studied at Fermilab and at HERA. Hard-diffractive processes can be described by the convolution of diffractive parton distribution functions (dPDFs) and hard scattering cross sections, which are calculable in pQCD. While in $e$-$p$ scattering the cross section can be successfully factorized, in hadron-hadron collider the factorisation is broken because of soft rescattering between the spectator partons. The related cross section reduction factor is usually referred in terms of Rapidity Gap Survival (RGS) probability. Dijets events
Figure 2: The CMS differential cross section for dijet production as a function of $\tilde{\xi}$.

were selected by CMS at $\sqrt{s}=7$ TeV\cite{17} requiring transverse momentum $p_T > 20$ GeV for both jets, jet axis pseudorapidity in the range $-4.4 < \eta < 4.4$ and $\eta_{\text{max}} < 3(\eta_{\text{min}} > -3)$. The dijet cross section was studied as a function of $\tilde{\xi}^{\pm} = C \Sigma(E^i \pm p^i_z)/\sqrt{s}$, a variable that approximates the fractional momentum of the pomeron, where $E^i$ and $p^i_z$ are the energy and the longitudinal momentum of the $i^{th}$ particle-flow object and $C$ is a correction factor for detector effects. The data were compared with several Monte Carlo models: as a first step non diffractive (ND) events were generated by PYTHIA 6 and by PYTHIA 8. These Monte Carlo, as expected, cannot reproduce the data at low $\xi$. Then diffractive events were generated by PYTHIA8(SD+DD), POMWIG (based on HERWIG) and by POMPYT (based on the PYTHIA framework), all of them using a diffractive parton distributions based on H1 experiment data fit. The main difference between POMWIG or POMPYT with respect to PYTHIA 8, is a different pomeron flux parametrization. POMWIG and POMPYT overestimate the event yield at low $\xi$, while PYTHIA 8(SD+DD) has to be scaled by a factor $\simeq 2$ to match the data. Considering both POMWIG and POMPYT do not include the RGS, and that in the data a fraction of the scattered proton excites into a low-mass state which escapes undetected in the forward region, the discrepancy between their expectation and the data, $(0.21 \pm 0.07)$ can be considered as a RGS upper limit. After a correction for the proton dissociation, an estimate of the RGS probability can be extracted, giving $(0.12 \pm 0.05)$.

6 Conclusions

The data collected from $\sqrt{s} = 0.9$ to 7 TeV offered the possibility to study many aspects of the soft QCD at LHC. The results from different experiments are in excellent agreement but the event generators still need further improvements to give appropriate predictions: as an example the strangeness production is not properly reproduced yet. The study of
the minimum bias event topology allowed a reasonable tuning of the single and double
diffraction in the event generators, leading to a sucessful measurement of the total inelastic
cross section. The ATLAS and CMS calorimeters succesfully studied the rapidity gap, the
dijet and the W production in diffractive events, providing informations on the pomeron flux
and on the diffractive structure functions. In the next years LHC will unveil the evolution
of the hadronic system beyond 10 TeV and the study of other soft processes, as the central
diffraction, will give a more detailed picture of the low \( p_T \) event production at high energy.

References

[10] The CMS collaboration, CMS PAS FSQ-12-014, CMS PAS QCS-10-007.
[16] The TOTEM collaboration, CERN-PH-EP-2012-239; see also the talk by F. Ferro at
this conference.
Theoretical perspectives on the heavy ion LHC program

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1 Introduction

One of the most important discoveries at RHIC is a centrality dependent suppression of large transverse momentum hadrons [1, 2]. This phenomenon – although established on the basis of single-inclusive hadrons – is known as ‘jet quenching’ and is commonly interpreted as being due to radiative energy loss (i.e. QCD bremsstrahlung) of energetic partons in the dense and hot QCD matter produced in ultra-relativistic collisions of heavy nuclei.

2 Analytical approaches

There are several analytical calculations of non-Abelian bremsstrahlung [3, 4, 5, 6, 7, 8]. Despite the different approaches and techniques these calculations have a few things in common. Firstly, they find that the phenomenology is dominated by an interference that can be understood as the non-Abelian analogue of the Landau-Pomerantchuk-Migdal (LPM) effect. Secondly, they operate in a particular kinematical limit, namely the eikonal limit in which the radiating particle’s energy is asymptotically large. This has important consequences, for instance in that there is no collisional energy loss. In this limit the action of the medium on the fast parton is characterised by the transport coefficient \( \tilde{q} \). Finally, all analytical calculations consider the radiation of a single gluon that is then iterated probabilistically. Apart from neglecting possible interferences this does not do justice to the well-known QCD jet evolution. Consequently, these approaches are suitable for describing single inclusive observables, but not for more exclusive observables and jets. An study comparing the different calculations in the same set-up found that they all describe the RHIC hadron suppression data equally well, albeit with very different transport coefficients [9]. A detailed investigation by the TECHQM collaboration concluded that this is due to the fact that the kinematical situation in the experiments is far from the eikonal limit and therefore the models are pushed outside their region of validity [10].
3 Jet Quenching at the LHC

Measurements of the single-inclusive hadron spectra at the LHC have shown a similar amount of suppression as at RHIC, but a different transverse momentum dependence (which is at least partly caused by the different shape of the underlying spectrum) [11, 12]. At the LHC also properties of reconstructed jets in heavy ion collisions are accessible and have been measured. For instance, a large transverse momentum asymmetry was found in di-jet events, while the azimuthal angle between the two jets remains unchanged [13, 15]. The missing momentum is carried by soft particles far away from the jet axis [15]. Furthermore, the intra-jet fragmentation functions are largely unmodified at intermediate and large momentum fractions [16, 17]. All these observations indicate that the jets lose energy and transverse momentum because soft components get transported outside the jet cone while the hard core is not altered. This interpretation is supported by a simple formation time argument [18]: The formation time of medium induced (bremsstrahlung) emissions is given by $\tau_{\text{med}} = \sqrt{2\omega/\hat{q}}$, where $\omega$ is the emitted gluon’s energy. The angle of the emitted gluon with respect to the radiating parton can be estimated as $\theta_{\text{med}} \approx (2\hat{q})^{1/4}/\omega^{3/4}$, i.e. soft gluons decohere first and at large angles. At the same time the formation time of hard emissions from normal (vacuum) QCD evolution is parametrically of the form $\tau_{\text{vac}} = 2\omega/k_{\perp}^2$, where $k_{\perp}$ is the transverse momentum of the radiated gluon. This means that the formation of hard gluons is delayed by a boost factor and thus protected from interactions in the medium.

On the theoretical side technical advances have been made, for instance various calculations have been equipped with more realistic models for the medium. They generally agree at least qualitatively with the hadron suppression data [19, 20, 21, 22], but the conceptual issues have not been resolved. In order to make progress jet-medium interactions need to be formulated in more general non-eikonal kinematics. Then, however, elastic and inelastic interactions cannot be unambiguously separated any more and the ambiguity between the two needs to be resolved. Multi-gluon emissions have to be formulated consistently treating all sources of radiation (vacuum and medium-induced) on equal footing and keeping the interference responsible for the LPM-effect. Also the back-reaction of the jet on the medium has to be understood and modelled. Moreover, in order to obtain credible results all aspects of the calculation need to be controlled and uncertainties quantified.

4 Monte Carlo models

As Monte Carlo codes are widely used in particle physics to simulate complex multi-particle final states, it seems plausible that at least some of these problems can be solved with Monte Carlos. However, one thing to keep in mind is that Monte Carlo
models relying on analytical results to simulate medium-induced gluon emissions also inherit the conceptual weaknesses. Still, Monte Carlo techniques can be used to exploit approaches that cannot be treated analytically.

The established Monte Carlo models for jet quenching are HIJING [23], HYDJET++/PYQUEN [24], JEWEL [25], Q-PYTHIA/Q-HERWIG [26, 27], YaJEM [28] and MARTINI [29]. Some of them are based on analytical results while others build on new ideas. They all include some form of jet evolution and produce final states that can in principle be compared to jet measurements. Although the Monte Carlo models typically succeed in reproducing for instance the di-jet asymmetry at least qualitatively, no consistent picture has emerged yet as it is sometimes unclear to what extent all aspects of the modelling are controlled.

5 Conclusions

Jet quenching measurements at the LHC indicate that the hard core of the jets stays intact while soft modes get transported to large angles. This picture supports the interpretation that perturbative, coherent gluon bremsstrahlung is responsible for the observed modification of jets. However, detailed comparisons of theory predictions and data suffer from large systematic theory uncertainties. Therefore, in order to make the most of the LHC data, new developments on the theory side are necessary. Also, with a wealth of jet data new theory tools such as Monte Carlo codes are needed. Monte Carlo models are starting to overcome the limitations of analytical calculations, but most of them still don’t provide a controlled and consistent framework.

References


Particle Correlation Results from the ALICE Experiment at LHC

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Abstract

Measurements of two-particle correlations of inclusive and identified charged particles performed with the ALICE detector in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are presented. The near-side jet shape is analyzed in the low $p_T$ regions ($1 < p_T < 8$ GeV/$c$). While the RMS of the peak in $\Delta \varphi$-direction is independent of centrality within uncertainties, we find significant broadening in $\Delta \eta$-direction from peripheral to central collisions. The near-side $p/\pi$ ratio of particles associated to a trigger particle from jet fragmentation in the central Pb–Pb collisions is consistent with vacuum fragmentation in the measured momentum region ($1.5 < p_T < 4.5$ GeV/$c$).

1 Introduction

In-medium modification of jet fragmentation functions (FF) in heavy ion collisions is thought to be a direct manifestation of the parton energy loss in the medium \cite{1,2,3,4,5}. Despite of the large parton energy loss signaled by the suppression of high transverse momentum hadrons \cite{6} and the substantial imbalance of the jet transverse energies in di-jet events \cite{7}, it has been found that jet FF in Pb–Pb collisions are quite similar to the ones measured in $pp$ collisions \cite{8}. However there are several caveats in this analysis \cite{8} that should be mentioned, a quite high momentum cut ($4$ GeV/$c$) is imposed on the input particles for the jet reconstruction and a rather small cone size ($R=0.3$) is used. For $4$ GeV/$c$ hadrons from the model prediction \cite{1}, one expects only 20-30% modification in the yield for a 100 GeV jet. Also note that the statistical and systematical errors on the results are of similar magnitude as the expected modification.

Since the radiated energy may result in low $p_T$ particles emitted at large angles w.r.t the jet-axis \cite{7} and the coupling to the longitudinally flowing medium \cite{9} will lead to broadening that is larger in $\Delta \eta$ than in $\Delta \varphi$, the motivation for the present analysis in ALICE is to extend the jet shape studies into low $p_T$ particles ($p_T < 8$ GeV/$c$) in large $\Delta \eta$ region (wide angular range w.r.t the jet-axis). Furthermore, identified particle ratios associated with the jet and those from the bulk are measured in order to study the jet hadrochemistry \cite{10} as well as to test coalescence or recombination mechanism \cite{11,12,13}.

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2 Detectors and Data Samples

A description of the ALICE detector and its performance can be found in [14]. In this analysis, the following detector subsystems were used: the Time Projection Chamber (TPC) [15], the Inner Tracking System (ITS), two forward scintillator arrays (VZERO) and the Time-Of-Flight array (TOF) [16]. The TPC is the main tracking detector, providing full azimuthal coverage in the pseudo-rapidity range \( |\eta| < 1.0 \). The VZERO detectors cover the pseudo-rapidity ranges \(-3.7 < \eta < -1.7\) and \(2.8 < \eta < 5.1\). They are used to determine the centrality in Pb–Pb collisions. For particle identification (PID) the specific energy loss measured in the TPC as well as the time of flight measured by the TOF system are used. About 15 million minimum-bias Pb–Pb events at \( \sqrt{s_{NN}} = 2.76 \) TeV and 55 million pp events at \( \sqrt{s} = 2.76 \) TeV are analyzed.

3 Two Particle Correlations

The per trigger yield of associated hadrons is measured as a function of the azimuthal angle difference \( \Delta \varphi = \varphi_{\text{trig}} - \varphi_{\text{assoc}} \) and pseudo-rapidity difference \( \Delta \eta = \eta_{\text{trig}} - \eta_{\text{assoc}} \)

\[
\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{assoc}}}{d \Delta \varphi d \Delta \eta} \big|_{p_{T,\text{trig}}, p_{T,\text{assoc}}, \text{centrality}}
\]

where \( N_{\text{assoc}} \) is the number of particles associated to the given number of trigger particles \( N_{\text{trig}} \). This quantity is measured for different ranges of trigger and associated particle transverse momentum in various centrality bins. The measured distributions are corrected with mixed events to correct for two-track acceptance in bins of centrality and vertex position, where the different \( z \) vertex bins are combined by calculating a weighted average as described in the following equations. First we measure the per trigger yield of associated hadrons in different \( z \) vertex bin ( Eq. (2)) and weight it by the number of triggers in \( z \) bin and calculated the weighted average ( Eq. (4)). The normalization for the mixed events is chosen to be 1 where \( \Delta \varphi \) and \( \Delta \eta \) is zero ( Eq. (3)). Also this per trigger yield of associated hadrons are corrected for tracking efficiency and contamination.

\[
\frac{d^2 N_{\text{raw}}}{d \Delta \varphi d \Delta \eta} (\Delta \varphi, \Delta \eta, z) = \frac{1}{N_{\text{trig}}(z)} \frac{N_{\text{same}}(\Delta \varphi, \Delta \eta, z)}{N_{\text{pair}}(\Delta \varphi, \Delta \eta, z)} \beta(z)
\]

\[
\beta(z) = N_{\text{pair}}(\Delta \varphi = 0, \Delta \eta = 0, z)
\]

\[
\frac{d^2 N}{d \Delta \varphi d \Delta \eta} (\Delta \varphi, \Delta \eta) = \frac{1}{\sum_z N_{\text{trig}}(z)} \sum_z N_{\text{trigg}}(z) \times \frac{d^2 N_{\text{raw}}}{d \Delta \varphi d \Delta \eta} (\Delta \varphi, \Delta \eta, z)
\]
4 Results

4.1 Near Side Peak Shapes

Figure 1: Per trigger yield of associated hadrons before (a) and after (b) $\eta$-gap subtraction. The middle panel shows the projection of the per trigger yield of associated hadrons (a) to $\Delta \varphi$ in $|\Delta \eta| < 1$ (black) and $|\Delta \eta| > 1$ (red).

The near side jet shapes are studied in low momentum ranges of trigger and associated particles. Fig. 1(a) shows a two dimensional ”per trigger yield of associated hadrons” in $\Delta \varphi$ and $\Delta \eta$ space in central (0-10%) Pb–Pb collisions. The trigger particle momentum is from 4 to 8 GeV/c and associated particle transverse momentum from 1 to 2 GeV/c. We have estimated the background yields from $\Delta \eta$-independent sources such as flow in the region of $|\Delta \eta| > 1$. The middle panel in Fig. 1 shows the 1-dimensional projection of Fig. 1(a), where the flow background, long range correlation $|\Delta \eta| > 1$ (normalized by the acceptance), is shown in red and the mix of short and long range correlation in black ($|\Delta \eta| < 1$). In the near side, we see a clear excess of correlated jet signal above the background. Once we subtract the long range correlation from the region $|\Delta \eta| < 1$, we obtain the final Fig. 1(b) where we see a clear jet peak. We repeat this procedure in different trigger, associated particle momentum bins as well as various centrality bins. The results are shown in Fig. 2. Peripheral and $pp$ look similar and we observe wider distribution in central collisions as compared with the peripheral and $pp$ collisions.

4.2 Jet Shape Characterization

The jet shape is quantified with RMS and excess kurtosis which is a measure of its peakedness. The near side peak was fitted with a sum of two 2 dimensional gaussians. The obtained results, $\sigma_{\Delta \eta}$ and $\sigma_{\Delta \varphi}$ are shown in Fig. 3 as a function of centrality for various trigger and associated particle momentum bins. The last data point in the centrality axis corresponds to the result extracted from $pp$ collisions.
Figure 2: Evolution of the per trigger yield of associated hadrons for two different trigger and associate particle momentum ranges in central, peripheral and pp collisions. Trigger and associated particle momentum range and centrality selection is shown on the figure. pp data is on the right panel.

Figure 3: Centrality dependence of $\sigma_{\Delta \phi}$ (left) and $\sigma_{\Delta \eta}$ (right) for three different bins of $p_T^{\text{trigg}}$ and $p_T^{\text{assoc}}$. The lines are extracted from AMPT [17, 18] (A MultiPhase Transport Code; version 2.25 with string melting in PbPb) and Pythia [19] simulations (pp).
As expected, $\sigma_{\Delta \eta}$ and $\sigma_{\Delta \varphi}$ in higher $p_T$ bins are smaller than low $p_T$ bins since the jet is more collimated. But while we do not see any significant centrality dependence of $\sigma_{\Delta \varphi}$, we observe a significant increase of $\sigma_{\Delta \eta}$ towards central events for every particle momentum bin shown in this figure. For the lowest $p_T$ bins, the eccentricity $((\sigma_{\Delta \eta} - \sigma_{\Delta \varphi})/(\sigma_{\Delta \eta} + \sigma_{\Delta \varphi}))$ is about 0.2. The evolution from peripheral to $pp$ is smooth. Fig. 4 shows the excess kurtosis in same trigger and associated particle momentum bins as a function of centrality. A clear $p_T$ dependence of the excess Kurtosis is seen and it increases with $p_T$. The excess kurtosis decreases from $pp$ to peripheral and central events. The RMS and excess kurtosis of the near-side peak are well reproduced by the AMPT model [17, 18] shown in lines both in Fig. 3 and Fig. 4.

In the lowest $p_T$ bin shown in Fig. 5 ( $2 < p_{T,\text{trigg}} < 3$, $1 < p_{T,\text{assoc}} < 2$ GeV/$c$) in 0-10% central collisions, one sees a structure with a flat top in $\Delta \eta$ while this is not seen in $\Delta \varphi$. This is a surprising result which might be explained by the interplay of jets with the flowing bulk [9, 17, 18].

4.3 $p/\pi$ Ratio in Bulk and Jet Region

Baryon over meson ratios differ significantly between heavy ion and $pp$ collisions which might be attributed to radial flow and coalescence or recombination mechanism [11, 12, 13]. Few years back, S. Sapeta, U.A Wiedemann have studied the jet fragmentation in heavy ion collisions for various particle species [10]. They show that medium-modification of the parton shower can result in significant changes in jet hadrochemistry [10], e.g, strong enhancement of proton compared to pion yield in the medium is expected from this model. ALICE has utilized the correlation method
to measure the $p/\pi$ ratio in Pb–Pb collisions where this ratio is measured both in the jet region and bulk region separately.

In this analysis, 5 to 10 GeV/c charged hadrons are used as the trigger particles. The associated particles are identified as $\pi$ or proton in the momentum range from 1.5 to 4.5 GeV/c. Combined particle identification with specific energy loss in the TPC and time of flight in the TOF was used. Fig. 6 (left panel) shows the two dimensional $\Delta \phi$ and $\Delta \eta$ per trigger yield of associated hadrons for associated particle momentum range from 2.0 to 2.5 GeV/c. Jet (peak) region is chosen in the range, $-0.4 < \Delta \eta < 0.4$, $-0.52 < \Delta \phi < 0.52$ in radian and bulk region is selected in long range correlation dominated region as discussed in the previous section. For those associated particles in the selected regions, the PID method is applied to get the yields of each species. These yields are corrected for tracking and PID efficiency. No correction for feeddown from e.g. $\Lambda$ decay has been applied. Once the yields are obtained both in the jet region and the bulk region, the yields for each species in the bulk region is subtracted from yields of the jet region to get final yields originating only from jets. The normalization factor for the jet region from the bulk region is given by the acceptance difference between the jet and bulk region.

The resulting $p/\pi$ ratio in the bulk region in 0-10% central collisions is shown in Fig. 6 on the right panel. It exhibits strong enhancement of protons for higher $p_T$ and it is consistent with the inclusive measurement [20]. However, the ratio in the jet region is much smaller than in the bulk region. While we do not have the same result in $pp$ collisions yet, the ratio in jet region is compared with PYTHIA
Figure 6: Left panel: Jet and bulk regions. Right panel: $p/\pi$ ratio in the bulk (squares) and peak-bulk (circles) regions compared to the PYTHIA (line)

(pythia6.4) [19] for $pp$ collisions. Both results agree within the errors. This indicates no significant change of near side jet hadrochemistry in the central Pb–Pb collisions in the measured momentum region (1.5 to 4.5 GeV/c).

5 Summary

Two-particle correlations have been used to quantify the signatures of the modified jet fragmentation in the medium in the low $p_T$ regions ($1 < p_T < 8$ GeV/c) in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. While the RMS of the near-side peak in $\Delta \phi$-direction is independent of centrality within uncertainties, we find significant broadening in $\Delta \eta$-direction from peripheral to central collisions. The RMS and excess kurtosis of the near-side peak are well reproduced by the AMPT model, which might explain the interplay of jets with the flowing bulk [17, 18]. The near-side $p/\pi$ ratio of particles from jets in central Pb–Pb collisions is similar as that of PYTHIA [19]. This indicates no significant change of near side jet hadrochemistry in the central 0-10% Pb–Pb collisions compared with $pp$ collisions in the measured momentum region (1.5 < $p_T$ < 4.5 GeV/c).
References

Strangeness with ALICE: from \( pp \) to Pb-Pb

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1 Introduction

The physics of relativistic heavy ion collisions is studied to answer questions about primordial quark-gluon matter (QGP) that existed in nature up to \( 10^{-6} \) sec after the Big Bang. Today, we can create such matter in high energy heavy ion accelerator-colliders. The newest, the Large Hadron Collider (LHC), is currently capable of accelerating lead ions to collide at \( \sqrt{s_{NN}} = 2.76 \) TeV, and protons to energy as high as \( \sqrt{s} = 8 \) TeV. One way to characterize the quark chemistry and density, and to investigate particle-production mechanisms in the QGP, is to study the production of the strange quark (\( s \)) in Pb-Pb and pp collisions. This is done by identifying and measuring the properties of particles containing one or more \( s \)-quarks. Comparing the spectra of such particles produced in pp collisions to calculations and phenomenological models can help constrain fragmentation functions; pp spectra also provide a necessary baseline for measurements in Pb-Pb. In this article, we review the measurements of strange particles performed by the ALICE Collaboration and relate these measurements to matter produced at the LHC.

2 Data and the experimental setup

All data presented here were obtained using the ALICE detector at the LHC. Details of detector configuration and capabilities of ALICE are described elsewhere [1]. In Pb-Pb, collision centrality was determined using the signals from VZERO detector and tracklets obtained in the Inner Silicon Tracking (ITS) system. Strange and multistrange particle spectra were measured using tracks reconstructed in the ITS and the Time Projection Chamber (TPC). Proton, pion, and kaon tracks were identified using particle energy loss in the TPC. Using topological considerations, \( \Lambda \) (\( \Lambda \to \pi^-+p^+ \)), \( \Xi^- \) (\( \Xi^- \to \Lambda+\pi^- \)) and \( \Omega^- \) (\( \Omega^- \to \Lambda+K^- \)) baryons and their anti-particles, as well as \( K^0_S \) mesons (\( K^0_S \to \pi+\pi \)) were reconstructed via the corresponding decay channels, as described, for example, in [2]. After reconstruction, the spectra were corrected for acceptance and detector effects, and normalized to the inelastic event cross-section.
3 Results

ALICE measured multi-strange baryon spectra in pp at two energies, $\sqrt{s} = 0.9$ TeV and 7 TeV. The trends, together with a 0.2 TeV measurement by STAR [3], are shown in Fig. 1. To increase statistics, the particle and the anti-particle yields and $\langle p_T \rangle$ are added together, and denoted as $\Omega^\pm$ (for $\Omega^-$ and $\Omega^+$) and $\Xi^\pm$ (for $\Xi^-$ and $\Xi^+$). The $\Omega^\pm$ and $\Xi^\pm$ spectra at 7 TeV were also compared to several PYTHIA tunes [4]. The PYTHIA Perugia-2011 tune [5] was the best match to our spectra. The comparison between model and experimental data is shown in panel (b) of Fig. 2. Perugia-2011 differs from other PYTHIA tunes in that the pop-corn meson production mechanism is turned off.

In Pb-Pb collisions, a broad range of measurements were made. Strange particle yields, together with non-strange pions and protons, were fit to a thermal model [6], as seen in Fig. 3. The elliptic flow coefficient, $v_2$, for strange and multi-strange particles was determined, and is shown in Fig. 4 together with low-viscosity ($\eta/s=0.2$) VISH2+1 hydrodynamical calculations [7]. To get a handle on the $p_T$ range at which particle production via coalescence is applicable, $\Lambda/K_0^0$ ratios were constructed for all Pb-Pb centralities and for the two pp data sets, as seen in Fig. 5. In Fig. 6, the nuclear modification ratio, $R_{AA}$, of strange particles is shown together with the $R_{AA}$ of all charged particles measured by ALICE. Finally, in Fig. 7, we show the enhancement in the production of particles with $s$-quarks with respect to baseline collisions (pBe at NA57, and pp in others) as a function of collision centrality (characterized by $N_{\text{part}}$, number of participant nucleons) and the $s$-quark content.
Figure 3: Particle ratios measured by ALICE in 2.76 TeV Pb-Pb collisions, and two thermal model fits, at T=148 MeV (dashed line), and at T=164 MeV (solid line). $\gamma_s$ and $\mu_B$ are set to 1.

Figure 4: $v_2$ for pions, protons, kaons, and $\Xi$ and $\Omega$ baryons in 20-40% central Pb-Pb collisions (symbols). Also plotted are VISH2+1 with $\eta/s=0.2$ curves for the same particles.

4 Summary and conclusions

Particles containing the $s$-quark are a multi-faceted probe, used in relativistic heavy ion collisions with great success to test low to high $p_T$ regimes, help measure fragmentation functions in pp collisions, and characterize the collective properties of the medium in Pb-Pb events. ALICE measurements have validated the PYTHIA Perugia-2011 tune’s removal of the pop-corn meson creation mechanism, since it improved significantly the description of the multi-strange data in 7 TeV pp collisions [4]. In Pb-Pb collisions, the strange quark seems to be thermalized at T=164 MeV, when $\gamma_s$ is set to 1 (i.e., strangeness production is saturated). We also measure a large volume enhancement in the multi-strange particle production, consistent with previous observations and predictions [8]. Particles with more $s$-quarks experience a greater enhancement with respect to the baseline. However, another trend is confirmed – the amount of enhancement decreases with increased collision energy, most likely due to the power-law increase in baseline yields as collision energy increases. Collective effects in Pb-Pb collisions are consistent with light-flavour non-strange particle observations and also with those observed at lower energies. At 2.76 TeV, the strange-particle $v_2$ measurements are consistent with a low-viscosity medium, the meson-baryon ratios at intermediate $p_T$ point to the dominance of recombination in that region, and at high $p_T$ the strange particles seem to be suppressed as much as charged particles.
Figure 5: $\Lambda/K_0^0$ as a function of $p_T$ at all 2.76 TeV Pb-Pb collision centralities, and in 0.9 and 7 TeV pp collisions.

Figure 6: $R_{AA}$, for $K_0^0$, $\Lambda$ and charged particle spectra in 2.76 TeV Pb-Pb 0-5% central collisions.

Figure 7: Strange particle production as a function of $\langle N_{\text{part}} \rangle$ for $\sqrt{s_{NN}} = 0.017, 0.2$, and 2.76 TeV collisions relative to pBe (NA57) and pp (STAR, ALICE).

References

Heavy-Flavour Production in Pb–Pb collisions at the LHC with ALICE

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Results on open heavy-flavour production in Pb–Pb collisions at \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \) measured with ALICE at the LHC are presented. The nuclear modification factors, extracted in three different channels, show a strong suppression in central collisions. The measured D-meson azimuthal anisotropy indicates a non-zero \( v_2 \), which is similar to the one of charged hadrons.

1 Introduction

According to calculations of lattice Quantum Chromodynamics (QCD) [1] matter is expected to undergo a phase transition from a hadronic phase to a Quark-Gluon Plasma (QGP) at energy densities larger than 0.5 GeV/fm\(^3\). In the QGP phase quarks and gluons are deconfined and chiral symmetry is restored. Collisions of Pb nuclei at LHC generate an extended volume of high energy density (initial energy density \( \approx 15 \text{ GeV/fm}^3 \)). Heavy quarks, i.e. charm and beauty quarks, are among the most interesting and powerful probes to investigate the properties of the QGP. They are, due to their heavy mass, produced on a very short time scale in initial hard scattering processes and thus they experience the whole history of the collision. They interact strongly with the deconfined medium, loose energy and may participate in the collective expansion. Therefore they enable us to study parton energy loss as well as its color and quark mass dependence. The measurement of the elliptic flow \( v_2 \) of D and B mesons probes on the one hand the degree of thermalization of massive quarks in the medium at low transverse momentum and on the other hand the path length dependence of energy loss at high transverse momentum.

ALICE (A Large Ion Collider Experiment) is well suited to detect and identify open charm and beauty hadrons due to a momentum resolution better than 2% for \( p_T < 20 \text{ GeV/c} \), a transverse impact parameter resolution better than 65(20) \( \mu \text{m} \) for a \( p_T > 1(20) \text{ GeV/c} \) and because of various systems for particle identification, e.g. Time Projection Chamber (TPC), Time of Flight system (TOF), Muon Spectrometer. The experiment and its heavy-quark detection performance are described in detail in [2]. In this paper open heavy-flavour production in Pb–Pb collisions is presented in the following channels:
• Open charm and beauty - reconstruction of electrons from semi-electronic decays: D, B \rightarrow e + X in |y_e| < 0.8
The electrons were identified using the signals in the TOF and the TPC. To extract electrons from heavy-flavour hadron decays a data-tuned Monte Carlo cocktail of electrons from background sources was subtracted from the inclusive electron spectrum. Further details can be found in [3].

• Open charm and beauty - reconstruction of muons from semi-muonic decays: D, B \rightarrow \mu + X in -4 < y_\mu < -2.5
Single muons were measured in the Muon Spectrometer by matching reconstructed tracks with tracks in the muon trigger chambers [2]. Background muons from the decay-in-flight of light hadrons were estimated by extrapolating K^\pm and \pi^\pm spectra measured at mid-rapidity to forward rapidities and by applying the corresponding decay kinematics. Further information can be found in [4].

• Open charm - fully reconstructed hadronic decays:
D^0 \rightarrow K^-\pi^+, D^+ \rightarrow K^-\pi^+\pi^+, D^{++} \rightarrow D^0\pi^+ and charge conjugates in |y| < 0.5
The reconstruction is based on the invariant mass analysis of fully reconstructed decay topologies displaced with respect to the primary vertex. The large combinatorial background was reduced by identifying charged pions and kaons in the TPC and TOF. The correction for feed-down from B-meson decays was done using FONLL calculations [5]. More details on the analysis are described in [6].

The results presented in this contribution were obtained from the first two Pb–Pb runs at \sqrt{s_{NN}} = 2.76 TeV, which took place in 2010 and 2011. The Silicon Pixel Detector (SPD) at mid-rapidity and the forward VZERO scintillator counters provide a minimum-bias (MB) interaction trigger, and are also used to derive the centrality of the collisions. In total 17M MB Pb–Pb collisions (2010) were used for analysis. The elliptic flow results are based on 9.5M events (2011) in the 30-50% centrality class.

2 Open heavy-flavour suppression

An observable to quantify the interaction of hard partons with the medium is the nuclear modification factor \( R_{AA} \), where one compares particle production in Pb–Pb collisions with pp collisions at the same centre-of-mass energy:
\[
R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}.
\]
\( \langle T_{AA} \rangle \) denotes the average nuclear overlap function for a given centrality range, \( dN_{AA}/dp_T \) and \( d\sigma_{pp}/dp_T \) represent the particle yield in nucleus-nucleus collisions and the cross section in pp collisions, respectively.

Figure 1 shows the nuclear modification factor of background-subtracted electrons for the centrality ranges 0-10% and 60-80%. The pp reference spectrum is obtained by scaling the measured spectrum of electrons from heavy-flavour decays in pp at \( \sqrt{s} = 7 \) TeV to 2.76 TeV based on FONLL calculations [7]. In contrast to peripheral events, a suppression of a factor of 1.5-4 is found for 0-10% central collisions in the \( p_T \)
region 3.5-6 GeV/c, where charm and beauty decays a priori dominate [3]. Including the Transition Radiation Detector (TRD) and the Electromagnetic Calorimeter for particle identification will lead to an extension of the $p_T$ range of the $R_{AA}$ towards low and high $p_T$ as well as to a reduction of the systematic uncertainty. In the near future, the charm and beauty contributions will be disentangled via secondary vertexing.

Also, the heavy-flavour decay muon $R_{AA}$ for $p_T = 4$-10 GeV/c yields a suppression of a factor of 3-4 in central collisions (0-10%) with no significant $p_T$ dependence [4]. The FONLL [5] prediction indicates that beauty-decay muons dominate for $p_T > 6$ GeV/c. The average $R_{AA}$ of three D-meson species ($D^0$, $D^+$ and $D^{++}$) is shown in Fig. 2. The pp reference at $\sqrt{s} = 2.76$ TeV was obtained by scaling the measured 7 TeV spectrum with FONLL calculations [7]. The respective spectrum was cross-checked against the measured result of a short pp run taken at $\sqrt{s} = 2.76$ TeV. For the 0-20% centrality class a suppression of a factor of 3-4 for $p_T > 5$ GeV/c is found. The supression is reduced when going to more peripheral collisions and at lower transverse momentum. Soon the errors will be reduced by including data from the second Pb–Pb run (2011), where 6-7 times more statistics in the 0-7.5% centrality range were collected. Using next-to-leading order (NLO) pQCD calculations, the effect of shadowing on the D-meson $R_{AA}$ was estimated to be $\approx 15\%$ for $p_T > 6$ GeV/c. Thus the visible strong suppression is most likely a final state effect. The upcoming p-Pb run (scheduled for 2013) will allow to measure directly the initial state effects. In Fig. 2 the $R_{AA}$ of prompt D mesons is compared with the one of charged hadrons, pions [9] and non-prompt $J/\psi$ from B decays [8]. There is an indication for $R_{AA}^{D^0} > R_{AA}^{\pi}$, whereas the suppression for non-prompt $J/\psi$ seems weaker. However a more differential and precise measurement of the $p_T$ dependence is necessary for a conclusive statement on color and mass ordering effects.

![Figure 1: $R_{AA}$ of background-subtracted electrons for central and peripheral Pb–Pb collisions.](image1)

![Figure 2: Comparison of the $R_{AA}$ of D mesons, charged hadrons and pions as well as non-prompt $J/\psi$ mesons in the 0-20% centrality class.](image2)
3 Elliptic flow $v_2$

In non-central heavy ion collisions the spatial anisotropy with respect to the reaction plane (defined by the beam axis and the impact parameter of the colliding nuclei) is translated into a momentum anisotropy due to multiple collisions. The magnitude of this asymmetry can be quantified using a Fourier decomposition of the $p_T$-dependent azimuthal distribution of particles w.r.t. the estimated reaction plane (called event plane). The second harmonic is called elliptic flow coefficient, $v_2$.

The measurements of the $D^0$ and $D^+$ $v_2$ (see Fig. 3) indicate a non-zero $v_2$ in the $p_T$ range 2-6 GeV/c. These results are similar to the charged hadron $v_2$ measured with ALICE in the same rapidity region.

In conclusion, we have measured in several decay channels a strong suppression of heavy-flavour production in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. There is a hint of a lower suppression for $D$ mesons than for pions. The measured elliptic flow of $D$ mesons seems non-zero and is within uncertainties comparable with the one of charged hadrons. These results indicate strong coupling of heavy quarks to the medium. In the near future, the contributions of charm and beauty quarks will be separated where applicable. The $p_T$ range will be extended as well as uncertainties reduced by increasing statistics and improving particle identification. Finally, initial and final state effects will be disentangled by measuring p-Pb collisions scheduled for the beginning of 2013.

References

Identified particle $p_T$ spectra and particle contents in pp collisions measured with ALICE at the LHC

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1 Introduction

ALICE is a general-purpose heavy-ion experiment at the LHC. The design is optimized for reconstruction and particle identification (PID) in a wide range of transverse momentum ($p_T$) [1, 2]. Since 2009 it has collected data from pp collisions at $\sqrt{s} = 0.9, 2.76, 7$ and $8$ TeV.

The main focus of ALICE is the study of Pb-Pb collisions. Measurements of relevant observables in pp collisions constitute a baseline for the interpretation of the results in nucleus-nucleus collisions. Moreover, the ALICE capabilities allow also to study some important aspects of pp physics. For example, at LHC energies the bulk of the particles produced at mid-rapidity have low transverse momentum ($< 2 \text{ GeV}/c$). Since perturbative Quantum Chromo-Dynamics (p-QCD) is not applicable, the particle production is modeled following phenomenological approaches. Hence, the measurement of identified particle production at low $p_T$ is a valuable input for models of hadronization process. For higher momenta ($> 7 \text{ GeV}/c$), $p_T$ spectra of identified particles provide important information to constrain the fragmentation functions (FFs) at large $z$ (momentum fraction of the hadron relative to the parent parton).

The relevant detectors for PID which were used to produce the present results are: Inner Tracking System (ITS), Time Projection Chamber (TPC) and Time Of Flight detector (TOF) [3], they are located in the central barrel of ALICE inside a large solenoidal magnet providing a uniform 0.5 T field [1, 2].

The ITS is composed of six cylindrical layers of silicon detectors. The two innermost layers are pixel detectors (SPD), followed by two layers of drift detectors (SDD) and two layers of double-sided silicon strip detectors (SSD). SDD and SSD provide measurements of the specific energy loss $dE/dx$ for charged particles.

The TPC is the main tracking device. It is a large cylindrical drift detector with a central membrane maintained at -100 kV and two readout planes at the end-caps composed of 72 multi-wire proportional chambers. The active volume is limited to
$85 < r < 247 \text{ cm}$ and $250 < z < 250 \text{ cm}$ in the radial and longitudinal directions, respectively. With this detector we can measure the specific energy loss $dE/dx$ relying on a sample of up to 159 points per charged track. Charged pions, kaons and (anti)protons are well separated at low $p_T (< 1 \text{ GeV}/c)$. The identification can be extended up to $20 \text{ GeV}/c$ using a statistical approach based on the relativistic rise where the separation of particles with different masses is almost constant.

The TOF detector consists of 18 azimuthal sectors, each containing 91 Multi-gap Resistive Plate Chambers (MRPCs) distributed in five gas-tight modules. Particles are identified by measuring their momentum and velocity simultaneously.

The strange and multi-strange particles: $K^0_S$, $\phi$, $\Lambda(\bar{\Lambda})$, $\Xi^-(\Xi^+)$ and $\Omega^-(\Omega^+)$ are identified from their weak decay topologies, more details can be found in [4, 5].

## 2 Results

Figure 1 shows the $\pi^+$, $K^+$ and $p$ transverse momentum spectra measured in pp collisions at $\sqrt{s} = 7 \text{ TeV}$. ALICE results are compared with predictions from Phojet [6] and Pythia-6 [7] (tunes: D6T, Perugia-0 and Perugia-2011). We observe that the models cannot describe the three yields simultaneously, e.g. Perugia-2011 only describes quite well the kaon yield. We obtain similar results if we consider their antiparticles, actually the $p/\pi$ ratio is independent of both rapidity and transverse momentum [8].

![Figure 1: Comparison of the measured $\pi^+$ (left), $K^+$ (middle) and $p$ (right) $p_T$ spectra in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ with predictions from Phojet and Pythia-6.](image)

The ratios $(K^+ + K^-)/(\pi^+ + \pi^-)$ and $(p + \bar{p})/(\pi^+ + \pi^-)$ can be used to probe the fraction of strange to non-strange particles and the baryon to meson ratio, respectively. Figure 2 shows both ratios as a function of $p_T$ for pp collisions at $\sqrt{s} = 0.9$ and 7 TeV. Within systematic and statistical uncertainties, both ratios seem to be energy independent, moreover, from [3] one can see that $K/\pi$ is constant from $\sqrt{s} = 0.2$ up to 7 TeV. Except from Pythia-6 tune D6T which describes well $p/\pi$, the event generators investigated here do not reproduce the data.
Figure 2: \((K^+ + K^-)/(\pi^+ + \pi^-)\) and \((p + \bar{p})/(\pi^+ + \pi^-)\) ratios as a function of \(p_T\) measured in pp collisions at \(\sqrt{s} = 0.9\) and 7 TeV. ALICE data are compared with predictions from Phojet and Pythia-6.

The agreement between data and event generators is even worse for predictions of strange baryon production \([4, 5]\). For instance, at \(\sqrt{s} = 0.9\) TeV the production of \(\Lambda\) is underestimated up to a factor \(\sim 5\). For multi-strange baryons, Figure 3 shows the measured \(\Xi^- (\Xi^+)\) and \(\Omega^- (\Omega^+)\) spectra for \(\sqrt{s} = 7\) TeV data. The results are compared with Perugia-2011. The agreement between data and theory is better for \(\Xi^- (\Xi^+)\) and especially at high transverse momentum (\(> 5\) GeV/c). However, for lower \(p_T\) (1-4 GeV/c) theory underestimates the production by a factor \(\sim 2\). On the other hand, the production of \(\Xi^- (\Xi^+)\) is underestimated by a factor larger than 3.

The measurement of TPC-dE/dx on the relativistic rise allows to extend the identification of \(\pi^\pm/K^\pm/p(\bar{p})\) up to \(\sim 20\) GeV/c. Figure 3 also shows the charged pion spectra measured in pp and Pb-Pb collisions at \(\sqrt{s_{NN}} = 2.76\) TeV. The spectrum for pp collisions seems harder than the ones for central Pb-Pb collisions because the medium suppresses the production of high \(p_T\) particles.

3 Conclusions

Transverse momentum spectra for identified particles were measured by ALICE. So far the event generators which were tested do not describe the various observables simultaneously. That is true even for Perugia-2011 which was tuned using the early LHC data and optimized to increase the strange hadron production \([9]\). This tune describes reasonably well the inclusive charge particle \(p_T\) spectrum at 7 TeV. However it does not succeed in describing the particle composition, especially the multi-strange baryon production. The aforementioned observations represent a challenge for hadro-production models.

The measured high-\(p_T\) charged pion production is important, because it provides
Figure 3: (Left) $\Xi^-(\Xi^+)$ and $\Omega^- (\Omega^+)$ measured baryon spectra in pp collisions at $\sqrt{s} = 7$ TeV superimposed with Tsallis fits [5]. The bottom panel shows a comparison with Pythia-6 tune Perugia-2011. (Right) Measured high-$p_T$ charged pion spectra from Pb-Pb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV. For heavy-ions, different centrality classes are shown.

data to probe the Parton Distribution Functions and Fragmentation Functions at low $x$ and large $z$, respectively.

References

Measurements of particle production and energy flow in pp collisions at $\sqrt{s} = 7$ TeV with the LHCb experiment

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We present the results on the charged particle multiplicity and energy flow measured with minimum-bias data collected by the LHCb experiment in pp collisions at $\sqrt{s} = 7$ TeV. The measurements are performed in the pseudorapidity range $2 < \eta < 5$ and compared to predictions given by several Monte Carlo (MC) generators.

1 Introduction

The measurements of particle production and forward energy flow (EF) are important inputs to tune Monte Carlo generators and to model the soft component of a hadron-hadron collision, called the underlying event (UE).

Designed for precise measurements of B meson decays, the LHCb experiment [1] at CERN is a one arm forward spectrometer, providing particle reconstruction in a unique kinematic range of $2 < \eta < 5$ and low transverse momenta. The forward region is of special interest as it is much less covered by other experiments and QCD models have large uncertainties. The vertex locator (VELO) provides an excellent vertex resolution and two RICH detectors allow high quality particle identification. The calorimeter system consists of a scintillating pad- and preshower detector (SPD/PS), the electromagnetic and the hadronic calorimeter. A loose minimum bias trigger requiring at least one track segment in the detector is used for the analysis presented here.

These proceedings present the measurements of charged particle multiplicities and densities in Section 2 followed by the energy flow measurements in Section 3. Measurements of strange particle production [2, 3] and hadron ratios [4] are not included in these proceedings.

2 Charged particle multiplicity

Charged particle multiplicity is a basic observable that characterizes the hadronic final state. In this analysis [5] the charged particles produced in pp collisions or from short lived particles are reconstructed in the VELO. This subdetector was designed to provide high efficiency in the forward ($2 < \eta < 4.5$) and in the backward
$(-2.5 < \eta < -2)$ regions. In the absence of almost any magnetic field no momentum information is available, hence the measurement can only be performed as a function of pseudorapidity. In this analysis a sample of 3 million events from the low luminosity running phase in early 2010 is used. A set of quality criteria to minimise the contribution of secondary particles and fake tracks is imposed. The reconstructed multiplicity distributions are corrected for the tracking and selection efficiencies and the background contribution. The charged particle multiplicity is then measured using an unfolding procedure.

Figure 2 shows the multiplicity distribution in the forward region compared to different MC predictions. Only events with at least one track in the forward $\eta$ range are selected. All generators underestimate the mean multiplicity distributions, with

![Figure 1: The multiplicity distribution in the forward $\eta$ range with predictions of different event generators and UE tunes.](image.png)

the LHCb tune giving the best description of the data. The agreement is improved excluding the diffractive processes in Pythia. Figure 2 shows the charged particle pseudorapidity density $\rho$ as a function of pseudorapidity, normalised to events with at least one charged particle in the forward acceptance, in comparison with different generator predictions. As a consequence of the requirement of at least one track in the forward range the data show an asymmetry between the forward and the backward region. The predictions fail to describe the data but a better agreement is obtained
when diffractive processes have been excluded.

3 Forward energy flow

The energy flow (EF) is defined as the average energy created in a particular $\eta$ interval ($E_{\text{TOTAL}}$) per inelastic pp interaction ($N_{\text{inter}}$) and normalised to the $\eta$ bin size:

$$EF = \frac{1}{N_{\text{inter}}} \frac{dE_{\text{TOTAL}}}{d\eta}$$

At large values of pseudorapidity it is expected to be directly sensitive to the amount of parton radiation and multiparton interactions (MPI), which represent an important contribution to the soft component of a hadron-hadron collision.

In this analysis [6] reconstructed tracks of good quality traversing the full LHCb tracking system were used. The charged EF was estimated from the reconstructed momentum and it was corrected for detector effects. Finally the total EF was estimated from the corrected charged EF using a data-constrained MC estimate of the neutral component. The experimental results on the total EF presented here refer to events with at least one track in $1.9 < \eta < 4.9$ with $p > 2 \text{ GeV}/c$ (inclusive minimum bias events).

In Figure 3 the results are compared to the predictions given by PYTHIA based [7, 8, 9] and cosmic-ray [10] MC event generators. Energy flow development as a function of $\eta$ is reasonably well reproduced by MC models. Nevertheless, the PYTHIA-based generators underestimate the corrected data at large $\eta$, while all the cosmic-ray interaction models overestimate it except the SYBILL generator.
4 Conclusions

LHCb is an excellent detector for particle production measurements in the forward region. The charged particle multiplicities and the energy flow are underestimated by PYTHIA based MC generators. Most of the cosmic-ray interaction models overestimate the energy flow.

References

Recent CMS Results on Forward and Small-\(x\) QCD Physics

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1 Introduction

Recent CMS results on Forward and Small-\(x\) QCD Physics are presented. Those include the measurement of the Underlying Event activity and the study of jet production at large rapidity separation.

2 Measurement of the UE activity

The Underlying Event (UE) in a \(p \bar{p}\) collision is everything except the hard scattering. It includes the initial state radiation (ISR), the final state radiation (FSR), the multiple partonic interactions (MPI) and the beam remnants. A good understanding of the UE activity is important in order to extend our knowledge of Quantum Chromodynamics (QCD) towards the soft limit, for precision measurements of Standard Model processes and searches for new physics. Since the UE is produced by soft or semi-hard interactions, its dynamics can not be fully described by perturbative QCD. As a consequence phenomenological models have to be used whose parameters have to be tuned to data.

The measurement of the UE requires a physically motivated separation between the soft and hard components of the collision. In the central region, where there is no separation in pseudorapidity \(\eta\) between the hard scattering and the UE, the traditional approach is to divide the phase-space in different \(\varphi\) regions wrt. the leading \(p_T\) object. The UE activity is then investigated through the measurement of the energy and particle densities in the so-called towards, transverse and away regions, respectively defined by \(|\Delta \varphi| < 60^\circ\), \(60^\circ < |\Delta \varphi| < 120^\circ\) and \(|\Delta \varphi| > 120^\circ\). This approach is followed in the study of the UE activity in the Drell-Yan (DY) process \(q \bar{q} \rightarrow \gamma^* / Z^{(*)} \rightarrow \mu^+ \mu^- [1]\) which offers a clean separation between the hard scattering and the soft component, is experimentally clean and theoretically well understood. There is furthermore no QCD FSR and limited bremsstrahlung from the muons,
which are required to have $p_T > 20$ GeV/c and $|\eta| < 2.4$. The UE activity is determined from the primary charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$ and is measured as a function of the dimuon invariant mass $M_{\mu\mu}$ and transverse momentum $p_T^{\mu\mu}$. Figure 1 shows the particle density (left) and energy density (middle) at $\sqrt{s} = 7$ TeV as a function of $M_{\mu\mu}$ in the towards and transverse regions $|\Delta \phi| < 120^\circ$, with $p_T^{\mu\mu} < 5$ GeV/c. Particle density as a function of $p_T^{\mu\mu}$ in the away region (right), with $81 < M_{\mu\mu} < 101$ GeV/$c^2$.

An alternative approach to study the UE activity at central rapidity, for which no subdivision in $\varphi$ is needed, is to look at the jet $p_T$ per jet area in the $(\eta, \varphi)$ plane [2]. The median $\rho'$ of the distribution is a measure of the soft activity in each event and is robust to outliers, in particular to the leading jets. The jets are reconstructed in the region $|\eta| < 1.8$ with the $k_T$ algorithm with a radius $R = 0.6$. Figure 2 shows the mean values of the $\rho'$ distributions as function of leading jet $p_T$ at $\sqrt{s} = 900$ GeV (left) and 7 TeV (middle). The typical UE behaviour manifests itself by a steep rise at small event scale, followed by a saturation of the activity at higher leading jet $p_T$. The PYTHIA6 Z1 tune gives the best description of the data, while it is difficult for the different tunes to reproduce the UE evolution with $\sqrt{s}$. 

Figure 1: Particle density (left) and energy density (middle) as a function of $M_{\mu\mu}$ in the towards and transverse regions $|\Delta \varphi| < 120^\circ$, with $p_T^{\mu\mu} < 5$ GeV/c. Particle density as a function of $p_T^{\mu\mu}$ in the away region (right), in the range $81 < M_{\mu\mu} < 101$ GeV/$c^2$.
Figure 2: Mean values of the $\rho'$ distributions versus leading charged particle jet $p_T$ at $\sqrt{s} = 900$ GeV (left) and 7 TeV (middle). Inclusive to exclusive dijet cross sections ratio (right) as function of the rapidity separation between jets.

Figure 3: Ratio of the energy density in the hard and inclusive samples as function of leading jet $p_T$ at $\sqrt{s} = 900$ GeV (left), 2.76 TeV (middle) and 7 TeV (right).

In the forward region, the hard scattering and the UE are separated by a large pseudorapidity interval $\Delta\eta$ which makes the phase-space subdivision in $\phi$ unnecessary and offers the possibility to study the $\phi$ dependence of the UE activity. In this approach, the UE activity is measured in the range $-6.6 < \eta < -5.2$ by comparing the energy density of two classes of events [3]. Inclusive events, where the energy density is not much affected by MPI are compared to events with a hard scale, in which MPI strongly affect the energy density. The hard scale is defined by the $p_T$ of the central leading charged particle jet with $p_T > 1$ GeV/c and $|\eta| < 2$. The energy density in the hard sample is normalized to the inclusive one, making the results independent of calibration and minimizing the systematic uncertainties. Figure 3 shows the ratio of the energy density in the hard and inclusive samples as function of leading charged particle jet $p_T$ at $\sqrt{s} = 900$ GeV (left), 2.76 TeV (middle) and
7 TeV (right). At 7 TeV, the typical UE behaviour shows itself by a fast rise at low \( p_T \) followed by a plateau for \( p_T > 8 \) GeV. At 900 GeV, the energy density in the inclusive sample is bigger than the hard one and the ratio is smaller than unity. At this energy, the proton remnant fragments in the \( \eta \) range of the measurement, and the increase of the UE activity in the central region with increasing \( p_T \) depletes the energy in the hard sample. At 2.76 TeV one observes a much reduced increase of the energy ratio and the activities in both samples are close to each other. The data are well described by PYTHIA6 tunes fitted to LHC data, while the pre-LHC tune PYTHIA6 D6T predicts too much MPI.

3 Jet production at large rapidity separation

Dijet production is studied as function of the rapidity separation \( \Delta y \) between the jets[4], for jets with \( p_T > 35 \) GeV and \( |y| < 4.7 \). Two classes of events are considered: inclusive events, with at least one pair of jets, and exclusive events, with exactly one pair of jets. The ratio \( R_{incl} \) of the cross section of all pairwise combinations of jets from the inclusive sample to the exclusive dijet cross section is presented on figure 2 (right) as a function of the rapidity difference between the jets \( |\Delta y| \). This observable is expected to be sensitive to effects beyond collinear factorization, as the radiation probability increases with \( |\Delta y| \) rather than with \( p_T \). The predictions of the MC event generators PYTHIA6 and PYTHIA8 agree with the measurements, while the HERWIG++ predictions exhibit a more pronounced rise with \( |\Delta y| \). The BFKL-motivated generators CASCADE and HEJ+ARIADNE predict for these ratios a significantly stronger rise than observed.

References


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Associated production of W and Z bosons with jets from light and heavy quarks at CMS experiment

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1 Motivations

The measurement of the vector boson production in association with jets at the CMS experiment is of fundamental importance for testing the Standard Model prediction and providing better knowledge of the leading background in the related physics searches. For example the measurement of the production rate of vector boson $V$ in association with $n-$jets will shed light on the current perturbative QCD calculation: NLO predictions are available up to $n=4$ for $V=Z$ or $W$ only with a $10-30\%$ precision [1] [2]. At the same time, the measurement of the production of a Z boson in association with jets originating from b-quarks is of fundamental importance both as a benchmark channel to the production of the Higgs boson in association with b quarks, as well as a Standard Model background to Higgs and new physics searches in final states with leptons and b-jets.

2 Vector boson plus jets production rate

This measurement exploits the data sample recorded by the CMS experiment [3] during 2010, amounting to an integrated luminosity of $36 \pm 4\, \text{pb}^{-1}$. Events containing leptonic decays of $Z$ and $W$ bosons are selected according to the following categories: lepton pairs (tight and loose requirements) in the invariant mass range $60 < M_{ll} < 120\, \text{GeV}$ are classified as Z-sample. Those falling out, satisfying an additional requirement on the $M_T > 20\, \text{GeV}$, are classified as W-sample. Tracks and deposits in a jet are clustered with the PF anti-KT algorithm, required to be inside the Tracker acceptance and being well separated by electrons ($\Delta R > 0.3$). The signal yield is estimated using an extended likelihood fit to $M_{ll}$ for the Z + jets sample and to $M_T$ for the W +jets sample, as shown in Figure 1. The overall normalization of the true distribution is allowed to float within a Poissonian constraint on the number of observed events. For the Z event samples, the contamination from the
main background processes, dominated by $t\bar{t}$ and $W + \text{jets}$, is small and does not produce a peak in the invariant mass distribution: $M_H$ is fitted with two components, one for the signal and one that accounts for all background processes. For the $W$ sample, background contributions can be divided into two components, one which exhibits a peaking structure in $M_T$, dominated by $t\bar{t}$ and another which does not, dominated by QCD multi-jet events. Therefore a two-dimensional fit to the $M_T$ distribution and to the $b$-jets multiplicity in the event is performed. In order to estimate the scaling rule of the jets at the particle level, an unfolding procedure that removes the effects of imperfect jet energy resolution and reconstruction efficiency is applied. Furthermore, in order to provide model-independent estimate, the results are not corrected for the acceptance, but rather quoted within acceptance, as defined by the lepton and jet fiducial and kinematic cuts. The efficiencies for lepton reconstruction, identification, isolation and trigger are obtained from data by means of a tag-and-probe method performed on $Z/\gamma + \text{jets}$ data samples, evaluated in different jet multiplicity bins. In order to reduce the systematic uncertainties associated with the integrated luminosity measurement, the jet energy scale and the lepton reconstruction and trigger efficiencies, the yields are normalized according to the inclusive $W$ and $Z$ cross sections. The cross section ratios is also measured $\sigma(V+n-jets)/\sigma(V+(n-1)-jets)$ where $n$ stands for the inclusive number of jets in the event. An example of the results is shown in left plot of Figure 2 together with the most relevant uncertainties for each measured value. Within the uncertainties the measured ratios are found to be in agreement with MADGRAPH theoretical predictions. From the former normalization, the staircase scaling is tested as well and is found to be in reasonable agreement.
with the theoretical expectations with deviations that are within one or two standard deviations depending on the channel \[4\].

With a similar lepton selection and ad-hoc requirements on jet topology \[5\], the di-jet invariant mass has been investigated in the W+jets channel and compared to the observation from the CDF experiment \[6\], exploiting the full 2011 statistics. Using an unbinned likelihood technique to fit the background in the sidebands and a parametrized fit shape for the W+jets signal component, no enhancement has been observed in the mass region $120 < M_{jj} < 160$ GeV, as visible in Figure 2 (right).

![Figure 2](image)

**Figure 2:** Left: Ratio $\sigma(Z + n\text{-jets})/\sigma(Z)$ in the muon channel compared to expectations from MADGRAPH and PYTHIA. Right: Distribution of the invariant mass spectrum of the leading two jets after subtraction of all SM components except the electroweak diboson WW/WZ. Error bars correspond to the statistical uncertainty. The band represents the systematic uncertainty in the sum of the SM components.

### 3 Z boson production in association with b-jets

Calculations of the theoretical cross section for this process, driven by perturbative QCD, are currently derived in two schemes: fixed-flavour \[7\] and variable flavour \[8\]. The main experimental backgrounds arise from the production of Z with jets of other flavours misidentified as b jets and from $t\bar{t}$ + jets events: is therefore essential to reduce them as much as possible and finally quantify the remaining contribution in a precise and reliable way. The production of b jets in association with a Z boson has been studied in 2.1 fb$^{-1}$ of proton-proton collision data at a centre-of-mass energy of 7 TeV and recorded by the CMS detector. Jets and leptons are reconstructed...
according to standard criteria described in [9]. Opposite charges for the leptons are required when forming pairs, and the lepton invariant mass $M_{ll}$ is required to lie between 60 and 120 GeV. Separation between leptons and jets is also applied ($\Delta R > 0.5$). Jets originating from b quarks are tagged by taking advantage of the long b-hadron lifetime. The Simple Secondary Vertex (SSV) algorithm, requiring secondary vertices built from at least three tracks in order to improve the purity of the selection, is exploited. The cross section for the production of a $Z$ boson in association with at least one hadron level b jet is then extracted from the selected numbers of dilepton+b-jet events ($N_{ll+b}$), taking into account the b-jet purity $P$, the fraction fitted of $t\bar{t}$ events ($f_{t\bar{t}}$), the b-tagging efficiency $\epsilon_b$, the lepton efficiency $\epsilon_\ell$, the correction factor $C_{hadron}$ for detector and reconstruction effects, and the lepton acceptance $A_\ell$, using the following equation:

$$\sigma_{hadron}(Z + b, Z \rightarrow \ell\ell) = \frac{N_{ll+b} \times (P - f_{t\bar{t}})}{A_\ell \times C_{hadron} \times \epsilon_\ell \times \epsilon_b \times \mathcal{L}}$$

The extraction of the purity $P$ is based on a (data-driven) template fit of the mass of the secondary vertex of the leading-$p_T$ b jet, as shown in Figure 3, resulting in a fraction of $83.4 \pm 3.6\%$ ($81.5 \pm 2.9\%$) for the di-electron (di-muon) channel. The $t\bar{t}$ contribution is extracted from extrapolation of upper sideband of $M_{ll}$ under the signal region $[60-120]$ GeV, and it is found to be of the order of $18.7 \pm 2.2\%$ ($18.4 \pm 2.3\%$).
The **MADGRAPH** simulation interfaced with **PYTHIA** is used to derive the correction from the reconstructed level to the hadron level and to evaluate the other efficiencies.

The Z+b-jets cross section, for events with $Z \rightarrow \ell\ell$ where $\ell\ell = ee$ or $\mu\mu$, lepton pair invariant mass $60 < M_{\ell\ell} < 120$ GeV, and at least one b jet at the hadron level with $p_T > 25$ GeV and $|\eta| < 2.1$, with a separation between leptons and jets of $\Delta R > 0.5$, is found to be $5.84 \pm 0.08({\text{stat.}}) \pm 0.72({\text{syst.}}) ^{+0.55(\text{theory})}_{-0.72}$ pb. The shapes of the kinematic variables are found to be in fair agreement with the predictions made by the **MADGRAPH** event generator, and normalised to the integrated luminosity in data using the cross-section value which includes the NNLO corrections to the inclusive Z production. The residual discrepancy, for example noticeable in the dilepton $p_T$ spectrum of Figure 3 (right), may be a consequence of the higher order terms absent in the **MADGRAPH** tree-level simulation in the variable-flavour scheme with massless b quarks and it has been noticed also in subsequent measurements [10].

**References**


[10] [CMS Collaboration], CMS-PAS-SMP-12-003
Physics with Electroweak Gauge Bosons at LHCb

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1 Introduction

The LHCb detector is a single arm spectrometer fully instrumented in the forward pseudorapidity (η) region 2.0 < η < 5.0. It has been designed to search for new physics in the decays of B and D mesons in proton-proton collisions, but it is also well suited for studies of QCD and Electroweak physics. The pseudorapidity coverage of LHCb overlaps with the general purpose detectors (GPDs), ATLAS and CMS, in the region 2.0 < η < 2.5, but uniquely covers the region 2.5 < η < 5.0, allowing complementary studies to the GPDs. More information about the LHCb detector can be found in [1]. This contribution presents an overview of the LHCb results on electroweak boson production at √s = 7 TeV.

Measurements of electroweak boson production are an important benchmark of Standard Model processes at the LHC, and allow constraints to be placed on PDFs [2]. In these measurements, LHCb provides unique information [3]. As LHCb occupies the forward region, collisions require one parton from high Bjorken-x and one from low x. PDFs at high x are already well constrained by existing measurements. However, LHCb probes previously unexplored regions of phase space at low x and a range of Q², from measurements of W, Z and lower mass Drell Yan production. In this region, the PDF uncertainties on cross-sections are large, and LHCb plays an important role in providing new constraints. This and the kinematic region probed by LHCb are shown in Fig. 1.

2 Electroweak Boson Production at LHCb

LHCb has measured inclusive Z production in the dimuon [4], dielectron [5] and ditau [6] channels. These measurements are performed in the fiducial acceptance

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60 < M(\ell\ell) < 120 \text{ GeV}, 2.0 < \eta(\ell) < 4.5, \ p_T(\ell) > 20 \text{ GeV}. \text{ In addition, inclusive } W \to \mu\nu \text{ production has been measured} \text{ [4], in the fiducial acceptance } 2.0 < \eta(\mu) < 4.5, \ p_T(\mu) > 20 \text{ GeV}. \text{ The results in the muon channels are summarised in Fig. 2. The LHCb results are consistent with each other and with next-to-next-to-leading order (NNLO) predictions, and test the Standard Model up to an accuracy of 1.7\% (in the ratio of the } W^+ \text{ to } W^- \text{ production cross-sections). The LHCb measurement of the } W \text{ lepton charge asymmetry, shown in Fig. 3, also probes PDF predictions as this distribution is particularly sensitive to the ratio of the up quark PDF to the down quark PDF [3]. The LHCb acceptance covers an interesting region where this distribution changes sign } (W^- \text{ production becomes favoured over } W^+ \text{ production). This feature is due to the } V - A \text{ structure of the weak interaction.}

Jet production in } Z \to \mu\mu \text{ events has also been measured [7]. Jets are reconstructed using a particle flow approach, and clustered using the anti-} k_T \text{ algorithm [8] with radius parameter } R = 0.5. \text{ The jet energies are corrected back to the hadron level. Jets are required to have } 2.0 < \eta < 4.5, \ p_T > 10 \text{ GeV and to be separated from both the decay muons of the } Z \text{ in } \eta - \phi \text{ space by a distance } \Delta R > 0.4. \text{ The fraction of jet events is found to be } 0.229 \pm 0.006 \pm 0.009, \text{ where the first uncertainty is statistical, and the second is systematic. The results are compared against a NLO prediction from FEWZ [9] using MSTW08 PDFs [2], and found to be consistent.}

LHCb has also measured low mass Drell-Yan production in the } \mu\mu \text{ channel [10] in the fiducial acceptance } 2.0 < \eta(\mu) < 4.5, 5 < M(\mu\mu) < 120 \text{ GeV}, p(\mu) > 10 \text{ GeV,}
and $p_T(\mu) > 3(15)\text{ GeV}$ for $M(\mu\mu) > 5(40)\text{ GeV}$. NLO predictions agree reasonably well with the LHCb measurement.

3 Conclusions

Electroweak boson production has been studied extensively at LHCb. Measurements at LHCb are complementary to those from the GPDs. The results presented are consistent with Standard Model theory predictions, and can be used to provide new constraints on PDFs in a previously unexplored region of phase space.

References


Figure 3: The lepton charge asymmetry, \( \frac{\sigma(W^+)-\sigma(W^-)}{\sigma(W^+)+\sigma(W^-)} \) as a function of \( \eta(\mu) \) measured at LHCb (shown as bands) is consistent with NNLO predictions (points). From [4].


[5] LHCb Collaboration, R. Aaij et al., Measurement of the cross-section for \( Z^0 \rightarrow e^+e^- \) production in pp collisions at \( \sqrt{s} = 7 \text{ TeV} \), LHCb-CONF-2012-011.

[6] LHCb Collaboration, R. Aaij et al., Z cross-section measurement at \( \sqrt{s} = 7 \text{ TeV} \) using the channel \( Z \rightarrow \tau\tau \), LHCb-CONF-2011-041.

[7] LHCb Collaboration, R. Aaij et al., Measurement of jet production in \( Z^0/\gamma^* \rightarrow \mu^+\mu^- \) events at LHCb in \( \sqrt{s} = 7 \text{ TeV} \) pp collisions, LHCb-CONF-2012-016.


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W Boson Mass Measurement from CDF

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1 Introduction

The \( W \) boson mass receives self-energy corrections due to vacuum fluctuations involving virtual particles. Thus the \( W \) boson mass probes the particle spectrum in nature, including particles that have yet to be observed directly. The \( W \) boson mass can be calculated at tree level using the precise measurements of the \( Z \) boson mass, the Fermi coupling \( G_F \) and the electromagnetic coupling \( \alpha_{em} \). In order to extract information on new particles, we need to account for the radiative corrections to \( M_W \). With the discovery of a 'Higgs like' particle at the LHC [1], the measured \( M_W \) can be used as a consistency check when compared with the predicted \( W \) boson mass in the Standard Model (including radiative corrections due to the Higgs boson loop). At the Tevatron, \( W \) bosons are mainly produced by valance quark-antiquark annihilation, with initial state gluon radiation generating a typical transverse boost. The transverse momentum (\( p_T^l \)) distribution of the decay lepton has a characteristic Jacobian edge whose location is sensitive to the \( W \) boson mass. The neutrino transverse momentum (\( p_T^\nu \)) can be inferred by imposing \( p_T \) balance in the event. The transverse mass, defined as \( m_T = \sqrt{2p_T^l p_T^\nu (1 - \cos[\phi^l - \phi^\nu])} \), includes both measurable quantities in the \( W \) decay. We use the \( m_T, p_T^l \) and \( p_T^\nu \) distributions to extract \( M_W \). These distributions do not lend themselves to analytic parameterizations, which leads us to use a Monte Carlo simulation to predict their shape as a function of \( M_W \).

2 Momentum and Energy Scale Calibration

The key aspect of the measurement is the calibration of the lepton momentum, which is measured in a cylindrical drift chamber called the Central Outer Tracker (COT). The electron energy is measured using the central electromagnetic (EM) calorimeter and its angle measurement is provided by the COT trajectory. The momentum scale is set by measuring the \( J/\Psi \) and \( \Upsilon(1S) \) masses using the dimuon mass peaks. The \( J/\Psi \) sample spans a range of muon \( p_T \), which allows us to tune our ionization energy loss model such that the measured mass is independent of muon \( p_T \). We obtain
consistent calibrations from the $J/\Psi$, $\Upsilon(1S)$ mass fits shown in Fig. 1 (left). The momentum scale extracted from the $Z \to \mu\mu$ mass fit, shown in the same figure, is consistent, albeit with a larger, statistics-dominated uncertainty. Given the tracker momentum calibration, we fit the peak of the $E/p$ distribution of the signal electrons in the $W \to e\nu$ sample (Fig. 1 right) in order to calibrate the energy measurement of the electromagnetic (EM) calorimeter. The energy scale is adjusted such that the fit to the peak returns unity. The model for radiative energy loss is constrained, by comparing the number of events in the radiative tail of the $E/p$ distribution. The calorimeter energy calibration is performed in bins of electron $E_T$ to constrain the calorimeter non-linearity. The calibration yields a $Z \to ee$ mass measurement of $M_Z = 91230\pm30_{\text{stat}}$ MeV/$c^2$, in good agreement with the world average ($91187.6\pm2.1$ MeV/$c^2$ [2]); we obtain the most precise calorimeter calibration by combining the results from the $E/p$ method and the $Z \to ee$ mass measurement.

3 Hadronic Recoil Calibration

The recoil against the $W$ or $Z$ boson is computed as the vector sum of transverse energy over all calorimeter towers, where the towers associated with the leptons are explicitly removed from the calculation. The response of the calorimeter to the recoil is described by a response function which scales the true recoil magnitude to simulate the measured magnitude. The hadronic resolution receives contributions from ISR jets and the underlying event. The latter is independent of the boson $p_T$ and modeled using minimum bias data. The recoil parameterizations are tuned on the mean and $rms$ of the $p_T$-imbalance in $Z \to ll$ events as a function of boson $p_T$. 
4 Event Generation and Backgrounds

We generate $W$ and $Z$ events with resbos [3], which captures the QCD physics and models the $W$ $p_T$ spectrum. The resbos parametrization of the non-perturbative form factor is tuned on the dilepton $p_T$ distribution in the $Z$ boson sample. Photons radiated off the final-state leptons (FSR) are generated according to PHOTOS [4] and checked with HORACE [5]. We use the CTEQ6.6 [6] set of parton distribution functions (PDFs) at NLO and evaluate their uncertainties on the $W$ boson mass and verify that the MSTW2008 [7] PDFs give consistent results.

Backgrounds passing the event selection have different kinematic distributions from the $W$ signal and are included in the template fit according to their normalizations.

5 Results and Conclusions

The fits to the three kinematic distributions $m_T$, $p_T^l$ and $p_T^{\nu}$ in the electron and muon channels give the $W$ boson mass results shown in Table 1. The transverse mass distribution for the $W \rightarrow \mu \nu$ channel is shown in Fig. 2 (left). We combine the six $W$ boson mass fits including all correlations to obtain $M_W=80387\pm12\text{ (stat)}\pm15\text{ (syst)}$ MeV/c$^2$. The uncertainties for the combined result on $M_W$ are summarized in Table 2. With a total uncertainty of 19 MeV/c$^2$, this measurement is the most precise measurement to date. The new world average becomes $M_W=80385\pm15$ MeV/c$^2$ [8], which is in good agreement with the Standard Model prediction of $M_W=80359\pm11$ MeV/c$^2$ [9]. This is illustrated in Fig. 2 (right), which shows the $\Delta \chi^2$ vs $M_W$ from the Standard Model fit as the blue (grey) band, including (excluding) the 'Higgs like' discovery at the LHC [1] at a mass near $\sim126$ GeV/c$^2$. The world average measured $M_W$ is represented by the red point. The updated world average $W$ boson mass impacts the global precision electroweak fits for the Higgs boson mass $M_H=94^{+29}_{-22}$ GeV/c$^2$ [2] which is also in good agreement with the discovery at the LHC [1]. Sensitivity to beyond the Standard Model physics contributions to $M_W$ requires an improved direct

<table>
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<th>Distribution</th>
<th>Fitted $M_W$ [e-channel] (MeV/c$^2$)</th>
<th>Fitted $M_W$ [$\mu$-channel] (MeV/c$^2$)</th>
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<tr>
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<tr>
<td>$p_T^{\nu}$</td>
<td>80431$\pm25_{\text{stat}}\pm22_{\text{syst}}$</td>
<td>80406$\pm22_{\text{stat}}\pm20_{\text{syst}}$</td>
</tr>
</tbody>
</table>

Table 1: Fit results from the distributions used to extract $M_W$ with uncertainties.
Figure 2: Left: Transverse mass fit in the muon decay channel. Right: $\Delta\chi^2$ vs $M_W$ from the Standard Model fit is shown in the blue band [9], the world average measured $M_W$ is represented by the red point.

Table 2: Uncertainties for the combined result on $M_W$.

<table>
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<th>Source</th>
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<td>$p_T(W)$ Model</td>
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<tr>
<td>Total Uncertainty</td>
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</table>

measurement of $M_W$, as well as improvements in the theoretical prediction of the $W$ boson mass. An improved $W$ boson mass measurement can be achieved by using the full Tevatron datasets and on the longer term, making precise measurements using LHC data. The theoretical predictions are currently limited by uncertainties on $\alpha_{em}$, the top quark mass and higher order calculations.

I would like to thank my colleagues from the CDF collaboration in particular the $W$ boson mass group for their hard work on this important analysis.
References


W and Z properties and cross sections measured with ATLAS

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1 Introduction

Precise measurements of W and Z production have been performed using the ATLAS detector [1] at LHC with data at a centre of mass energy $\sqrt{s} = 7$ TeV where large production rates of W and Z bosons are observed. The studies of the production of W and Z bosons provide the understanding of electroweak processes and stringent tests of QCD. The studies in this report used data with approximately 36pb$^{-1}$ of integrated luminosity collected in 2010. The ATLAS detector consists of a tracking system inside a 2T solenoid magnet, calorimeters and muon spectrometers using approximately 3.9Tm toroidal magnets. The samples are collected by using unique signatures of Drell-Yan processes: $W^\pm \rightarrow l^\pm \nu$ and $Z \rightarrow l^+l^-$, where $l$ stands for $e$, $\mu$ and $\tau$. The lepton identifications (ID) have a very important role in the selection. Restrictions on reconstructed mass are applied to obtain pure samples. Samples of signals and backgrounds are simulated with several Monte Carlo generators and parton density functions (PDF). The details are described in the references.

2 Measurements

The inclusive cross sections of $W^\pm \rightarrow l^\pm \nu$ and $Z \rightarrow l^+l^-$ provide important testing ground of QCD, especially for the parameterisations of PDFs of the proton. The differential cross section for $e$ and $\mu$ decay channels has been measured as a function of rapidity $y$ or pseudo rapidity $\eta$ [2]. Combined results of muon and electron channels for each process are shown in Figure 1. The data provide some PDF discrimination. The integrated cross sections are calculated for each channel in common fiducial phase space and extrapolated to the full phase space. Results are combined for each lepton flavour and for of $W^+$ and $W^-$ processes. The comparison of total cross sections $\sigma_{W^+}^{fid} \cdot BR(W^+ \rightarrow l^+\nu)$ to $\sigma_{W^-}^{fid} \cdot BR(W^- \rightarrow l^-\Bar{\nu})$ and combined W processes $\sigma_{W^\pm}^{fid} \cdot BR(W^\pm \rightarrow l\nu)$ to $\sigma_{Z}^{fid} \cdot BR(Z \rightarrow l^+l^-)$ are shown in Figure 2. The data are
Figure 1: Differential cross sections for $Z \rightarrow l^+l^-$ process as a function of $|y_z|$ at left, and $W^+ \rightarrow l^+\nu$ and $W^- \rightarrow l^-\bar{\nu}$ as a function of $|\eta|$ at middle and right, respectively, where results from muon and electron processes are combined [2].

The cross section measurements of lepton channels are completed by the cross section of $\tau$ decay channel [5, 6]. This is shown in Figure 4 together with $e$ and $\mu$

compared with several theoretical expectations. The ratios of total cross sections of the $e$ and $\mu$ decay channels of $W$ and $Z$ are $R_W = Br(W \rightarrow e\nu)/Br(W \rightarrow \mu\nu) = 1.006 \pm 0.024(1.017 \pm 0.019)$ and $R_Z = Br(Z \rightarrow ee)/Br(Z \rightarrow \mu\mu) = 1.018 \pm 0.031(0.9991 \pm 0.0024)$, respectively, where the error is the total uncertainty and the world averages from PDG [3] are shown in the parentheses. As show in Figure 2, both results show a good agreement with the world average.

The polarisation of $W^+ \rightarrow l^+\nu$ and $W^- \rightarrow l^-\bar{\nu}$ was obtained by using the $W$ decay angular distributions projected onto the transverse plane [4]. The angular distribution was analysed in terms of helicity fractions $f_0$, $f_L$, and $f_R$ in two ranges of $W$ transverse momentum ($p_T^W$). Figure 3 shows the correlation between $f_0$ and $f_L - f_R$ in two $p_T^W$ ranges. The results are in good agreement with theoretical predictions.
predictions. Using the selected decay channels. Although the results have slightly larger systematic errors than for $e$ and $\mu$, due to energy scales and lepton ID efficiencies, they agree well with theoretical predictions. Using the selected $\tau$ samples, the $\tau$ polarisation $P_\tau = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$ has been measured using one prong hadronic decays of $\tau$ leptons from $W \rightarrow \tau\nu$ [7]. The measurement is carried out by observing the charge asymmetry of $\tau$ lepton decaying to $\rho\nu$, $\mathcal{Y} = (E_T^\tau - E_T^\rho)/|E_T^\tau + E_T^\rho|$, since it is correlated with the $\tau$ polarisation. The $\mathcal{Y}$ distribution is fitted by using two templates which are produced for left-handed $\tau$ and for right-handed $\tau$ separately. The results are shown in Figure 4 and are in good agreement with the Standard Model prediction.

The strange quark density of the proton is studied within a QCD framework jointly with inclusive deep inelastic scattering data from HERA [8]. The ATLAS data show sensitivity to the light quark sea composition at Bjorken $x \sim 0.01$. The results of the fit show that the strange quark density with respect to the down sea quark density $r_s = 0.5(s(x) + \bar{s}(x))/d(x)$ is not suppressed. The result is compared with four theoretical expectations in Figure 5.
Figure 5: The ratio of the strange quark density to the down sea quark density in the proton at $Q^2 = 1.9 GeV^2$, $x = 0.023$ and comparison with different PDF [8].

3 Summary

The studies of the production of W and Z bosons are carried out using data collected by the ATLAS detector mainly in 2010. The comparisons of the results with several theoretical expectations provide stringent tests of QCD and some contribution to improve the theoretical expectations. The analysis using data collected in 2011 and 2012 will provide more accurate results in near future.

References

Particle Production and Diffraction in ATLAS

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On behalf of the ATLAS Collaboration

1 Introduction

The study of soft QCD provides insight into the physics of hadronic cross-sections and hadron formation, while also enabling the validation and tuning of models of particle production and helping to describe and correct for pile-up or soft backgrounds to other processes. Soft QCD measurements in ATLAS [1] at the LHC mainly use the inner tracking detectors, sensitive to charged particles with $p_T > 100$ MeV and $|\eta| < 2.5$, and the electromagnetic and hadronic calorimeters, sensitive to electrons, photons and hadrons that have $E_T$ greater than a few hundred MeV and $|\eta| < 4.9$. Most such measurements utilise Minimum Bias events: inclusive collisions which have been triggered by scintillators located in the region $2.1 < |\eta| < 3.8$.

2 Inclusive Two Particle Angular Correlations

Correlations in $\Delta \eta$ and $\Delta \phi$ were examined through a variable which takes into account both inter-event and intra-event correlations. Results, corrected using the HBOM unfolding technique [2] (repeatedly applying detector folding $n$ times and extrapolating to the hypothetical $n = -1$ case), were compared to several PYTHIA 6 tunes [3], PYTHIA 8 and HERWIG++ [4], with the data not satisfactorily described by any of these. A large difference between PYTHIA and HERWIG++ is visible, reflecting the string/cluster hadronisation modelling difference [5].

3 Forward-backward Correlations

Correlations between the forward and backward regions were measured as a function of the multiplicity and $\sum p_T$ of charged particles in bins of $|\eta|$. The data were corrected for detector effects using multiple regression. This was the first measurement of $\sum p_T$ correlations, with the latest Monte Carlo tunes accurately reproducing the data [6].
4 Azimuthal ordering of charged hadrons

A spectral analysis of correlations between angular, energy and $p_T$ orderings was performed. After correcting for detector effects, the comparison with Monte Carlo simulation showed too much correlation for high-$p_T$ charged particles, but too little correlation at low-$p_T$ (see Figure 1).

Increasing the level of underlying event in the Monte Carlo could improve the agreement at high $p_T$, while increasing the levels of initial state radiation could improve the agreement at low $p_T$. The net result is a problem for Monte Carlo tuning - simply changing the typical settings will not find a tune that can fit all of the data.

![Figure 1: Angular/energy correlations at high $p_T$ (left) and low $p_T$ (right) [7].](image)

The measured spectra show features consistent with helix-ordered gluon chain models [8], which impose correlations between angular and $p_T$ orderings; including such effects could improve soft particle production and hadronisation models [7].

5 Inelastic cross-section as a function of forward rapidity gap size

Cross-sections, corrected to the hadron-level, were measured as a function of $\Delta \eta_F$, the largest $\eta$-region containing no particles with $p_T$ above $p_T^{cut}$, counting inwards from the edge of the detector acceptance, at $|\eta| = 4.9$.

At low values of $\Delta \eta_F$, this measurement tests the reliability of hadronisation models in describing rapidity fluctuations in final-state particle production; at higher values it probes the diffractive cross-section. Figure 2 shows that the rise of the cross-section at the largest $\Delta \eta_F$ values is not reproduced in Monte Carlo (left) and also indicates that the data contain a higher proportion of low mass single-diffractive events than any of the theoretical models (right): this is shown by the steepness of the transition between ATLAS and TOTEM data [9].
Figure 2: Rapidity gap cross sections in Pythia 6, Pythia 8, Phojet and data, with $p_T^{cut} = 200$ MeV (left). The total cross-section as a function of $\xi_X = M_X^2/s$, where $\xi_{cut}$ is a minimum (right), comparing data against various theoretical predictions [9].

6 $K^0_S$ and $\Lambda$ production

$K^0_S$ and $\Lambda$ candidates were identified by fitting pairs of opposite-sign tracks to a common vertex and cutting on the transverse flight distance between primary and secondary vertices and on the angle between this vector and the particle momentum.

The observed distributions of $p_T$, $y$ and multiplicity for $K^0_S$ and $\Lambda$ hadrons were corrected to the hadron level and compared to Monte Carlo simulations. While the $K^0_S$ distributions agreed to within 15%, the $\Lambda$ $p_T$ distribution showed substantial discrepancies visible in both the Herwig and Pythia predictions and across multiple generator tunes [10].

7 Underlying event in charged-particle jet events

Underlying event (UE) is used to describe any hadronic activity not associated with the hard scattering process. In typical measurements, the highest $p_T$ jet in the event used to define a “transverse region”, the area satisfying $\pi/3 < |\phi_{\text{particle}} - \phi_{\text{jet}}| \leq 2\pi/3$, where $\phi$ is the azimuthal angle. The multiplicity and $\sum p_T$ of charged particles are used to characterise the UE.

Several Monte Carlo simulations are compared to the unfolded data, with Pythia 6 (AUET2B tune) showing the best agreement. The analysis is performed using a range of different anti-$k_t$ $R$-parameters to identify the jets [11]. Figure 3 shows the ratio at different $R$-parameters of number of charged tracks identified in the transverse region as a function of the $p_T$ of the jet. The number of tracks identified has a strong dependence on the $R$-parameter, both in data and Monte Carlo, indicating that the choice of hard scatter has a crucial effect on UE distributions [12].
Figure 3: Ratio of number of charged tracks for different anti-$k_t$ $R$-parameters [12].

References


Quarkonium Production at LHCb

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1 Introduction

The LHCb detector [1] is a single-arm forward spectrometer covering the pseudorapidity range \( 2 < \eta < 5 \), designed for the study of particles containing \( b \) or \( c \) quarks. Its excellent performance in reconstructing decays of heavy hadrons allows to study the production of quarkonia states both in a unique rapidity range and at the new energy frontier brought by the LHC. As an example, the combined performance of the vertexing, tracking and muon identification detectors allow to reconstruct \( J/\psi \rightarrow \mu^+\mu^- \) decays with a mass resolution of about 15 MeV/c\(^2\) and a background contamination at the per cent level. Moreover, the trigger of the experiment is able to effectively select high–mass dimuons and single muons with relatively low (∼ 1.5 GeV/c) transverse momentum threshold, and about one half of the trigger bandwidth, reaching 5 kHz in 2012, is devoted to muon and dimuon lines.

The first data sample collected during the 2010 run, corresponding to a 37 pb\(^{-1}\) integrated luminosity of \( pp \) collisions at \( \sqrt{s} = 7 \text{ TeV} \), allowed for the first production studies. Processes more statistically limited are studied using the 2011 data sample, corresponding to 1.1 fb\(^{-1}\). The experiment is actually running at \( \sqrt{s} = 8 \text{ TeV} \), aiming at collecting 1.5 fb\(^{-1}\) by the end of 2012.

2 Production of charmonium and bottomonium

The production cross-sections for \( J/\psi \), \( \psi(2S) \) and \( \Upsilon(nS) \) (\( n=1,2,3 \)) are studied using the dimuon decay mode. Such measurements provide a testbench for QCD production models, notably to probe for possible color octet (CO) contributions beside the predictions obtained in the framework of the the color singlet exchange model (CSM). For the charmonium states, the prompt component is cleanly separated from the delayed component due to \( b \) decays using the excellent proper time resolution of the detector. Already with the 2010 data sample, the systematic error, notably from the unknown state polarization, dominates the total uncertainty.

The measured cross-sections as a function of the transverse momentum \( p_T \) are compared to theoretical predictions, bearing in mind that most calculations only predict the direct component (excluding feed–down from higher states) and often do not
cover the lowest $p_T$ region. A few of these comparisons [2, 3, 4] are shown in Fig. 1. An excess by two order of magnitudes of the observed charmonium production with respect to leading order CSM predictions at high $p_T$ is observed, confirming the Tevatron findings. Recently available NLO and NNLO calculations based on CSM seem to explain the gap, yet with large uncertainty. When available, non–perturbative calculations including CO contributions seem to reproduce the experimental observations more accurately. The production of $J/\psi$ and $\psi(2S)$ from $b$ decays agree remarkably well with the prediction in the FONLL approach [5].

![Figure 1: The upper plots show the $p_T$ dependence of the $J/\psi$ production cross section for the prompt (left) and delayed (right) components. The lower plots show the results for two of the bottomonium states. The results for $\Upsilon(3S)$, free from feed–down due to higher states, and for prompt $J/\psi$ are compared with NLO and NNLO predictions based on CSM perturbative calculations [6]. The result for $\Upsilon(1S)$ is compared with effective models including CO contributions: NRQCD [8] and CEM [7].](image)

The production of $\chi_c$ mesons has been studied using the radiative decay to $J/\psi$ [9]. Despite the low photon energy and the harsh hadronic environment, a clean sample of $\chi_c$ was obtained using converted and unconverted photons. The LO CSM
calculations are unable to reproduce the $p_T$ spectrum shape, as opposite to the NLO NRQCD predictions. The ratio of $\chi_{c2}$ to $\chi_{c1}$ production cross-sections seems larger than any prediction [10, 11].

All results assume unpolarized quarkonia states. The polarization can be measured via an angular analysis in order to reduce the main uncertainty on cross sections, but also to provide a crucial test of production models. Acceptance effects strongly affect the angular distributions, introducing potentially severe systematic effects. Results for the $J/\psi$ polarization are expected in the near future.

3 The $B_c^+$ meson

As the only meson consisting of two heavy quarks with different flavour, the $B_c^+$ provides another important testbench for hadronic models and has a rich spectroscopy to be explored. Only the ground state was observed so far at the Tevatron [12]. Using 2010 data, LHCb provided an accurate mass measurement using the $J/\psi \pi^+$ decay mode. A preliminary result was also obtained[13] for the $B_c^+$ production, normalized to the $B^+$, for $p_T > 4$ GeV/c, $2.5 < \eta < 4.5$:

$$\frac{\sigma(B_c^+) \times B(B_c^+ \rightarrow J/\psi \pi^+)}{\sigma(B^+) \times B(B^+ \rightarrow J/\psi K^+)} = (2.2 \pm 0.8_{\text{stat}} \pm 0.2_{\text{syst}})\%.$$ 

Using the 2011 data sample, both the statistical and systematic uncertainties, the latter being dominated by the uncertainty on the $B_c^+$ lifetime, will be improved. Other $B_c^+$ decay modes are expected to be discovered, the first of which being $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$, for which LHCb measures[14]

$$\frac{B(B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+)}{B(B_c^+ \rightarrow J/\psi \pi^+)} = 2.41 \pm 0.30_{\text{stat}} \pm 0.33_{\text{syst}},$$

in good agreement with the theoretical predictions, ranging from 1.5 to 2.3.

4 Double $c\bar{c}$ production

The energy and luminosity of the LHC also provides the possibility to study the production of multiple pairs of heavy quarks. Double $c\bar{c}$ production can be expected in single parton collisions via high order gluon-gluon diagrams, with strong sensitivity to possible CO contributions, but could also be enhanced by double parton scattering (DPS) and by the charm content of the proton. A simple, maybe naive, model for DPS consists in assuming the two simultaneous parton collisions (labeled 1 and 2) to occur independently:

$$\frac{\sigma_{C_1 \sigma_{C_2}}}{\sigma_{C_1C_2}} = \sigma_{eff}^{DPS} \quad (1)$$
where the constant $\sigma_{_{\text{DPS}}}^{\text{eff}}$ was determined, in this hypothesis, to be about 15 mb according to studies on multi-jet events performed at the Tevatron[17].

Double $J/\psi$ production is observed already from the 2010 sample, from which $116 \pm 16$ events are selected, corresponding to a production cross section[15] $\sigma(J/\psi J/\psi) = 5.1 \pm 1.0_{\text{stat}} \pm 1.1_{\text{syst}}$ nb. The result agrees with the LO CSM prediction, while the predicted 50% enhancement from DPS can not be excluded within the experimental and theoretical uncertainties.

The simultaneous production of a $J/\psi$ meson and an open charm state $C$ was also studied, with $C = D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^+_s \rightarrow \phi \pi^+$ or $\Lambda_c^+ \rightarrow pK^- \pi^+$, using 355 pb$^{-1}$.

Due to the highest production cross section of open charm modes [16], these modes are much more sensitive to DPS, whose contribution, according to eq. 1, exceeds by one order of magnitude the available LO CSM predictions for single collisions. The production of these four modes, together with six of the CC modes, was established with a significance of more than 3$\sigma$ [18]. As shown in Fig. 2, the results for the $J/\psi \ C$ modes agree nicely with the naive DPS prediction, though this is not the case for the CC modes, whose observed yields are lower by a factor 2 to 3 with respect to the same model.

![Figure 2: Results for double charm production involving open charm. The ratio of equation 1 is compared with the value $\sigma_{_{\text{DPS}}}^{\text{eff}}$ predicted by the simple DPS interpretation (shaded line) for the different observed modes.](image)

5 Conclusions and outlook

Unique measurements of the production of quarkonia and quarkonia–like states have been obtained with the LHCb experiment. These studies provide valuable input to improve the accuracy of theoretical models. These studies are being repeated for the higher energy of the 2012 run, and extended to other states as the $\chi_{b}$. New decay modes for the relatively unexplored $B_c^+$ are also expected to be observed, and the uncertainty on its lifetime will be reduced using the 2011 data. More exotic states as the recently reported X, Y, Z states, as well as tetra and pentaquark states, are also being actively searched for [19, 20].
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Onia production at ATLAS

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1 Introduction

The ATLAS detector [1] is a multipurpose particle physics apparatus built at the Large Hadron Collider (LHC). In addition to a wide range of measurements of high mass particles produced at high transverse momenta ($p_T$), both within or beyond the Standard Model, ATLAS has a rich quarkonium physics programme concentrating on low-$p_T$ di-muon final states. Quarkonia are formed from a quark-antiquark pair of the same flavour. Despite being among the most studied of the bound-quark systems, there is still no clear understanding of the production mechanisms that can consistently explain both the cross-section and spin-alignment measurements [2]. The LHC provides the opportunity to test existing models at a higher energy regime, a higher $p_T$ and a wider rapidity ranges than previously.

2 Quarkonia production and observation of $\chi_b(3P)$

In order to allow efficient collection of low-$p_T$ di-muon samples, dedicated $b$-physics triggers had been developed. Two low-$p_T$ muons identified by hardware-based first level trigger are subsequently analysed by higher level software trigger algorithms. Once the muons are confirmed, a fit is performed to the combined vertex and mass constraints are applied. Figure 1 shows the di-muon mass spectrum for events recorded in the first half of 2011 data taking period. The coloured histograms show the significant data samples collected by the dedicated $b$-physics triggers. In 2010 and 2011, ATLAS has recorded 48 pb$^{-1}$ and 5.6 fb$^{-1}$ of data, respectively, from $pp$ collisions at a centre of mass energy of 7 TeV.

ATLAS has measured the differential cross-sections of inclusive, prompt and non-prompt $J/\psi$ production using 2.2 pb$^{-1}$ of 2010 data [4]. Trigger and reconstruction efficiencies were measured in data and validated with Monte Carlo simulations. Weights incorporating acceptance and efficiency corrections were applied to quarkonia candidates on an event-by-event basis before fits were used to extract cross-section. $J/\psi$ can be produced either promptly from the hard interaction or non-promptly via decay of a $b$-hadron. $J/\psi$ from $B$-decays have positive displaced di-muon vertices and can be distinguished from the prompt production via the pseudo-proper time discriminant,
Figure 1: Invariant mass of oppositely charged muon candidate pairs selected by a variety of ATLAS triggers. The coloured histograms show events selected by the dedicated $b$-physics triggers compared to those triggered by the single muon trigger (grey). The different colours correspond to triggers with different mass ranges [3].

$$\tau = L_{xy} \cdot m_{J/\psi}^{J/\psi}/p_{T}^{J/\psi},$$

where $L_{xy}$ is the transverse decay length of the $J/\psi$ vertex. Figure 2 shows the inclusive $J/\psi$ cross-section as a function of the $p_{T}^{J/\psi}$ for one rapidity bin (left) and the $\tau$ distribution (right). By combining these two measurements, the prompt and non-prompt $J/\psi$ cross-sections were derived. The largest source of systematic uncertainty of the cross-section measurement is due to the unknown spin alignment of the $J/\psi$. Five spin alignment scenarios were identified that induce the largest envelope of variation on visible cross-sections. Figure 3 shows the non-prompt (left) and prompt (right) $J/\psi$ production cross-sections as a function of $p_{T}^{J/\psi}$ compared to theoretical predictions. The measured non-prompt cross-section is in good agreement with Fixed-Order Next-to-Leading-Log theoretical predictions. The prompt cross-section is compared to colour-singlet model (CSM) NLO and NNLO* pQCD predictions and to the phenomenological Colour Evaporation Model (CEM). The CEM predictions describe the shape better and the NNLO* prediction shows a significant improvement in the normalisation over the NLO prediction.

Production cross-sections of $\Upsilon(1S)$ have been derived in bins of rapidity and $p_{T}^{\Upsilon(1S)}$ with 1.1 pb$^{-1}$ of 2010 data [5]. The measurement was restricted to the fiducial region, $p_{T}^{\Upsilon} > 4$ GeV and $|y| < 2.5$, to remove the uncertainty due to the spin alignment. Unfolded differential cross-sections are compared to CSM NLO prediction in figure 4 left and significant disagreement is observed. However, the prediction does not include feed-down from higher mass states estimated to contribute a factor of two at the Tevatron [6].

ATLAS observed a new $\chi_b(3P)$ state through its radiative decays to $\Upsilon(1S)$ and $\Upsilon(2S)$ with 4.4 fb$^{-1}$ of data collected in 2011 [7]. Radiative decays of $\chi_b(3P)$ have been reconstructed from the photon emitted during the transition, and the subsequent decay of the $\Upsilon$ into two muons. Figure 4 right shows the mass distribution...
3 Summary

The ATLAS quarkonia programme has produced many important measurements of production cross-sections which are already providing valuable input for theoretical models. A new bottomonium state, $\chi_b(3P)$, has been observed for the first time.

References

Figure 3: Non-prompt (left) and prompt (right) $J/\psi$ production cross-sections as a function of $p_T^{J/\psi}$. The non-prompt (prompt) cross-section is compared to predictions from FONLL (NLO, NNLO* and the CEM). Coloured bands show the changes of the results under spin-alignment scenarios representing a theoretical uncertainty [4].

Figure 4: Left figure shows $\Upsilon(1S)$ cross-section for $|y^{\Upsilon(1S)}| < 1.2$ as a function of $p_T^{\Upsilon(1S)}$. Also shown is the CSM and the NRQCD predictions. Right figure shows the mass distribution of $\chi_b \rightarrow \Upsilon(kS)\gamma$ ($k = 1, 2$) candidates for converted photons. $\chi_b \rightarrow \Upsilon(1S)\gamma$ and $\chi_b \rightarrow \Upsilon(2S)\gamma$ decays are plotted using circles and triangles, respectively. Solid (dashed) lines show the total (background) fit result for each mass window [5, 7].
J/$\psi$ production in $pp$ collisions with the ALICE experiment

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1 Introduction

After almost forty years from its discovery, the theoretical description of J/$\psi$ hadroproduction is still an open topic. Given the high mass of the $c$ quark, charmonia production involves different energy scales: the formation of the quark-antiquark pair is a hard process and can be reliably described through perturbative QCD calculations, but the dynamics of the bound state formation and evolution are intrinsically non-relativistic and they involve soft energy scales.

For this reason, no full-QCD description of quarkonium production can be carried out and many theoretical models have been developed. Among them, the effective field theory NonRelativistic QCD (NRQCD) at LO was found to reproduce the cross-sections measured at the Tevatron [1], which were significantly underestimated by Color Singlet Model (CSM) calculations at LO. Nevertheless, the prediction on the J/$\psi$ degree of polarization was contradicted by the measurement of CDF [2], hence opening an issue which still remains and on which the Large Hadron Collider (LHC) is expected to provide a crucial contribution.

ALICE (A Large Ion Collider Experiment) [3] is the experiment at the LHC dedicated to the study of heavy ion collisions. Nevertheless, the study of $pp$ collisions allows to obtain reference data for heavy-ion physics and to investigate open issues in elementary particle physics.

ALICE is able to detect heavy quarkonia through their leptonic decay: in the central rapidity region ($|y| < 0.9$) this measurement is performed through the detection of $e^+e^-$ pairs in the Inner Tracking System (ITS) and in the Time Projection Chamber (TPC), while at forward rapidity ($2.5 < y < 4$) the $\mu^+\mu^-$ channel is analyzed by means of the Muon Spectrometer.

In this work, ALICE’s results on J/$\psi$ production in $pp$ collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 2.76$ TeV are presented, discussed and compared to theory.

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2 Results

The integrated and differential cross sections for inclusive $J/\psi$ production were measured at forward and central rapidity at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 2.76$ TeV [4]. Both measurements extend down to zero $p_T$ and, when comparing the 7 TeV result with those obtained by the other LHC experiments, a fair agreement is found. In Figure 1(a) the double differential cross section ($d^2\sigma/dydp_T$) for inclusive $J/\psi$ production at forward rapidity ($2.5 < y < 4.$) and at the two center of mass energies is shown. The comparison with NLO NRQCD calculations [5] performed in the region $p_T > 3$ GeV/c shows a good agreement inside the theoretical uncertainty coming from the variation of the factorization, renormalization and NRQCD scales.

Figure 1: (a) $d^2\sigma/dydp_T$ for inclusive $J/\psi$ production at forward rapidity at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 2.76$ TeV. (b) Polarization parameters $\lambda_\theta$ and $\lambda_\phi$ in the helicity and Collins-Soper frames for inclusively produced $J/\psi$ as a function of $p_T$.

$J/\psi$ polarization was studied, at forward rapidity, through the analysis of the angular distribution of the decay products [6], which follows the general formula:

$$W(\cos \theta, \phi) \propto \frac{1}{3 + \lambda_\theta} \cdot \left(1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi \right), \quad (1)$$

where $\theta$ and $\phi$ are the polar and azimuthal angles of one of the two muons with respect to a given reference frame [7] (helicity and Collins-Soper were considered for this analysis) and $\lambda_\theta$, $\lambda_\phi$ and $\lambda_{\theta\phi}$ are the polarization parameters. Due to statistics restrictions and acceptance issues, the analysis was limited to the first two parameters,
assuming the third one to be zero (an a-posteriori check confirmed this assumption). Moreover, an integration of the two-dimensional Eq.1 over $\phi$ and $\cos \theta$ was performed in order to extract the $\lambda_\theta$ and $\lambda_\phi$ respectively in a one-dimensional approach. Possible biases in the acceptance correction were avoided by means of an iterative procedure. The result, shown in Figure 1(b), is that no significant polarization is observed in both the considered frames; in the helicity frame a $1.6\sigma$ hint for a negative $\lambda_\theta$ value can be found at low $p_T$. The comparison with NLO calculations of CSM and NRQCD, reported in [8], shows a better qualitative agreement with the second one, but a firm conclusion will be possible when higher $p_T$ will be reached by the experiments.

Figure 2: (a) Relative $J/\psi$ yield as a function of the relative charged particle multiplicity density at mid-rapidity. (b) $d^2\sigma/dp_Tdy$ for prompt $J/\psi$ production at mid-rapidity as a function of $p_T$.

The measurement of the $J/\psi$ production yield as a function of the charged particle multiplicity [9] was carried out by ALICE both at forward and mid-rapidity. The results (see Figure 2(a)) show a linear increase of the $J/\psi$ yield with the multiplicity in both the rapidity ranges. For a complete understanding of this result, in clear disagreement with the decreasing trend expected from MC simulations (PYTHIA 6.4 Perugia-0 tuning), more experimental and theoretical work are needed.

ALICE has also been able to study prompt $J/\psi$ production for $|y| < 0.9$ and down to $p_T = 1.3$ GeV/c [10], thus complementing the higher-$p_T$ measurements of ATLAS and CMS [11]. The subtraction of the non-prompt component was carried out
by means of an unbinned 2-dimensional likelihood fit to the invariant mass and the pseudo-proper decay length distributions. The result, shown in Figure 2(b), significantly extends the $p_T$ range reached by the other LHC experiments and the agreement with NLO NRQCD calculations [5], already found in the inclusive case at forward rapidity, is again verified.

3 Conclusions

ALICE has been studying $J/\psi$ hadroproduction in the two rapidity regions $2.5 < y < 4$ and $|y| < 0.9$, down to $p_T = 0$. The inclusive production cross-sections at 7 TeV and at 2.76 TeV are in fair agreement with NRQCD calculations at NLO. The produced $J/\psi$ are basically unpolarized at forward rapidity in the region $2 < p_T < 8$ GeV/c in both the helicity and Collins-Soper frames and the inclusive $J/\psi$ yield, at both mid and forward rapidities, shows a linear increase as a function of the charged particle multiplicity. The prompt $J/\psi$ cross section was measured for $|y| < 0.9$ and down to $p_T = 1.3$ GeV/c, finding good agreement with NLO NRQCD calculations.

References

QCD and Heavy Quark Physics at the Tevatron

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1 Introduction

Recent results from the Tevatron experiments CDF and D0 in QCD and heavy quark measurements are summarized. These results include updates to earlier measurements. In many cases the analysis is based on the full Run 2 data set of approximately 10 fb⁻¹. QCD and heavy quark measurements in areas such as inclusive jet production, photon+heavy quark production, CP asymmetries, fragmentation studies, rare decays, and lifetimes are covered.

The Tevatron collider at Fermilab has been used to study proton-antiproton collisions at high energy from 1985 through September 30, 2011. This article discusses results from Run 2 of the collider, which ran from 2001 through 2011. The accelerator delivered about 12 fb⁻¹ of luminosity to each experiment at a center of mass energy of 1.96 TeV.

2 QCD Physics

QCD analyses are used to study strong interactions in p¯p collisions. Some of the specific areas addressed are calculations of interaction probabilities at different orders of αs, measurements of and comparisons to different parameterizations of parton distribution functions (pdf’s), measurements at higher precision and in new kinematic regimes, processes now accessible because of increased statistics, and processes where the initial p¯p state allows for unique measurements.

D0 has measured inclusive jet cross sections in the kinematic range $-2.4 < \eta < 2.4$ and $50 < p_T < 600$ GeV/c [1]. The measurement provides information that can probe the quark and gluon structure of the proton. The differential cross section of inclusive jets is compared to theoretical predictions using a large variety of pdf’s and good agreement is found in most cases. Figure 1(left) shows the cross sections for jets measured in bins of $\eta$.

CDF and D0 have measured the production of $\gamma + b$ jets and $\gamma + c$ jets at the Tevatron. The contributions to the production of $\gamma + b$ jets and $\gamma + c$ jets are $Q$+gluon ($Q = b, c$) and $q\bar{q}$ annihilation. The D0 measurement selects central ($|y| < 1$) or forward ($1.5 < |y| < 2.5$) photons with $30 < p_T < 300$ GeV and jets with $|y| < 1.5$ and uses 8.7 fb⁻¹. The $b$-jet fraction is determined by fitting the data

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Figure 1: (left) Inclusive jet differential cross section; (right) $\gamma + b$ jets inclusive cross section.

to templates of secondary vertex mass distribution shapes derived from simulation. The differential cross section as a function of $p_T$ of the photon is compared to NLO calculations and is shown in figure 1(right). The calculations agree with data at $p_T < 70$ GeV but higher order QCD corrections are required to match the data at higher $p_T$ where a contribution from $q\bar{q} \rightarrow \gamma + g (g \rightarrow Q\bar{Q})$ is dominating [2].

In the CDF measurements $\gamma + b$ jets and $\gamma + c$ jets are measured in the kinematic range $30 < E_T^\gamma < 300$ GeV, $|y^\gamma| < 1.0$ and $E_T^{jet} > 20$ GeV with $|y^{jet}| < 1.5$ using 9.1 fb$^{-1}$ of integrated luminosity. The contributions from $b$, $c$ and light quark jets are fit using templates from simulated events. Cross sections are calculated and compared to NLO predictions. As in the D0 analysis the calculations agree with data at low $E_T$ and do not match at large $E_T$.

3 Heavy Quark Physics

The study of heavy quark production and decay in hadron colliders is an excellent technique for better understanding of the fundamental nature of matter and forces in particle physics. It provides an ideal laboratory for the study of beyond-standard-model physics at higher energy scales. Recent results in fragmentation, CP asymmetries, rare branching ratios, and lifetimes are discussed.
3.1 Fragmentation

CDF has performed a study [3] of fragmentation in $D_s^+/D^+$ meson production using the properties of associated $K^\pm$ mesons to measure the fragmentation chain in $p\bar{p}$ collisions. This study uses 360 pb$^{-1}$ of data to study the same-sign and opposite-sign $K^\pm$ rate associated with $D^+$ and $D_s^+$ mesons. The rates show the expected qualitative behavior. When compared to model calculations from PYTHIA and HERWIG, some differences in the same-sign rates for both $D^+$ and $D_s^+$ are seen, indicating a need for further tuning of fragmentation in models.

3.2 CP Asymmetry in $D^0 \rightarrow h^+h^-$ and $D^0 \rightarrow K_{S}^{0}\pi^+\pi^-$ decays

Measuring CP asymmetries in the decays of charm mesons is a useful way to investigate physics effects beyond the standard model. CDF has measured the individual CP asymmetries in the decays $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ [4]. CDF also measured the difference in the CP asymmetries, defined as $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$. An update on $\Delta A_{CP}$ using the full Run 2 data set is presented. The selection criteria are relaxed to take advantage of the fact that many of the systematic errors cancel in the difference measurement. This leads to a significant increase in the number of signal events. The $D^0(D^0)$ is tagged by the slow pion from the $D^*\pm$ decay. Approximately 550K $D^0 \rightarrow \pi^+\pi^-$ and 1.21M $D^0 \rightarrow K^+K^-$ decays are used in the analysis. Fits are made to identify signal, background from combinatorics, and background from multibody decays. The mass distributions are shown in Figure 2. The final result is $\Delta A_{CP} = (-0.62 \pm 0.21(\text{stat}) \pm 0.10(\text{syst}))\%$ [5]. This value is 2.7$\sigma$ from zero and has similar precision and provides confirmation of the LHCb result of $\Delta A_{CP} = (-0.83 \pm 0.21(\text{stat}) \pm 0.11(\text{syst}))\%$ [6].

Additional understanding of CP asymmetry in charm decays can be investigated by measuring CP decay properties of many decay modes of the $D^0$ meson. A measurement of CP asymmetry was made by CDF in the $K_{S}^{0}\pi^+\pi^-$ decay mode. A $D^*$ tag is used to identify the $D^0$ flavor. Two methods were used to measure the asymmetry; a full Dalitz fit using the isobar model and a model-independent bin-by-bin comparison. No CP asymmetry is found in any sub-resonance and integrating over all modes CDF measures $A_{CP} = -0.0005 \pm 0.0057(\text{stat}) \pm 0.0054(\text{syst})$ [7].

3.3 $B \rightarrow \mu^+\mu^-$ searches

Processes involving flavor-changing neutral currents are highly suppressed in the standard model and are therefore an excellent place to search for new physics that may increase measurable quantities such as decay rates. In the standard model the predictions for the neutral $B$ meson branching ratios are $B^0 \rightarrow \mu^+\mu^- = (1.0 \pm 0.1) \times 10^{-10}$ and $B_s^0 \rightarrow \mu^+\mu^- = (3.2 \pm 0.2) \times 10^{-9}$. 
CDF published upper limits on both branching ratios using 7 fb$^{-1}$ of data [8]. The analysis was extended to the full Run 2 data set of 9.7 fb$^{-1}$ using the same analysis methods. A neural network (NN) is used to discriminate the signal-like events from background, and the branching ratio is normalized to the $B^+ \to J/\psi K^+$ decay. The challenge in this analysis is to reject a large background while keeping most of the signal. 14 discriminating variables were used to build an optimized neural net classifier. The combinatorial background is estimated from the mass sidebands and the fake muon peaking backgrounds are estimated from $B \to hh$ simulation and $B \to K\pi$ decays in data. The results are binned in NN ranges and from the data/background comparison the branching ratios are measured. The final results are $BR(B^0 \to \mu^+\mu^-) < 4.6 \times 10^{-9}$, $BR(B^0_s \to \mu^+\mu^-) < 3.1 \times 10^{-8}$, both at 95% C.L. Assuming that the observed excess in the $B^0_s$ is due to a signal, CDF finds $BR(B^0_s \to \mu^+\mu^-) = 1.3^{+0.9}_{-0.7} \times 10^{-8}$.

The results are closer to the SM expectation and represents a big step in the program of measuring the branching ratio with better sensitivity.

### 3.4 $B^0_s$ decays and branching ratios

CDF has measured the branching ratios of $B^0_s$ decays to $D^{*+}D_s^-$, $D_s^{*+}D_s^-$ and $D_s^{*+}D_s^-$, where the $D_s^+$ decays to $\phi\pi^+$ or $K^{*0}K^+$ and the $D_s^{*+}$ decays to $D_s^+\gamma$ or $D_s^+\pi^0$, with the $\gamma$ or $\pi^0$ not detected. The measurement was made using a data sample of 6.8 fb$^{-1}$. A neural net was used to separate signal and background contributions, giving a total of approximately 750 $B^0_s \to D^{(*)+}D^{(*)-}$ decays. Branching ratios were determined by
normalizing to the well-measured $B^0 \to D^+_s D^-$ decay branching ratio. The results, now the world’s best measurements [9] are consistent with but lower than recent Belle results.

CDF uses the full Run 2 data set to measure $\text{BR}(B^0_s \to J/\psi \phi)$ and to constrain the value of $f_s/f_d$, as well as to investigate $f_s/f_d$ as a function of $p_T$. The $B^0 \to J/\psi \phi$ is normalized to the $B^0 \to J/\psi K^*$ decay mode. Approximately 11,000 $B^0$ and 57,000 $B^0$ events are used in the analysis. The final value for the ratio of the branching ratio multiplied by $f_s/f_d$ is found to be $0.239 \pm 0.003 \pm 0.019$. Using the value of $f_s/f_d$ measured by CDF and the PDG value [10] of $\text{BR}(B^0 \to J/\psi K^*)$, CDF finds $\text{BR}(B^0 \to J/\psi \phi) = (1.18 \pm 0.02(\text{stat}) \pm 0.09(\text{syst}) \pm 0.014(\text{frag}) \pm 0.05(\text{pdg})) \times 10^{-3}$. This is the world’s best measurement of the quantity. The analysis is also performed in bins of $p_T(B^0)$, showing no dependence on $p_T$ within statistics. Using Belle’s latest value of $\text{BR}(B^0_s \to J/\psi \phi)$ a value of $f_s/f_d$ can be computed and is found to be $f_s/f_d = 0.254 \pm 0.003(\text{stat}) \pm 0.020(\text{syst}) \pm 0.044(\text{pdg})$.

D0 has performed a measurement of the relative branching ratio of the $B^0_s \to J/\psi f_2'(1525)$ decay to the $B^0 \to J/\psi \phi$ decay. For this measurement the entire Run 2 data set of 10.4 fb$^{-1}$ was used. Monte Carlo templates for decay modes with the same four-body final states were fit as a function of the $K^+K^-$ mass to extract the $J/\psi f_2'(1525)$ contribution. A fit to the angular distributions of the decay show that the spin of the $K^+K^-$ is consistent with a combination of spin 0 and spin 2 and is inconsistent with spin 1. The final result for the ratio of branching ratios is [11] $\text{BR}(B^0 \to J/\psi f_2')/\text{BR}(B^0 \to J/\psi \phi) = 0.22 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})$.

### 3.5 $\chi_b \to \Upsilon(1S)\gamma$ studies

D0 combines $\Upsilon(1S)$ candidates in the mass range of $9.1 < M_{\mu^+\mu^-} < 9.7$ GeV with photons that have been identified by their conversion to $e^+e^-$ pairs. The mass difference $M_{\mu^+\mu^-} - M_{\mu^+\mu^-}$ is calculated for each event. Three clear states are seen, corresponding to the $\chi_b(1P)$, the $\chi_b(2P)$ and a new state. The mass of the third state is measured to be $10.551 \pm 0.014(\text{stat}) \pm 0.017(\text{syst})$ [12], consistent with the mass measured by ATLAS in the same decay mode [13].

### 3.6 Measurement of the $\Lambda_b$ lifetime

The $\Lambda_b$ lifetime measurements and predictions present a few puzzles. The measurements from various experiments and decay modes do not fully agree and the measurements are not all consistent with the theoretical predictions. This is an area where new measurements are needed to help resolve the mysteries.

D0 has made a new measurement of the $\Lambda_b$ lifetime, using the full Run 2 data set of 10.4 fb$^{-1}$ luminosity. In this analysis two topologically similar decay modes are measured, $\Lambda_b \to J/\psi \Lambda$ and $B^0 \to J/\psi K^0_s$. Separate fits are made to each decay
mode. The results are $\tau(\Lambda_b) = (1.303 \pm 0.075 \text{(stat)} \pm 0.035 \text{(syst)}) \text{ps}$, $\tau(B^0) = (1.508 \pm 0.025 \text{(stat)} \pm 0.043 \text{(syst)}) \text{ps}$ and $\tau(\Lambda_b)/\tau(B^0) = 0.864 \pm 0.052 \text{(stat)} \pm 0.033 \text{(syst)}$ [14]. These values can be compared to the PDG values and to the latest CDF values. Further measurements will be needed to help resolve the inconsistency.

4 Conclusions and Summary

The study of QCD and heavy quark physics in $p\bar{p}$ collisions at the Tevatron is a fruitful way to advance our knowledge of fundamental interactions and properties of matter. The results described provide interesting and novel information about parton distributions, parton interactions, quark decay properties, fragmentation, and CP asymmetries.

References

A dominant part in the analysis of early LHC data is played by general-purpose Monte-Carlo (MC) event generators [1], which are employed by both experimentalists and theorists to obtain particle level predictions for collider experiments. Hundreds of final-state particles are typically produced in LHC collisions, and the reactions involve both large and small momentum transfer. The high-dimensional phase space and the non-abelian, nonlinear nature of Quantum Chromodynamics (QCD) make an exact solution of the problem impossible. Instead, MC event generators resort to factorization, which allows to split events into different stages, ordered descending in invariant momentum transfer. In this picture, a hard interaction, described through fixed-order perturbation theory, is followed by multiple Bremsstrahlung emissions off initial- and final-state particles and, eventually, by the hadronization process. Each step is simulated independently.

Three general-purpose Monte-Carlo event generators are currently available which implement this paradigm: HERWIG [2], Pythia [3] and Sherpa [4]. A comprehensive description of the physics models implemented in these programs can be found in [1].

Traditionally, multi-purpose event generators compute hard processes at the lowest order in the perturbative expansion. This approximation leads to serious deficiencies in the description of final states with large jet multiplicity. Tree-level matrix element generators have therefore been constructed, which can cope with arbitrary final-states. The most widely used programs nowadays are ALPGEN, AMEGIC, Comix, HELAC and MadGraph [5]. Parton-level events produced by these tools are processed by general-purpose event generators to implement parton showers and hadronization. Although independent programs in principle, matrix-element generators like the above should thus be viewed as an integral part of the simulation chain in general-purpose programs. Their extension to new physics scenarios is handled by FeynRules [6], a Mathematica package, which automatically derives interaction vertices from virtually arbitrary Lagrangians.

Predictions for observables in multi-jet final states involve high powers of the strong coupling, and thus, they have large associated uncertainties. It is therefore desirable to improve the description of high-multiplicity events through next-to-leading order (NLO) calculations. Real and virtual NLO corrections can be combined in an automated way using universal infrared subtraction algorithms [7], which are implemented in various tree-level matrix-element generators [8]. The computation of many
Table 1: Total cross sections in nb for jet production at the LHC, using the anti-$k_T$ jet algorithm with $R = 0.4$. ATLAS are compared against LO, ME+PS and NLO theoretical predictions. Numerical integration uncertainties are given in parentheses, the scale dependence is quoted as super- and subscripts. The last column gives NLO results including non-perturbative corrections computed with Sherpa. Uncertainties shown with the ATLAS data are statistical, jet energy scale, and detector unfolding. Table taken from [9].

<table>
<thead>
<tr>
<th>no. jets</th>
<th>ATLAS</th>
<th>LO</th>
<th>ME+PS</th>
<th>NLO</th>
<th>NLO+NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 2</td>
<td>$620 \pm 1.3_{-10}^{+10}$</td>
<td>$958(1)_{-221}^{+221}$</td>
<td>$559(5)$</td>
<td>$1193(3)_{-135}^{+135}$</td>
<td>$1130(19)_{-129}^{+129}$</td>
</tr>
<tr>
<td>≥ 3</td>
<td>$43 \pm 0.13_{-1.7}^{+1.7}$</td>
<td>$93.4(0.1)_{-30.3}^{+30.3}$</td>
<td>$39.7(0.9)$</td>
<td>$54.5(0.5)_{-19.9}^{+19.9}$</td>
<td>$50.2(2.1)_{-18}^{+18}$</td>
</tr>
<tr>
<td>≥ 4</td>
<td>$4.30_{-0.24}^{+1.04}$</td>
<td>$9.98(0.01)_{-3.95}^{+3.95}$</td>
<td>$3.97(0.08)$</td>
<td>$5.54(0.12)_{-2.44}^{+2.44}$</td>
<td>$5.11(0.29)_{-1.32}^{+1.32}$</td>
</tr>
</tbody>
</table>

Challenging background processes at the LHC was accomplished with the help of these tools. Prominent examples include $pp \rightarrow W/Z + 4$ jets, $pp \rightarrow 4$ jets and $pp \rightarrow t\bar{t}b\bar{b}$ [9].

A variety of processes can now be computed in a fully automated fashion by linking the matrix element generators described above with dedicated programs for one-loop virtual matrix elements through a standardized interface [10]. Computing virtual corrections often poses the greatest challenge, both because of complexity and numerical stability. Tremendous progress was made in this field, leading to new computational algorithms based on generalized unitarity. Automated calculations of one-loop corrections have since become available in the BlackHat, GoSam, HelacNLO, MadLoop, OpenLoops and Rocket [11,12] programs, as well as several others [13]. Additionally, more traditional, Feynman-digraph based techniques have been extended and applied for example to the process $pp \rightarrow W^+W^-b\bar{b}$ [14]. They are also used in the program OpenLoops [12]. Table 1 shows an example of next-to-leading order results for 4 jet production. The calculation was performed with BlackHat and Sherpa, which exemplifies the possible synergy between programs for one-loop calculations and leading order event generators.

While the production of jets in high-energy collisions is typically described very well by fixed-order calculations, the modeling of inner jet structure in this approach is poor. The composition of jets in terms of several partons should therefore be simulated by parton showers, which employ collinear factorization properties of scattering amplitudes to sum leading and certain subleading logarithmic corrections to hard scattering processes. The difference between existing parton-shower implementations in HERWIG [15], Pythia [16] and Sherpa [17] lies in the parametrization of the radiative phase space, the splitting functions which are employed and, in particular, the splitting kinematics.

Sherpa implements a dipole-like parton shower [17], which is based on the Catani-Seymour dipole subtraction method in the large-$N_c$ approximation. The advantage compared to traditional parton showers is an improved description of soft-collinear re-
regions, which arises as a consequence of the dependence of the splitting function on the kinematics of the spectator parton. Similar ideas are implemented in HERWIG [18]. Within Pythia, recent development focused on improved matching to hard processes at next-to-leading order and on incorporating multiple scattering and rescattering effects into parton shower simulations [16]. First attempts have been made in HERWIG to include all possible color correlations into the parton shower [19].

Higher-order tree-level calculations and parton showers, as introduced above, are two essentially complementary approaches to simulating perturbative QCD interactions in general-purpose Monte-Carlo. It is desirable to combine both, in order to obtain the best possible description of jet production and evolution. To this end, two different strategies have been exploited, which are known as matching and merging.

Matching algorithms either aim at replacing parton-shower splitting operators with the ratio of complete higher-order matrix elements divided by the Born, or they provide means to correct for the difference between the two. The main problem to be solved is that parton showers alter the kinematics of partonic final states. If the underlying parton-level calculation is performed at NLO, this implies that the Born contribution times the parton shower leads to spurious terms of order $\alpha_s$, which must be subtracted to avoid double counting that would spoil the NLO accuracy. Two universally applicable methods to accomplish this task were suggested in the past, which are dubbed MC@NLO and POWHEG [22]. Both methods were applied to a

Figure 1: Left: Transverse momentum of the Higgs boson in $h+jet$ events at the LHC (7 TeV). Results from POWHEG simulations with different scale choice are compared against each other and against predictions from HqT [20]. The simulation was performed by combining MadGraph with MCFM and the POWHEG Box. Right: Di-jet mass in $W+2jet$ events at the Tevatron (1.96 TeV). Results from aMC@NLO are compared against predictions from ALPGEN and against an NLO calculation. Figures taken from [21].
variety of processes, using the event generation frameworks of HERWIG and Pythia.

The MC@NLO method has also been automated in the aMC@NLO framework, based on MadLoop and HERWIG [23]. In contrast to MC@NLO, the POWHEG technique does not depend on the parton-shower algorithm, hence, independent implementations exist [24]. Within Sherpa, the POWHEG and MC@NLO methods have been automated [25]. Figure 1 displays results for Higgs boson plus jet and W boson plus two jets production, which are some of the most challenging processes recently implemented using matching methods.

To improve the description of hard QCD radiation by general-purpose event generators, so-called merging algorithms were proposed in the context of the LEP physics program [28], and subsequently extended for hadron collisions [29]. The aim of these techniques is to replace the parton-shower approximation with fixed-order matrix elements for only those partons or parton ensembles, which can be identified with experimentally observed jets. Merging algorithms define an unambiguous way to separate the phase-space of real parton emission into a soft and a hard regime. Soft regions, where higher-order corrections must be resummed, but can be approximated, are filled by the parton shower. Hard regions, where soft and collinear approximations are unsuitable, are filled by fixed-order calculations. Since fixed-order calculations are inclusive, they must be made exclusive using the parton-shower no-branching proba-
bility, commonly referred to as the Sudakov factor. In this manner, double-counting of logarithmically enhanced terms is avoided, while sub-leading logarithms and finite corrections are correctly included in the hard domain.

An extension of the original merging approaches, which generically maintains the exact logarithmic accuracy of the parton shower while respecting the phase-space separation cut, was achieved in [30]. The first merging at the leading to next-to-leading order was been presented in [26], in a method based on explicit subtraction of the LO and NLO contributions from the parton shower. The technique introduced in [27] is based instead on an extended modified subtraction similar to MC@NLO, which is implemented using truncated vetoed parton showers in the spirit of [30]. The two existing implementations of a merging method at the NLO in [26] and [27] both indicate a substantial reduction of theoretical uncertainties, as exemplified in Fig. 2.

Monte-Carlo event generators have a variety of free parameters, which can be tuned such that predictions better match experimental data. Many of these parameters are connected to fragmentation models and underlying-event simulation, or more general, to models for non-perturbative QCD effects. The resulting parameter space can be quite large, which makes it impossible to find an optimal solution by hand.

Two new tools have been developed recently, which attack these problems using a generator-independent validation and tuning strategy. Rivet [31], implements analyses from the LEP, Tevatron and LHC experiments in a common framework and allows simultaneous tests of Monte-Carlo output against all available collider data. Professor [32] employs Rivet to semi-automatically find the best point in the parameter space of the event generator.

In summary, modern general-purpose event generators are highly sophisticated tools for LHC phenomenology. They often implement perturbative QCD calculations at next-to-leading order in the strong coupling and they provide parton showers to include resummation effects. Extensions of event generators allow them to become a platform for testing new physics models and improved descriptions of perturbative QCD in the same framework. Validation and tuning has been in the focus of interest during the first years of LHC running and has been simplified by dedicated tools.

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References

**B Physics: Theory Overview**

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1 Introduction

A great deal of work on $B$ physics has been done over the past 15-20 years. At first, it was mostly in the context of the $B$ factories BaBar and Belle. This included finding methods for measuring the standard model (SM) parameters, examining ways of looking for new physics (NP), analyzing the results, etc. Unfortunately, most of the measurements at the $B$ factories agreed with the SM. Although there were several hints of NP, mostly in $b \rightarrow s$ transitions, there were no statistically-significant signals.

CDF and DO then demonstrated that $B$ physics can be done at hadron colliders. They made a number of measurements involving $B^0_s$ mesons, in particular $B^0_s$-$\overline{B}^0_s$ mixing.

The LHC will continue this exploration of $B$ physics. They will focus mainly on $B^0_s$ mesons, but may well be able to repeat (and perhaps improve upon?) some of the measurements made at BaBar and Belle. As always, the hope is to find a signal of NP. It seems clear now that very large signals are ruled out. But the LHC may well have the precision to detect even small deviations from the SM. In this talk, I will discuss a number of $B$-physics measurements to be made at the LHC that have the potential for revealing NP.

2 $B^0_s$-$\overline{B}^0_s$ Mixing

In the presence of $B^0_s$-$\overline{B}^0_s$ mixing, the mass eigenstates $B_L$ and $B_H$ [$L$ ($H$) corresponds to “light” (“heavy”)] are admixtures of the flavour eigenstates $B^0_s$ and $\overline{B}^0_s$:

\begin{align}
|B_L\rangle &= p |B^0_s\rangle + q |\overline{B}^0_s\rangle, \\
|B_H\rangle &= p |B^0_s\rangle - q |\overline{B}^0_s\rangle,
\end{align}

(1)

with $|p|^2 + |q|^2 = 1$. The initial flavour eigenstates oscillate into one another according to the Schrödinger equation with $H = M^s - i\Gamma^s/2$ ($M^s$ and $\Gamma^s$ are the dispersive and...
absorptive parts of the mass matrix), and lead to the time-dependent states $B_s^0(t)$ and $\bar{B}_s^0(t)$. The off-diagonal elements $M^s_{12}$ and $\Gamma^s_{12}$ are generated by $B_s^0-\bar{B}_s^0$ mixing.

Defining $\Delta M_s \equiv M_H - M_L$ and $\Delta \Gamma_s \equiv \Gamma_L - \Gamma_H$, we have

$$
\Delta M_s = 2|M_{12}'|, \quad \Delta \Gamma_s = 2|\Gamma_{12}'| \cos \phi_s, \quad \frac{q}{p} = e^{-2i\beta_s},
$$

(2)

where $\phi_s \equiv \text{arg}(-M^s_{12}/\Gamma^s_{12})$ is the CP phase in $\Delta B = 2$ transitions. The weak phases $\phi_s$ and $2\beta_s$ are independent. The SM predicts that both $\phi_s$ and $2\beta_s$ are very small (but $\phi_s \neq -2\beta_s$). $\Delta \Gamma_s$ is sizeable and is positive in the SM. In the presence of NP, one can have $2\beta_s \neq 0$ and $\Delta \Gamma_s < 0$.

$J/\psi\phi$: In 2008 CDF and DO measured the indirect CP asymmetry in $B_s^0 \to J/\psi\phi$, and found a hint for CPV. The 2011 update gives (at 68% C.L.) [1]

$$
2\beta_{s}^{\psi\phi} \in [2.3^\circ, 59.6^\circ] \cup [123.8^\circ, 177.6^\circ], \quad \text{CDF},
$$

$$
\in [9.7^\circ, 52.1^\circ] \cup [127.9^\circ, 170.3^\circ], \quad \text{DO}.
$$

(3)

Note that the measurement is insensitive to the transformation $(2\beta_{s}^{\psi\phi}, \Delta \Gamma_s) \leftrightarrow (\pi - 2\beta_{s}^{\psi\phi}, -\Delta \Gamma_s)$. This implies that $2\beta_{s}^{\psi\phi}$ has a twofold ambiguity, which is reflected in the two ranges of possible solutions above.

LHCb has greatly improved upon this result. First, the twofold discrete ambiguity has been removed by measuring $\text{sign}(\Delta \Gamma_s)$: $\Delta \Gamma_s = 0.120 \pm 0.028 \text{ ps}^{-1}$ [2]. This is done using the decay $B_s^0 \to J/\psi\phi(\to K^+K^-)$, and looking at the interference between the $s$- and $p$-wave $K^+K^-$ angular momentum states.

Second, they find [3]

$$
2\beta_{s}^{J/\psi\phi} = (-0.06 \pm 5.77 \text{ (stat)} \pm 1.54 \text{ (syst)})^\circ,
$$

(4)

in agreement with the SM. Still, the errors are large enough that NP cannot be excluded.

To completely search for NP, LHCb has to measure $B_s^0-\bar{B}_s^0$ mixing in as many different decays as possible. This has already begun:

$J/\psi f_0(980)$: LHCb has measured $\beta_{s}^{J/\psi f_0} = (-25.2 \pm 25.2 \pm 1.1)^\circ$ [4]. The advantage of this decay is that, because the $f_0(980)$ is a scalar, no angular analysis is needed. The disadvantage is that, because the $f_0(980)$ is not a pure $s\bar{s}$ state, there are possibly other contributions to the decay, leading to hadronic uncertainties [5].

$J/\psi \pi^+\pi^-$: LHCb has measured $\beta_{s}^{J/\psi \pi^+\pi^-} = (-1.09^{+0.91+0.23}_{-0.97-0.17})^\circ$ [6]. $A \text{ priori}$, since this is a 3-body state, its CP can be $+$ or $-$, and so it cannot be used to cleanly extract weak-phase information. However, it has been shown that the $J/\psi \pi^+\pi^-$ state is almost purely CP $-$ [7], so that there is little error due to the CP $+$ state.

Other final states that are potentially of interest include (i) $D^+_sK^\mp$ [8] – here one extracts $(2\beta_s + \gamma)$, (ii) $D^+_sD^-_s$ [9] – here one has to deal with penguin pollution, (iii) $D^-_{CP}K\bar{K}$ [10] – here one requires a Dalitz-plot analysis.
Finally, $B^0_s \to K^{(*)0}\overline{K}^{(*)0}$ is a pure $b \to s$ penguin decay whose amplitude in the SM is $A = V_{tb}^* V_{ts} P_{tc} + V_{ub}^* V_{us} P_{uc}$. The second term is doubly Cabibbo suppressed with respect to the first term. If it is neglected, the indirect CP asymmetry vanishes in the SM, so that its measurement could reveal NP. However, $V_{ub}^* V_{us} P_{uc}$ is not entirely negligible. Including it, it is found that indirect CPV measures $|\beta_s^{eff}| \leq 14.9^\circ$ in the SM [11]. If a larger value of $|\beta_s^{eff}|$ is measured, this would imply NP.

3 Like-sign Dimuon Asymmetry

DO has reported an anomalously large CP-violating like-sign dimuon charge asymmetry in the $B$ system. The updated measurement is [12]

$$A_{sl}^b \equiv \frac{N_{b}^{++} - N_{b}^{--}}{N_{b}^{++} + N_{b}^{--}} = -(7.87 \pm 1.72 \pm 0.93) \times 10^{-3},$$

a 3.9σ deviation from the SM prediction, $A_{sl}^{b,SM} = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$.

Now, it has been shown that, if this anomaly is real, it implies NP in $B_s^0$-$\overline{B}_s^0$ mixing. Such NP effects can appear in $M_{s12}^*$ and/or $\Gamma_{s12}$. In fact, it has been argued that NP in $\Gamma_{s12}$ should be considered as the main explanation for the above result [13].

In the SM, the dominant contribution to $\Gamma_{s12}$ is $b \to s\tau^+\tau^-$. Significant NP contributions, i.e. comparable to that of the SM, can come mainly from $b \to s\tau^+\tau^-$. This is (in principle) straightforward to detect – if $B(B_s^0 \to \tau^+\tau^-)$ is observed to be at the percent level, this will be a clear indication of NP (in the SM, $B(B_s^0 \to \tau^+\tau^-) = 7.9 \times 10^{-7}$). Thus, this is one decay that LHCb should try to measure.

4 $B_s^0 \to V_1 V_2$ Decays

$B_s^0 \to V_1 V_2$ is really 3 decays. Being vector mesons, $V_1$ and $V_2$ can have relative orbital angular momentum $l = 0, 1$ or 2 ($s$, $p$ or $d$ wave). This is taken into account by decomposing the decay amplitude into components in which the polarizations of the final-state vector mesons are either longitudinal ($A_0$), or transverse to their directions of motion and parallel ($A_\parallel$) or perpendicular ($A_\perp$) to one another.

1) $f_T$, $f_L$: Naively, one expects $f_T \ll f_L$, where $f_T$ ($f_L$) is the fraction of transverse (longitudinal) decays in $B \to V_1 V_2$. However, it was observed that $f_T f L \simeq 1$ in $B \to \phi K^*$ [14]. One explanation of this “polarization puzzle” is that the $1/m_B$ penguin-annihilation (PA) contributions are important [15]. PA can be sizeable within QCD factorization (QCDf).

There are two penguin decay pairs whose amplitudes are the same under flavour SU(3), and for which there is a good estimate of SU(3) breaking within QCDf: $(B_s^0 \to$
\(\phi, B^0_d \rightarrow \phi K^{0*}\) and \((B^0_s \rightarrow \phi \overline{K}^{0*}, B^0_s \rightarrow \overline{K}^{0*} K^{0*})\) [16]. Given the polarization in the \(B^0_d\) decay, can predict the polarization in the \(B^0_s\) decay, and thus test PA.

This has been partially done – \(B^0_s \rightarrow \phi \phi\) has been measured:

\[
\frac{f_T(B^0_s \rightarrow \phi \phi)}{f_T(B^0_d \rightarrow \phi K^{0*})} = 1.36 \pm 0.59 ,
\]

\[
\frac{f_T(B^0_s \rightarrow \phi \phi)}{f_T(B^0_d \rightarrow \phi K^{0*})} = 1.25 \pm 0.11 .
\]

The theoretical error is large, but there is reasonable agreement.

(2) Triple Product (TP): In the B rest frame, the TP takes the form \(\vec{q} \cdot (\vec{\varepsilon}_1 \times \vec{\varepsilon}_2)\), where \(\vec{q}\) is the difference of the two final momenta, and \(\vec{\varepsilon}_1\) and \(\vec{\varepsilon}_2\) are the polarizations of \(V_1\) and \(V_2\). The TP is odd under both P and T, and thus constitutes a potential signal of CPV. There are two TP’s: \(A^{(1)}_T \propto \text{Im}(A_\perp A^*_0)\) and \(A^{(2)}_T \propto \text{Im}(A_\perp A_1^*)\).

The statement that “TP’s are a signal of CP violation” is not quite accurate. The \(A_i\ (i = 0, \perp, \parallel)\) possess both weak (CP-odd) and strong (CP-even) phases. Thus, \(\text{Im}(A_\perp A^*_0)\) and \(\text{Im}(A_\perp A^*_1)\) can both be nonzero even if the weak phases vanish. In order to obtain a true signal of CP violation, one has to compare the \(B\) and \(\overline{B}\) decays.

The TP’s for the \(\overline{B}\) decay are \(-\text{Im}\{A_\perp \overline{A}_0^*\}\) and \(-\text{Im}\{A_\perp \overline{A}_1^*\}\), in which \(A_0, A_\perp,\) and \(A_1\) are equal to \(A_0, A_\parallel,\) and \(A_1\), respectively, but with weak phases of opposite sign. \(A_\perp\) is pure \(p\) wave \((l = 1)\), and so the additional minus sign is generated when CP is applied and \(A_\perp \rightarrow \overline{A}_\perp\). The true (CP-violating) TP’s are then given by \(\frac{1}{2}[\text{Im}(A_\perp A^*_0) + \text{Im}(A_\perp \overline{A}_0^*)]\) and \(\frac{1}{2}[\text{Im}(A_\perp A^*_1) + \text{Im}(A_\perp \overline{A}_1^*)]\).

Now, CPV requires the interference of two amplitudes. The common way to look for CPV is via a nonzero rate difference between a decay and its CP-conjugate decay (direct CPV). The direct CP asymmetry is proportional to \(\sin \phi \sin \delta\), where \(\phi\) and \(\delta\) are the relative weak and strong phases of the two amplitudes. That is, direct CPV requires a nonzero strong-phase difference. On the other hand, the true TP is proportional to \(\sin \phi \cos \delta\), so no strong-phase difference is necessary. This helps in the search for NP. Also, in the SM, true TP’s are generally small (or zero) [17], so that TP’s are a good way to find NP.

CDF and LHCb have measured the true TP asymmetries in \(B^0_s \rightarrow \phi \phi\) [18]:

\[
A_u (\parallel \parallel) = -0.007 \pm 0.064 \text{ (stat)} \pm 0.018 \text{ (syst)} \quad \text{CDF} ,
\]

\[
= -0.064 \pm 0.057 \text{ (stat)} \pm 0.014 \text{ (syst)} \quad \text{LHCb} ,
\]

\[
A_v (\parallel 0) = -0.120 \pm 0.064 \text{ (stat)} \pm 0.016 \text{ (syst)} \quad \text{CDF} ,
\]

\[
= -0.070 \pm 0.057 \text{ (stat)} \pm 0.014 \text{ (syst)} \quad \text{LHCb} .
\]

These agree with the SM prediction \((A_u = A_v = 0)\).

There are also fake (CP-conserving) TP’s, due only to the strong phases of the \(A_i\)’s. These are given by \(\frac{1}{2}[\text{Im}(A_\perp A^*_0) - \text{Im}(A_\perp \overline{A}_0^*)]\) and \(\frac{1}{2}[\text{Im}(A_\perp A^*_1) - \text{Im}(A_\perp \overline{A}_1^*)]\).
In the SM, certain fake TP’s are very small [19]. This implies that one can partially distinguish the SM from NP through the measurement of the fake $A_T^{(2)}$ TP. This applies to $B \to \phi K^*$ and $B_s^0 \to \phi \phi$.

5 Measuring U-spin/SU(3) Breaking

Consider charmless $\bar{b} \to \bar{d}$ and $\bar{b} \to \bar{s}$ decays whose amplitudes are equal under U spin ($d \leftrightarrow s$). There are four observables: the CP-averaged $\bar{b} \to \bar{d}$ and $\bar{b} \to \bar{s}$ decay rates $B_d$ and $B_s$, and the direct CP asymmetries $A_d$ and $A_s$. In the U-spin limit, $X = 1$, where $X \equiv -(A_s/A_d)(B_s/B_d)$. Thus, by measuring the four observables, and computing the deviation of $X$ from 1, one can measure U-spin breaking [20].

This can be applied to 4 decay pairs involving $B_s^0$ decays: $B_s^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$, $B_s^0 \to \pi^+K^-$ and $B_s^0 \to K^-\pi^+$, $B_d^0 \to K^0\bar{K}^0$ and $B_s^0 \to \bar{K}^0K^0$, $B_d^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$. The first (second) decay is $\bar{b} \to \bar{d}$ ($\bar{b} \to \bar{s}$).

If one neglects annihilation- and exchange-type diagrams, there are 12 additional pairs of decays to which this analysis can be applied. These are not related by U spin, but are instead related by flavour SU(3).

6 Conclusions

In the past, there were a number of hints of NP in some $B$ decays, usually in $\bar{b} \to \bar{s}$ transitions. Unfortunately, with recent LHCb measurements, most of these have gone away. This suggests that, if NP is present, very large signals are unlikely.

Still, the LHC has the precision to detect small deviations from the SM predictions. To this end, it is best to make measurements of as many different processes as possible. In this talk, I have mentioned a number of different possibilities (some of which have already been measured). Hopefully, when these measurements are made, we will see a sign of NP.

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References


Mixing and CP violation

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1 Introduction

In the Standard Model (SM), neutral mesons ($M^0$) mix with their antiparticles ($\bar{M}^0$) via box diagrams. The mass eigenstates ($M_{L,H}$) are linear combinations of the flavour eigenstates: $M_{L,H} = p |M^0⟩ ± q |\bar{M}^0⟩$. This phenomenon can be characterized by the mass and decay width differences between the mass eigenstates, $\Delta m$ and $\Delta \Gamma$, and by the relative phase between off-diagonal terms of the mass and decay matrices: $\phi_{12} = \text{arg} (-M_{12}/\Gamma_{12})$. Three types of CP violation are usually distinguished: in the decay, in the mixing, and in the interference between decay and mixing. In these proceedings, we give an overview of recent experimental results in quark mixing and CP violation. The main actors in this area are recalled in Table 1, together with their main characteristics. In Section 2, we summarize the mixing and CP violation results related to charm mesons. In Section 3, we report on the $B^0_s$ mixing related parameters: $\Delta m_s$, $\Delta \Gamma_s$, $\phi_s$ and $A_{SL}$. In Section 4, we describe recent progresses towards the measurement of the $\gamma$ angle of the unitarity triangle.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Accelerator</th>
<th>Beam energies</th>
<th>$\sigma(b\bar{b})$</th>
<th>Int. lumi (end 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>PEP2, $e^+e^-$</td>
<td>3.1 + 9 GeV</td>
<td>1 nb</td>
<td>550 fb$^{-1}$</td>
</tr>
<tr>
<td>Belle</td>
<td>KEKB, $e^+e^-$</td>
<td>3.5 + 8 GeV</td>
<td>1 nb</td>
<td>1 ab$^{-1}$</td>
</tr>
<tr>
<td>CDF, DO</td>
<td>Tevatron, $p\bar{p}$</td>
<td>2 $\times$ 0.98 TeV</td>
<td>100 $\mu$b</td>
<td>10 fb$^{-1}$ each</td>
</tr>
<tr>
<td>LHCb</td>
<td>LHC, $pp$</td>
<td>2 $\times$ 3.5 TeV</td>
<td>300 $\mu$b</td>
<td>1 fb$^{-1}$</td>
</tr>
<tr>
<td>ATLAS, CMS</td>
<td>LHC, $pp$</td>
<td>2 $\times$ 3.5 TeV</td>
<td>300 $\mu$b</td>
<td>5 fb$^{-1}$ each</td>
</tr>
</tbody>
</table>

Table 1: Main actors in $B$ & $D$ mixing and CP violation. From left to right: experiment, accelerator, beam energies, $b\bar{b}$ cross-section and integrated luminosity registered by the end of 2011.

\footnote{on behalf of the LHCb Collaboration}
Table 2: Summary of experimental measurements of mixing and CP violation in neutral $D$ and $B$ mesons [1]. Red italic means “5σ” has not yet been established. The $B \Delta \Gamma$ convention is adopted for the charm, i.e. $\Delta \Gamma = \Gamma_{L} - \Gamma_{H}$. $\Gamma$ is the decay width of meson shown in each column. CP violation is not quantified by a unique number: values or examples are given to illustrate the status in June 2012.

2 Charm mixing and CPV

Charm mixing is established at 10.2σ, though no single experiment reaches 5σ yet. The world average for the mixing parameters $x = \Delta m/\Gamma$ and $y = \Delta \Gamma/2\Gamma$ are given in Table 2. In April 2012, BaBar and Belle presented new results concerning the CP violating parameters: $y_{CP} = \frac{\tau(D^{0} \rightarrow K^{+} K^{-})}{\tau(D^{0} \rightarrow hh)} - 1 = \frac{1}{2}(|q/p| + |p/q|) y \cos \phi - \frac{1}{2} (|q/p| - |p/q|) x \sin \phi$, where $hh = K^{+} K^{-}$ or $\pi^{+} \pi^{-}$, and $A_{\Gamma} = \frac{\tau(D^{0} \rightarrow hh) - \tau(D^{0} \rightarrow hh)}{\tau(D^{0} \rightarrow hh) + \tau(D^{0} \rightarrow hh)} = \frac{1}{2}(|q/p| - |p/q|) y \cos \phi - \frac{1}{2} (|q/p| + |p/q|) x \sin \phi$. The world average gives [1] $y_{CP} = (0.866 \pm 0.155)\%$, compatible with $y$ and $A_{\Gamma} = (-0.022 \pm 0.161)\%$, compatible with zero. Hence these results are compatible with CP conservation.

The charm result which created the most excitement is the one on $\Delta A_{CP}(D^{0} \rightarrow K^{+} K^{-}, \pi^{+} \pi^{-})$. This parameter is the difference of CP violating asymmetry measured in $D^{0} \rightarrow K^{+} K^{-}$ and $D^{0} \rightarrow \pi^{+} \pi^{-}$. In November 2011, LHCb reported a value of $\Delta A_{CP}$ 3.4σ away from zero [2]. In 2012, CDF found a similar result, bringing the significance of the deviation to 3.8σ [3]. The parameter $\Delta A_{CP}$ measures essentially the direct CP violation, which is expected to be very small within the SM. Figure 1 shows the indirect versus direct CP violating parameters measured in $D^{0} \rightarrow K^{+} K^{-}$ and $D^{0} \rightarrow \pi^{+} \pi^{-}$) [1]. The world average is $\Delta a_{CP}^{dir} = (-0.656 \pm 0.154)\%$ [1]. Theoretical work is ongoing to disentangle SM hadronic effects from possible New Physics. Experimental improvements are expected soon, since LHCb data sample will be 4 times larger by the end of 2012.
Figure 1: Direct versus indirect CP violating charm parameters [1]. Individual measurements are plotted as bands showing their ±1σ range. The no-CPV point (0,0) is shown as a filled circle, and the best fit value is indicated by a cross showing the one-dimensional errors. Two-dimensional 68% CL, 95% CL, and 99.7% CL regions are plotted as ellipses [1].

Figure 2: 68% CL regions in $B_s^0$ width difference $\Delta \Gamma_s$ and weak phase $\phi_s^{\ell \ell}$ obtained from individual and combined CDF [5], DO [6] and LHCb [4, 7] likelihoods of $B_s^0 \to J/\psi \phi$ and $B_s^0 \to J/\psi \pi^+ \pi^-$ [7] samples. The expectation within the SM [8, 9] is shown as the black rectangle.

3 \textit{B}_s^0 \textit{ mixing parameters (} $\Delta m_s$, $\Delta \Gamma_s$, $\phi_s$ \textit{) and} $A_{SL}$

We define $\phi_s^{\ell \ell}$ as the weak phase difference between the $B_s^0$–$\overline{B}_s^0$ mixing amplitude and the $b \to c\ell \ell$ decay amplitude. The golden mode to measure this phase is $B_s^0 \to J/\psi \phi$, though it has also been measured in $B_s^0 \to J/\psi \pi^+ \pi^-$. A summary of the results on $\phi_s^{\ell \ell}$ is given in Figure 2 and Table 3, together with the decay width difference between the $B_s^0$ mass eigenstate, $\Delta \Gamma_s$. It should be emphasized that this latter parameter has been measured for the first time with greater than 5σ significance from zero in 2012 [4]. When combined with other lifetime measurements, including $B_s^0$ decays to $K^+ K^-$, $J/\psi f_0(980)$, $D_s^- \ell^+ \nu_\ell$ and $D_s^- \pi^+$, the world average value is $\Delta \Gamma_s = +0.095 \pm 0.014 \text{ps}^{-1}$ [1]. The average value of $\Delta m_s$ is $17.719 \pm 0.043 \text{ps}^{-1}$ [1]. It is dominated by [10].

In 2011, DO reported a value of the dimuon asymmetry, $A_{SL}^b$, 3.9σ away from the SM expectation [11] (see Figure 3). This asymmetry is linked to the fundamental phase $\phi_s^{\ell \ell}$. Theoretical work is ongoing to determine whether the observed value can be accounted by New Physics effects in the mixing and/or decay matrices of $B_s^0$ and/or $B^0$ [12].
Table 3: Individual and average values of $\phi_s^{cs}$ and $\Delta \Gamma_s$ compiled by HFAG [1].

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Mode</th>
<th>$\phi_s = \phi_s^{cs}$</th>
<th>$\Delta \Gamma_s$ (ps$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF [5]</td>
<td>$J/\psi \phi$</td>
<td>$[-0.60, 0.12]$, 68% CL</td>
<td>$0.068 \pm 0.026 \pm 0.007$</td>
</tr>
<tr>
<td>DO [6]</td>
<td>$J/\psi \phi$</td>
<td>$-0.55^{+0.38}_{-0.36}$</td>
<td>$0.163^{+0.065}_{-0.064}$</td>
</tr>
<tr>
<td>LHCb [4]</td>
<td>$J/\psi \phi$</td>
<td>$-0.001 \pm 0.101 \pm 0.027$</td>
<td>$0.116 \pm 0.018 \pm 0.006$</td>
</tr>
<tr>
<td>LHCb [7]</td>
<td>$J/\psi \pi^+ \pi^-$</td>
<td>$-0.019^{+0.173+0.004}_{-0.174-0.003}$</td>
<td>—</td>
</tr>
<tr>
<td>Combined [HFAG’2012]</td>
<td></td>
<td>$-0.044^{+0.094}_{-0.085}$</td>
<td>$+0.105 \pm 0.015$</td>
</tr>
</tbody>
</table>

Figure 3: $A_{SL}^b$ measured by DO (plain magenta and yellow), $a_{sl}^b$ measured by DO (vertical green hatched) and $a_{sl}^d$ measured by the B-factories (horizontal black hatched). The SM model prediction is indicated as a black circle.

Figure 4: Constraints on $\gamma$ from world average $D^{(*)}K^{(*)}$ decays (GLW+ADS) and Dalitz analyzes (GGSZ), compared to the prediction from the global CKM fit (not including these measurements) [8].
4 Angle $\gamma$

$\gamma = \arg \left( -\frac{V_{ud}V_{ud}^*}{V_{cd}V_{cd}^*} \right)$ is the least well measured angle in the unitarity triangle. The indirect determination via a global fit to experimental other directly measured data gives $\gamma = (67.1 \pm 4.3)^o$ [8]. Its determination can be split in methods involving loop-mediated processes and methods dominated by tree-level diagrams.

The main news concerning the determination of $\gamma$ via loop-mediated processes comes from LHCb results on $B \to hh$ [13]. Some steps towards $\gamma$ have been reached: the world best measurement of direct CP violation in $B^0 \to K\pi$, $A_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011$(stat) $\pm 0.008$(syst) and the first evidence of CP violation in $B^0_s$ decay, $A_{CP}(B^0_s \to K\pi) = 0.27 \pm 0.08$(stat) $\pm 0.02$(syst). A first time-dependent CP asymmetry in $B^0_s \to K^+K^-$ is also achieved [14].

The world average direct measurement of $\gamma$ is dominated by $B$-factories results. Two groups obtain slightly different values: $\gamma = (67.1 \pm 12)^o$ [8] and $\gamma = (75.5 \pm 10.5)^o$ [15]. In LHCb, important milestones towards the $\gamma$ measurement have been reached recently, with the studies of $B \to D(hh, hh\bar{h})K$ [16, 17], $B \to DK^* $ [18], $B \to DK\pi\pi $ [19] and $B^0_s \to D_sK^\pm $ [20]. In [21], LHCb reported the first observation of $B^\pm \to [\pi K]_D K^\pm$ and overtook the $B$-factories in some “ADS” observables. Figure 4 gives the constraints on $\gamma$ from world average $D^{(s)}K^{(s)}$ decays (GLW+ADS) and Dalitz analyzes (GGSZ) [8]. The latest GGSZ result from Belle [22] was not included yet.

5 Epilogue

While completing these proceedings, several important new results have been obtained. LHCb has released a preliminary result on $a^s_{sl}$ [23]. Both BaBar [24] and Belle [25] have updated their BR($B \to \tau\nu$) measurements, decreasing the tension with $\sin 2\beta$. Atlas presented an untagged analysis of $B^0 \to J/\psi\phi$ decays [26], bringing new constraints on $\phi_s$ and $\Delta \Gamma_s$, though less precise than the LHCb ones. Belle presented an updated $\Delta A_{CP}(K\pi, \pi\pi)$ measurement [27], bringing the new world average value for this CP violating observable in charm $4.9\sigma$ away from zero.

6 Conclusions and prospects

A simplified summary of mixing and CP violation in $B$ and $D$ is given in Table 2. Charm mixing is well established $(10.2\sigma)$, though no single experiment has reached $5\sigma$ yet. A hint for CP violation in charm has been reported by LHCb and re-enforced recently by CDF and Belle, bringing the $\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-)$ observable $4.9\sigma$ away from zero. Theoretical work is ongoing to disentangle SM hadronic effect from
possible New Physics contributions. Experimental improvements are also expected, in particular in LHCb which will have 4 times more data by the end of 2012. All other charm CP measurements are compatible with CP conservation.

Concerning CP violation in the $B$-hadron sector, many outstanding new results have been obtained in 2012 by LHCb, the $B$-factories and the TeVatron. Uncertainties are much reduced or first measurement ever are reported. Everything is compatible with the Standard Model so far, bringing strong constraints on New Physics. The uncertainty on the CP violating phase $\phi_s^{cs}$ is below 0.09 rad. The parameter $\Delta \Gamma_s$ has been measured for the first time by LHCb, with a significance above $5\sigma$ from zero. The first evidence for CP violation in $B^0_s$ has been reported by LHCb. Important milestones towards a first measurement of the $\gamma$ angle at LHCb has been achieved. The long-standing tension between $\sin 2\beta$ and the branching ratio of $B^+ \to \tau^+ \nu_\tau$ has decreased following the updated measurement of the latter one by the $B$-factories. The tension in the dimuon asymmetry reported by DO in 2010 has also decreased, following the updated analysis by DO itself and also a new measurement of $a_{sl}^s$ by LHCb. Mixing and CP violating in the quark sectors bring stronger constraints than ever on possible extensions of the Standard Model.

**Acknowledgments**

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**References**


Heavy-flavour results in pp collisions at LHC with ALICE

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1 Introduction

Open heavy-flavour measurements at LHC are an important test of pQCD calculations based on the factorization approach in a new energy domain. They provide also a baseline reference for heavy-ion collisions, where the heavy quarks produced in the early stages of the interactions are used to probe and characterize strongly interacting matter produced at high energy density and temperature.

The ALICE detector [1] has good performance and specific detector characteristics to study open heavy flavour hadrons and quarkonia, at central and forward rapidities, thanks to its low momentum reach, particle identification capabilities and precise vertexing.

Open heavy flavour production is measured using semileptonic decays to electrons and muons or hadronic decays from charm mesons ($D^0$, $D^+$, $D^{*+}$ and $D_s$) at central rapidity. Recent results from measurements in pp collisions at different centre of mass energy (at $\sqrt{s} = 7$ TeV and 2.76 TeV) are presented.

2 Detector and data sample

A detailed description of the ALICE detector can be found elsewhere [1]. We highlight here only the key sub-detectors employed in heavy-flavour analyses. In the barrel region, the Inner Tracking System (ITS) is the detector closest to the beam pipe and comprises three detector layers, each using a different silicon technology. In the radial direction at $\eta < 0.9$ the material budget is only 7.7% $X_0$. This feature, coupled with a moderate (0.5 T) field in the barrel region, provides excellent coverage at low $p_T$. The vertex resolution is below 100 $\mu$m at low multiplicity. At mid-rapidity ($|\eta| < 0.9$) ALICE has powerful particle identification capabilities by means of its Time Projection Chamber (TPC), Transition Radiation Detector (TRD) and Time Of Flight (TOF) detectors, allowing the track by track identification of pions and kaons up to 2.5 GeV/$c$ momentum and electrons up to 8 GeV/$c$. Electron identification is also provided by the electromagnetic calorimeter (EMCAL). Coupled with tracking reconstruction based on its large TPC, in the barrel region ALICE identifies exclusive hadronic decay channels of charmed hadrons and semi-leptonic decays to electrons. Muons are identified via the forward muon spectrometer in the pseudorapidity range $2.5 < \eta < 4$.

The results presented here are based on pp data samples collected at $\sqrt{s} = 7$ TeV in 2010 and at $\sqrt{s} = 2.76$ TeV in 2011 with a minimum bias trigger based on ITS and V0 detectors (a scintillator array close to the beam pipe). The two data samples correspond, respectively, to an integrated luminosity $L_{\text{int}} = 5$ nb$^{-1}$ and $L_{\text{int}} = 1.1$ nb$^{-1}$.
3 Hadronic decays of D mesons

The measurement of charm production is carried out in ALICE through different channels (D⁰ → K⁻π⁺, D⁺ → K⁻π⁺π⁻, D⁺(2010)+ → D⁰π⁺ and Dₙ → φπ⁺) and results have been already published for three decay modes of D mesons, together with their charge conjugates at different center of mass energies [2, 3]. The ITS resolution allows for the identification of secondary vertices displaced few hundred μm from the primary vertex as the ones associated to D⁰ and D⁺ mesons (their mean proper decay lengths are cτ ≈ 123 and 312 μm respectively). The analysis strategy is based on the selection and reconstruction of secondary vertex topologies to reduce the large combinatorial background. The identification of charged kaons in the TPC and the TOF allow for further reduction of the background at low p_T.

The p_T-differential inclusive cross sections for prompt D⁰, D⁺ and D⁺⁺ are shown in Fig. 1. The feed-down from B mesons decays (about 10-15%) is subtracted using pQCD calculations. The cross sections are well described by two pQCD-based predictions [4, 5].

The extrapolation of the D cross sections to the full phase space allows us to measure the total charm production cross section at LHC energies. A comparison with other measurements is shown in Fig. 2, where ALICE results at \( \sqrt{s}=2.76 \text{ TeV} \) [3] and 7 TeV [2] are shown. While a satisfactory agreement among LHC experiments is achieved, it may be noted that all points populate upper side of the theoretical predictions, which is based on NLO MNR calculations [6].

A measurement [7] of the total b̅b cross section production was also obtained. Other exclusive channels studied at ALICE include Dₙ → φπ⁺ [8]. The study of the production rate of Dₙ with respect to non-strange D mesons allows for the investigation of the c fragmentation functions to strange and non-strange mesons.

![Figure 1](image-url)

**Figure 1:** p_T-differential inclusive cross section for prompt D⁰, D⁺ and D⁺⁺ mesons for |y| < 0.5 in pp collisions at \( \sqrt{s} = 7 \text{ TeV} \) [2], compared with FONLL [4] and GM-VFNS [5] theoretical calculations. The symbols are positioned horizontally at the centre of each p_T interval. The normalization uncertainty is not shown (3.5% from the minimum-bias cross section plus the branching ratio uncertainties).
Figure 2: Energy dependence of the total nucleon nucleon charm production cross section [3]. The NLO MNR calculation (and its uncertainties) is represented by solid (dashed) lines.

Figure 3: Invariant differential production cross sections of electrons from heavy-flavour decays measured by ALICE [9] and ATLAS [10] in pp collisions at \( \sqrt{s} = 7 \) TeV in different rapidity intervals. FONLL pQCD calculations with the same rapidity selections are shown for comparison.

4 Semi-leptonic decays of heavy-flavour quarks

Inclusive electron spectra coming from heavy-flavour decays have been measured at LHC energies by ATLAS in the \( 7 < p_T < 26 \) GeV/c range [10]. The above mentioned features allow ALICE to make that measurement at a much lower momentum. Electrons are identified thanks to the energy deposit in the TPC and the timing in the TOF below 4 GeV/c. At higher momenta additional cuts are applied making use of the TRD and the EMCAL detector information. The selection of tracks results in an almost pure sample of electrons with a remaining hadron contamination of less than 2% over the full \( p_T \) range. The heavy-flavour electron spectrum [9] is then obtained on a statistical basis by subtracting a cocktail of background electrons from the inclusive electron spectrum. Systematic uncertainties on the measured electron spectrum due to the electron cocktail amount to 10%. Figure 3 shows the ALICE measurement, which includes most of the total cross section, together with ATLAS data [10], which extend the measurement at high \( p_T \). Electrons from beauty decays are instead identified through displaced vertices [11] exploiting the large \( cT \) for B mesons (\( \approx 500 \) µm) or extracting the b-component from \( \Delta\phi \) electron-hadron correlation studies.

Single muons from heavy-flavour decays are studied at forward rapidity in ALICE using the forward muon spectrometer. The subtraction of the background component from decay muons (muons from primary pion and kaon decays, mainly) is based on simulations. Figure 4 shows the measured cross section at \( \sqrt{s} = 7 \) TeV [12], as a function of \( p_T \) and rapidity, compared to FONLL calculations. The measurement was also made at \( \sqrt{s} = 2.76 \) TeV.
Figure 4: $p_T$-differential (left) and $y$-differential (right) production cross section of muons from heavy-flavour decays [12]. In both panels, the error bars (empty boxes) represent the statistical uncertainties. The solid curves are FONLL calculations and the bands display the theoretical uncertainties. The FONLL calculations and systematic theoretical uncertainties for muons from charm and beauty decays are also shown.

5 Conclusions

Since the start of LHC operations, ALICE has produced a wide range of results related to heavy-flavour production in pp collisions at $\sqrt{s}=7$ and 2.76 TeV center of mass energies. Within uncertainties, both FONLL and GM-VFNS describe well data. Besides the interest to achieve a baseline reference for heavy-ion studies, production cross sections for c and b quarks have been measured in a broad rapidity range and at very low momentum down to $p_T=1-2$ GeV/c, thus complementing measurements performed by other LHC detectors. Applying these analysis techniques to forthcoming pPb data will allow for the investigation of possible nuclear modifications of the parton distribution functions.

References

Mixing and CP Violation in the B System

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The following sections summarize analyses of the measurement of the CP-violating weak phase $\phi_s$ in the $B_s^0 \rightarrow J/\psi \phi$ [1] and $B_s^0 \rightarrow J/\psi \pi^+\pi^-$ decays [2] (including the resolution of the ambiguity of $\phi_s$ associated with the sign of the decay width difference in the $B_s^0$ system [3]). Also presented is the time-integrated analysis of the $B_s^0 \rightarrow (\phi \rightarrow KK)$ ($\phi \rightarrow KK$) decay including the $T$-violating triple product asymmetries [4]. All analyses discussed are based on the full 2011 dataset of 1.0 fb$^{-1}$ collected with the LHCb detector at centre-of-mass (COM) energy $\sqrt{s} = 7$ TeV.

1 Direct $\phi_s$ Measurements

1.1 The $B_s^0 \rightarrow J/\psi \phi$ Analysis Method

The $B_s^0 \rightarrow J/\psi \phi$ decay is selected using a cut based method described in Aaij et al. (2011) [5]. This results in $\sim 21200$ signal events with low background. The decay time resolution of the $B_s^0 \rightarrow J/\psi \phi$ decay is accounted for in fitting through convolution of the probably density function (PDF) with a Gaussian function of width $S_i \sigma_t \cdot \sigma_i$, where $\sigma_i$ is the event-by-event decay time resolution of the $i^{th}$ event (determined from vertex and decay length uncertainty); $S_i$ is determined from prompt $J/\psi \rightarrow \mu^+\mu^-$ events to be $1.45 \pm 0.06$, where errors are both systematic (derived from simulation) and statistical.

Decay time acceptance effects due to time-biasing cuts used to select $J/\psi \rightarrow \mu^+\mu^-$ events are determined with the assistance of a prescaled, unbiased trigger. A small drop in acceptance is also seen at longer lifetimes due to the lower track finding efficiencies associated with tracks from vertices far from the beam line. A correction on $\Gamma_s$ is found from simulation to be $0.0112 \pm 0.0013$ ps$^{-1}$. Half of this value is applied as a systematic uncertainty.

The efficiency of reconstructing a $B_s^0 \rightarrow J/\psi \phi$ event also depends on the decay angles in the transversity basis (described in detail in Reference [5]). The correction applied in the fit is found using Monte Carlo $B_s^0 \rightarrow J/\psi \phi$ events. The difference in the spectra of kinematic observables of the tracks in simulated events compared to that observed in the data in addition to the limited quantity of simulated events are used to determine associated systematic uncertainties.
The sensitivity of the fit to the weak phase $\phi_s$ is greatly enhanced through the ability to determine the flavour of the $B^0_s$ meson when it is produced. The methods of determination of the flavour and associated uncertainties are described in detail in Reference [5].

1.2 The $B^0_s \to J/\psi \pi\pi$ Analysis Method

The analysis of the $B^0_s \to J/\psi \pi^+\pi^-$ decay [2] updates a previous study on the $B^0_s \to J/\psi f_0(980)$ decay [6] using the fact that the $775 < m(\pi^+\pi^-) < 1500$ MeV/c$^2$ invariant mass range is 97.5% CP-odd at 95% C.L. [7]. This then allows for $\phi_s$ to be measured without the need to disentangle CP eigenstates. As such, a fit to the decay time is sufficient to measure $\phi_s$. The tagging method and time resolution methods are the same as those used for the $B^0_s \to J/\psi \phi$ decay.

1.3 Results

Both the $B^0_s \to J/\psi \phi$ and $B^0_s \to J/\psi \pi^+\pi^-$ analyses utilize unbinned maximum log-likelihood fitting methods in the measurement of the weak phase $\phi_s$. A number of physics parameters are measured at the same time as $\phi_s$ in the analysis of the $B^0_s \to J/\psi \phi$ decay. These are the decay width ($\Gamma_s$), the decay width difference between the two $B^0_s$ mass eigenstates ($\Delta \Gamma_s$) and the polarization amplitudes of the P-wave ($|A_0|^2$, $|A_\parallel|^2$, $|A_\perp|^2$) and S-wave ($|A_S|^2$) contributions along with corresponding phases $^1$ ($\delta_0$, $\delta_\parallel$, $\delta_\perp$, $\delta_S$) defined at $t = 0$. Normalization is chosen such that $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$. In fits the $B^0_s$ oscillation frequency $\Delta m_s$ is constrained within errors of the LHCb measured value [8].

The results of the fit in the $B^0_s \to J/\psi \phi$ decay are given in Table 1. The 68% C.L. is quoted for $\delta_\parallel$ as the likelihood is not parabolic about the minimum for this parameter. This is due to the central value lying close to the ambiguous solution found through the transformation $\delta_\parallel \to -\delta_\parallel + 2\pi$.

In addition to the uncertainties discussed in Section 1.1, the only other dominant contribution is that of direct CP violation (DCPV), which is understood from simplified simulations. The uncertainties for tagging calibration, time resolution and $B^0_s$ oscillation frequency are included in the fit using Gaussian constraints within their uncertainties. Studies have shown that these inflate the statistical uncertainty on $\phi_s$ by no more than 5%.

The result of the measurement of the weak phase $\phi_s$ in the $B^0_s \to J/\psi \pi^+\pi^-$ decay is found to be $\phi_s = -0.02 \pm 0.17 \pm 0.02$ rad [2]. The systematic uncertainties arising from time resolution, time acceptance and tagging are treated in the same way as in the analysis of the $B^0_s \to J/\psi \phi$ decay.

$^1$The convention has been chosen such that $\delta_0 \equiv 0$. 

2
Both the analysis of the $B^0_s \to J/\psi \phi$ decay and the $B^0_s \to J/\psi \pi^+ \pi^-$ decay contain an ambiguity in the results associated with the transformations ($\phi_s \leftrightarrow \pi - \phi_s$; $\Delta \Gamma_s \leftrightarrow -\Delta \Gamma_s$) and associated strong phase changes [3]. This ambiguity has been resolved through measuring the difference in P-wave and S-wave strong phases in different $K\bar{K}$ invariant mass bins. Through the separation in to four bins chosen to have roughly equal numbers of events, a negative trend of strong phase difference is observed with increasing $K\bar{K}$ invariant mass with significance of $4.7\sigma$. This therefore implies that $\Delta \Gamma_s > 0$, hence only this result has been quoted throughout these Proceedings.

## 2 Time-integrated Analysis of the $B^0_s \to \phi \phi$ Decay

The $B^0_s \to \phi \phi$ decay is an example of a flavour changing neutral current (FCNC) interaction and as such, may only proceed via penguin diagrams in the Standard Model. A total of $801 \pm 29$ signal candidates are observed through a cut based selection optimized with the use of the $sPlot$ method [9] to distinguish signal from background.

The measurement of the polarization amplitudes ($|A_0|^2$, $|A_\parallel|^2$, $|A_\perp|^2$) and strong phase difference ($\cos \delta_\parallel$) is performed using a time-integrated, untagged PDF under the assumption that the time acceptance is uniform and that the $CP$-violating weak phase is zero. A maximum log-likelihood fit is then performed to the three helicity angles (see Reference [4] for more information). The lifetimes of the heavy and light $B^0_s$ mass eigenstates are constrained to be within the errors of the LHCb measured values [2] taking in to account correlations. S-wave contributions are ignored in the fit. Data-driven methods indicate the S-wave contribution to be $(1 \pm 1)\%$, therefore
systematic uncertainties are based on a 2% S-wave contribution. The angular acceptance is determined from simulated events. The limited number of simulated events determines the systematic uncertainty due to the angular acceptance. The time acceptance is understood from Monte Carlo events and simplified simulations are used to assign a systematic uncertainty from the assumption that it is uniform. The other major source of systematic uncertainty arises from the background model, where a background histogram from mass sidebands (defined to be between 60-150 MeV/$c^2$ away from the measured $B_s^0$ mass) is used instead of the nominal flat angular background. The polarization amplitudes and strong phase difference are measured to be

\[
|A_0|^2 = 0.365 \pm 0.022 \text{(stat)} \pm 0.012 \text{(syst)}, \\
|A_{\perp}|^2 = 0.291 \pm 0.024 \text{(stat)} \pm 0.010 \text{(syst)}, \\
|A_{\parallel}|^2 = 0.344 \pm 0.024 \text{(stat)} \pm 0.014 \text{(syst)}, \\
\cos(\delta_{\parallel}) = -0.844 \pm 0.068 \text{(stat)} \pm 0.029 \text{(syst)}.
\]

Triple product asymmetries are based on T-odd observables $U$ and $V$ (defined in Reference [4]). Events are separated into datasets according to whether $U(V) > 0$ and a simultaneous fit is then performed to obtain the asymmetries $(A_U, A_V)$ using the $KKKK$ invariant mass as the discriminating observable.

The main systematic uncertainties arise from the choice of signal and background model; the effect of ignoring the time acceptance and the angular acceptance of the $B_s^0 \to \phi\phi$ decay. The systematic uncertainties on the triple product asymmetries due to acceptance effects are estimated using simplified simulation studies (where both the time and angular acceptances are understood from simulated events).

Simultaneous fits to the $U(V)$ datasets yield triple product asymmetries of

\[
A_U = -0.055 \pm 0.036 \text{(stat)} \pm 0.018 \text{(syst)}, \\
A_V = 0.010 \pm 0.036 \text{(stat)} \pm 0.018 \text{(syst)}.
\]

### 3 Summary

Direct measurements of the $CP$-violating weak phase have been measured using the full 2011 dataset collected with the LHCb detector at $\sqrt{s} = 7$ TeV. The combination of $\sim 21200 \ B_s^0 \to J/\psi\phi$ decays and $\sim 7420 \ B_s^0 \to J/\psi\pi^+\pi^-$ decays yields a measurement of $\phi_s = -0.002 \pm 0.083 \text{(stat)} \pm 0.027 \text{(syst)}$ rad. This therefore provides the world’s most precise measurement of $\phi_s$. Also, it is worth mentioning that we observe the first measurement of $\Delta\Gamma_s$ different from zero and have resolved the ambiguity in the $\phi_s - \Delta\Gamma_s$ plane, i.e. that the heavy $B_s^0$ mass eigenstate lives longer.

We provide the most accurate measurements of the physics parameters in the $B_s^0 \to \phi\phi$ penguin decay. The most precise measurements of $CP$ violation in the $B_s^0 \to \phi\phi$ decay through triple product asymmetries is also reported.
References

CP Violation in Hadronic B Decays at LHCb

Daniel Johnson, University of Oxford, on behalf of the LHCb collaboration

This article describes measurements of CP violation in charmed tree-level and charmless loop-level decays of B mesons. Comparison between these two classes of decay is interesting given the potential for new physics effects appearing in loops and enhancing or suppressing the level of observed CP violation. Firstly a study in tree-level $B^\pm \to [hh']D K^\pm$ decays is presented, along with the progress towards a precise measurement of the CKM phase $\gamma$ at LHCb. Secondly an analysis of $B^0_{(s)} \to hh'$ decays is described where loop diagrams can contribute. The analyses exploit data recorded by the LHCb detector, a forward spectrometer with excellent tracking capability and the ability to distinguish pions and kaons using the Ring Imaging Cherenkov (RICH) detectors.

1 CP violation in tree-level $B^\pm \to [hh']D K^\pm$

Standard Model CP violation is parameterised entirely by complex phases in the Cabibbo Kobayashi Maskawa (CKM) matrix. The least well known of these is $\gamma$ which can be measured with low theoretical uncertainty by studying interference between the amplitudes for $B^\pm \to D^0 K^\pm$ and $B^\pm \to \overline{D}^0 K^\pm$ decay processes where the intermediate neutral $D$ meson decays to a common final state $F$, labelled by $[F]_D$. The complex phase between the two $B^\pm$ decay amplitudes is the sum or difference of the strong and weak phases, $\delta_B$ and $\gamma$ respectively. Studies where the $D$ meson decays to a non-CP eigenstate have been described in the proceedings for my poster at this conference entitled ‘Observation of CP Violation in $B^\pm \to D K^\pm$ Decays at LHCb’. In this section I concentrate only on decays of the $D$ meson to CP eigenstates $(D^0 \to K^+ K^-, \pi^+ \pi^-)$ in a GLW analysis [2]. The observables with sensitivity to $\gamma$ are $R_{CP}^+ = \frac{\Gamma(B^+ \to [K^+ K^-]_D K^\pm)}{\Gamma(B^+ \to [K^+ \pi^\pm]_D K^\pm)}$ and $A_{CP}^+ = \frac{\Gamma(B^- \to D_{CP} K^\mp) - \Gamma(B^+ \to D_{CP} K^\mp)}{\Gamma(B^- \to D_{CP} K^\mp) + \Gamma(B^+ \to D_{CP} K^\mp)}$ where $D_{CP}$ denotes a $D$ meson reconstructed in a final state of known CP. These observables depend on $\gamma$ e.g. $A_{CP}^\pm = \frac{\pm2r_B \sin(\delta_B) \sin(\gamma)}{R_{CP}^\pm}$.

Candidates were selected from the full 2011 1 fb$^{-1}$ LHCb data set, as described in the poster proceedings referred to earlier. The invariant mass spectra of the $B^\pm \to (K^+ K^-)_D K^\pm$ and $B^\pm \to (\pi^+ \pi^-)_D K^\pm$ are shown in Figure 1 along with the more prevalent $B^\pm \to D\pi^\pm$ mode used in each case to control aspects of the signal fit. A charge asymmetry is clearly visible in the sizes of the $B^\pm \to DK^\pm$ signals which translates to the following results for the CP observables where the first
uncertainty is statistical and the second is systematic: $R_{CP^+} = 1.007 \pm 0.038 \pm 0.012$ and $A_{CP^+} = 0.145 \pm 0.032 \pm 0.010$. In these results the dominant source of systematic uncertainty is the knowledge of the $B^\pm$ production asymmetries and the kaon and pion detection asymmetries.

Put together, the significance of the CP violation observed is $4.5\sigma$ and, combined with the results in the ADS final state, CP violation is observed at the level of $5.8\sigma$. It is interesting to note that the $B^\pm \to [\pi^\pm K^\mp]_D \pi^\pm$ ADS mode showed a hint of CP violation at the level of $2.4\sigma$ ($R_{ADS(\pi)} = 0.00410 \pm 0.00025 \pm 0.00005$ and $A_{ADS(\pi)} = 0.143 \pm 0.062 \pm 0.011$) where little is expected, but the importance of this effect will be clearer in future analyses.

The ADS and GLW measurements are compatible and competitive with the current world averages [3] and have been combined with analyses of other $D$ final states ($[K^0_S\pi^+\pi^-]_D, [K^0_S K^+ K^-]_D$ [4] and $[K^\pm \pi^+ \pi^+ \pi^-]_D$ [5]) to make a measurement of the CKM phase $\gamma$ using LHCb data [6].

![Figure 1: Invariant mass spectrum from GLW modes with $B^\pm \to DK^\pm$ signal (solid red line) and $B^\pm \to D\pi^\pm$ control (solid green line) [2].](image)

2 CP violation in loop-level $B^0_{(s)} \to hh'$

CP violation studies in two body $B^0_{(s)}$ decays are of great interest. CP violation has not yet been observed in the $B^0_s$ system and studies of charmless $B$ decays have potential sensitivity to new physics effects which could modify the observed level of CP violation [7]. Time dependent analyses of $B^0 \to \pi^+ \pi^-$ have been undertaken at BaBar [8] and Belle [9] but not all the results are in good agreement, motivating further study. The studies outlined here also allow a test of U-spin symmetry breaking. Two CP violation analyses of LHCb data taken in 2011 are described: a time-integrated study of $B^0_{(s)} \to K\pi$ decays (0.35 fb$^{-1}$) [10] and a time-dependent analysis of $B^0 \to \pi^+ \pi^-$ and $B^0_{(s)} \to K^+ K^-$ decays (0.69 fb$^{-1}$) [11].
In the first analysis, the measured observable is 

$$A_{CP} = \frac{\Gamma(B^0\rightarrow f_s) - \Gamma(B^0\rightarrow f)}{\Gamma(B^0\rightarrow f_s) + \Gamma(B^0\rightarrow f)}$$

where $f = K^+\pi^-,$ $f_s = K^-\pi^+.$ The invariant mass spectra of the selected $B^0(\bar{s})$ candidates display a clear raw asymmetry. The CP asymmetries extracted are $A_{CP}(B^0) = -0.088 \pm 0.011(stat) \pm 0.008(syst)$ and $A_{CP}(B^0_s) = 0.27 \pm 0.08(stat) \pm 0.02(syst)$ where the dominant systematic uncertainty originates from the knowledge of the production and detection asymmetries. This is the most precise measurement of CP violation in $B^0 \rightarrow K\pi$ decays, with a significance of greater than $6\sigma,$ and is the first evidence of CP violation in $B^0_s \rightarrow K\pi$ decays, with a significance of $3.3\sigma.$

The time-dependent asymmetries in $B^0 \rightarrow \pi^+\pi^-$ and $B^0_s \rightarrow K^+K^-$ are given by

$$A(t) = \frac{\Gamma(t)(B^0\rightarrow h^+h^-) - \Gamma(t)(B^0\rightarrow h^+h^-)}{\Gamma(t)(B^0\rightarrow h^+h^-) + \Gamma(t)(B^0\rightarrow h^+h^-)} = \frac{A^{dir}\cos(\Delta mt) + A^{mix}\sin(\Delta mt)}{\cosh(\frac{\Delta m}{2}) - A^{dir}\sinh(\frac{\Delta m}{2}) + t},$$

where $A^{dir}$ and $A^{mix}$ are the asymmetries originating from direct CP violation and from the interference between mixing and decay. In this analysis the abundant and kinematically similar mode $B^0 \rightarrow K\pi$ was used to determine the mis-tag rate and to account for the production asymmetry. A two dimensional fit to the invariant mass and $B^0_s$ decay time was then performed to determine the asymmetry (Figure 2 for $B^0_s \rightarrow K^+K^-$).

![Figure 2](image_url)

**Figure 2:** From left to right: $B^0_s \rightarrow K^+K^-$ invariant mass distribution, $B^0_s \rightarrow K^+K^-$ decay time distribution and measured raw asymmetry.

In the $\pi^+\pi^-$ mode the measurement of $A^{dir}$ was $0.11 \pm 0.21(stat) \pm 0.03(syst)$ which lies closer to the central value measured by BaBar [8]. In $\pi^+\pi^-,$ $A^{mix} = -0.56 \pm 0.17(stat) \pm 0.03(syst).$ In the $K^+K^-$ mode, the results were $A^{dir} = 0.02 \pm 0.18(stat) \pm 0.04(syst)$ which, as predicted by U-spin symmetry once bounds are placed on certain exchange/annihilation diagrams [12], is compatible with the time integrated asymmetry in $B^0 \rightarrow K\pi$ presented earlier, and $A^{mix} = 0.17 \pm 0.18(stat) \pm 0.05(syst).$ These results form the the first CP violation investigation in $B^0_s \rightarrow K^+K^-.$
3 Conclusion and outlook

Analyses in tree-level $B^\pm \to [hh']_D K^\pm$ and in loop-level $B^{0}_{(s)} \to hh'$ decays have been described, demonstrating the capabilities of the LHCb experiment in undertaking CP violation studies in hadronic $B$ decay modes. The former has been used in a tree-level LHCb measurement of the CKM phase $\gamma$ with a low theoretical uncertainty. The charmless modes are also sensitive to the phase $\gamma$ and future comparison between measurements in the two categories of decay (charmed and charmless) may yield sensitivity to new physics effects entering charmless loop processes. Analysis of the full 2011 and 2012 LHCb data sets is awaited with great interest.

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References


Charm mixing and CP violation at LHCb

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1 Introduction

LHCb [1], an experiment at the Large Hadron Collider (LHC), is dedicated to the study of b and c flavour physics. The abundance of charm particles produced in LHC offers an unprecedented opportunity for high precision measurements in the c sector, including measurements of CP violation and $D^0 - \bar{D}^0$ mixing. The high performance of LHCb detectors allows this potential to be fully exploited.

The charm sector is a promising field to probe for the effects of physics beyond the Standard Model (SM). The CP violation is expected to be small in the SM, while it can be enhanced by contribution from New Physics [3, 4]. Two measurements at the LHCb experiment are presented here: a measurement of time-integrated CP violation and measurements of time-dependent CP violation and mixing in two body $D^0$ decays.

2 Measurement of time-dependent CP violation in $D^0$ mixing

A measurement of CP violation in $D^0$ mixing can be performed in the study of two-body hadronic charm decays. It can be evaluated by the asymmetry of the proper-time ($\tau$) of flavour-tagged decays to which both the direct and indirect CP violation could play a role [2];

$$A_\Gamma \equiv \frac{\tau(D^0 \rightarrow K^-K^+) - \tau(D^0 \rightarrow K^-K^+)}{\tau(D^0 \rightarrow K^-K^+) + \tau(D^0 \rightarrow K^-K^+)} \approx \frac{1}{2} (A_m + A_d) y \cos\phi - x \sin\phi, \quad (1)$$

where $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/2\Gamma$ are the mixing parameters, $\phi$ is the CP violating weak phase, $A_m$ represents a CP violation contribution from mixing and $A_d$ from direct CP violation.
Figure 1: $\ln(\chi^2_{IP})$ fit projection, on the left, and lifetime fit projection, on the right, of $D^0 \to K^- K^+$ candidates on a logarithmic scale. The data are shown as points, the total fit (green), the prompt signal (blue), and the secondary signal (brown).

The flavour tagging of $D^0$ decays is obtained by reconstructing the decay $D^{*+} \to D^0 \pi^+_s$, where the charge of the slow pion ($\pi^+_s$) determines the flavour of the $D^0$ at the production. The trigger selection for heavy flavour decays reduces significantly the background, but it unavoidably biases the proper time distribution. A correction of these lifetime biasing effects is needed to properly extract $A_F$ via absolute lifetime measurements. This analysis uses a data driven approach to evaluate the proper time acceptance, that describes the selection efficiency as a function of the $D^0$ proper time: the so-called ‘swimming’ method [5, 6, 7, 8]. The signal yield and the background contribution are extracted from fits to the reconstructed invariant mass. The main component of the remaining background is due to the secondary charm, i.e. $D$ mesons produced from $b$ hadron decays. This kind of background, indistinguishable by the invariant mass distribution, would bias the proper time measurements. A statistic separation is applied in the fit procedure using the variable $\ln(\chi^2_{IP})$\(^1\) and its time dependency. The lifetime measurement is obtained by a simultaneous fit of proper time and $\ln(\chi^2_{IP})$ including the acceptance function evaluated by the swimming method.

The measured lifetime is an effective lifetime since the fitted distribution includes also mistagged events, in which the $D^0$ is associated with a random slow pion. The mistag rate is evaluated by the fit of the difference between the mass of $D^*$ and $D^0$ to be 1.8%. This has been taken in account in the evaluation of $A_F$.

This measurement is based on a data sample equivalent to 0.03 fb\(^{-1}\) taken in 2010. The number of candidates selected is about 15k for each flavour tag, $D^0$ and $\bar{D}^0$. The results of the $\ln(\chi^2_{IP})$ and lifetime fit for $D^0 \to K^- K^+$ decays are

\(^1\)The IP is the minimum distance of approach with respect to the primary vertex. The $\chi^2_{IP}$ is formed by using the hypothesis that the IP is equal to zero.
The asymmetry is evaluated from these lifetimes to be \( A_T = (−5.9 \pm 5.9_{\text{stat}} \pm 2.1_{\text{syst}}) \times 10^{-3} \) [8]. This result is consistent with zero and hence shows no evidence of CP violation and it is in agreement with the current world average [9]. The main contributions to the systematic error are due to neglecting the combinatorial background and to the separation of prompt and secondary charm decays. The systematic uncertainty is expected to be significantly reduced by an improved treatment of the background events, which will be possible for a larger data sample.

### 3 Search for CP asymmetry in the time integrated two body \( D^0 \) decays

The time integrated asymmetry for a \( D^0 \) final state \((f)\) is defined as

\[
A_{\text{RAW}}(f) = \frac{N(D^0(f)) - N(D^0(\bar{f}))}{N(D^0(f)) + N(D^0(\bar{f}))} = \frac{N(D^+ (D^0(f)\pi^+)) - N(D^+ (\overline{D^0} f\pi^-))}{N(D^+ (D^0(f)\pi^+)) + N(D^+ (\overline{D^0} f\pi^-))},
\]

where \( N(X) \) refers to the number of reconstructed events of decay \( X \) after background subtraction. The \( D^0 \) flavour is determined by the slow pion tagging method explained above.

The raw asymmetries may be written as a sum of various components, coming from both physics and detector effects:

\[
A_{\text{RAW}}(f)^* = A_{\text{CP}}(f) + A_P(D^*) + A_D(D^0) + A_D(\pi_s),
\]

where \( A_{\text{CP}}(f) \) is the physics CP asymmetry, \( A_P(D^*) \) the production asymmetry, \( A_D(D^0) \) and \( A_D(\pi_s) \) the detection asymmetry of the \( D^0 \) and of the slow pion.

Taking the asymmetry difference of the two final state, i.e. \( D^0 \to KK \) and \( D^0 \to \pi\pi \), the production and soft pion detection asymmetries will cancel. Moreover, for a two body decay of a spin-0 particle to a self-conjugate final state as in this case, there is no \( D^0 \) detector efficiency asymmetry contribution. No dependence remains on production or detection efficiencies, so this observable is extremely robust against systematic biases: \( \Delta A_{\text{RAW}} = A_{\text{RAW}}(KK) - A_{\text{RAW}}(\pi\pi) = A_{\text{CP}}(KK) - A_{\text{CP}}(\pi\pi) \).

In a proton-proton collider, the production of heavy-flavour hadrons could not be CP symmetric in a given region of phase space. Possible variations of both selection efficiency and production and detection asymmetry as a function of \( p_T \) and \( \eta \) could generate second-order yield asymmetries that do not cancel out. \( A_{\text{RAW}} \) extraction is performed in bins of \( \eta \) and \( p_T \). A binned maximum likelihood fit to the spectrum of the mass difference between \( D^* \) and \( D^0 \) (\( \delta_m \)) is used to evaluate the yields. Examples of the fit are shown in Fig. 2.

Systematic uncertainties are assigned by repeating the analysis with an alternative description of the mass spectra lineshapes; with different fit windows for the \( D^0 \) mass; selecting events with only one candidate; varying the possible contribution of peaking background; comparing with the result obtained with different kinematic binning
Figure 2: Fits to the $\delta m$ spectra of $D^0 \rightarrow K^- K^+$ candidates (a) and of $D^0 \rightarrow \pi^- \pi^+$ candidates (b), with mass lying in the window between 1844 and 1884 MeV/c$^2$. The dashed line corresponds to the background component in the fit.

and with different fiducial cuts. The full change in result is taken as a systematic uncertainty and all uncertainties are added in quadrature.

The analysed data sample has an integrate luminosity of 0.6 fb$^{-1}$ with a total signal yield of 1.8M tagged $D^0 \rightarrow K^- K^+$ and 381k tagged $D^0 \rightarrow \pi^- \pi^+$ candidates. A value of $\Delta A_{CP}$ is determined in each measurement bin using the result from $A_{RAW}(K^- K^+)$ and $A_{RAW}(\pi^- \pi^+)$. These values are found to be consistent throughout the $(p_T, \eta)$ space, as well as for the different time periods and for both settings of the magnet polarity. A weighted average is therefore performed to yield the result $\Delta A_{CP} = (-0.82 \pm 0.21_{\text{stat}} \pm 0.11_{\text{syst}})\%$ [10]. This results to be the first evidence of CP violation in charm with a significance of 3.5 $\sigma$.

4 Conclusions

First evidence for CP violation in the charm sector has been observed by LHCb in the measurements of the integrated CP asymmetry. This measurement and the other searches of CP violation are obtained with only a sub-sample of data collected by LHCb experiment. Significant improvements in the precision up to per mille level are expected with the large data set collected in 2011 and in 2012 with an expected total integrated luminosity of about 3 fb$^{-1}$. In addition to these measurements, many others are under way, e.g. in 2-body decays the measurement of the mixing parameters using doubly Cabibbo-suppressed $D^0 \rightarrow K^+ \pi^-$ decays. These results will allow to establish if and which New Physics effects are playing a role in the charm sector.
References

Rare decays at LHCb

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Rare leptonic and semileptonic decays are studied using 1.0 fb$^{-1}$ of $pp$ collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV collected by the LHCb experiment [1] in 2011. Branching fractions measurements, angular distributions and isospin asymmetries are presented using this data sample.

1 Introduction

Rare decays are excellent tests to infer the presence of physics beyond the Standard Model (BSM), as they occur through processes prohibited at tree level in the SM. Any deviation from the SM prediction in branching fraction or angular distributions of such decays can lead to indications of new physics.

2 Branching fraction measurements of $B^0_{(s)} \to \mu^+\mu^-$

The SM predictions for the branching fractions of the decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are small and have a low uncertainty: $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ and $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (0.10 \pm 0.01) \times 10^{-9}$ [2]. Taking into account the oscillation of the $B^0_s$ system, the time integrated branching fraction is evaluated to be [3]: $\mathcal{B}(B^0_s \to \mu^+\mu^-) = 3.4 \times 10^{-9}$. However, these values can be significantly enhanced within Minimal Supersymmetric extensions of the SM (MSSM) [4] due to contributions from new processes or new heavy particles. The LHCb results are the most constraining limits [5] on these branching fractions obtained with a single experiment to date at 95% C.L.: $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.0 \times 10^{-10}$.

3 Branching fraction measurement of $D^0 \to \mu^+\mu^-$

The decay $D^0 \to \mu^+\mu^-$ is very rare in the SM: $10^{-13} < \mathcal{B}(D^0 \to \mu^+\mu^-) < 6 \times 10^{-11}$ [6]. In the context of MSSM scenarios with R parity violation, the predicted branching fractions can be largely enhanced [7]. The LHCb measurement of the branching fraction of this decay is [8] $\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.3 \times 10^{-8}$ at 95% C.L., which is the world best limit to date.
4 Branching fraction measurement of $\tau^- \rightarrow \mu^- \mu^+ \mu^-$

The branching fraction of the decay $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ is extremely suppressed in the SM. In New Physics models this branching fraction can be substantially enhanced. For instance, in the context of Little Higgs models $\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 10^{-7}$ [9]. The LHCb measurement of this branching fraction ($\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 7.8 \times 10^{-8}$ at 95% C.L.) [10] is comparable with the current best limits.

5 Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

The angular distribution of the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay can be described with several $q^2$-dependent parameters that are predicted in the SM [11] with high precision: $A_{FB}$, $F_L$, $S_3$, and $A_{IM}$. The LHCb measurements of these quantities [12] show no deviation from the SM predictions, and are the most precise measurements to date. Figure 1 shows the LHCb result for $A_{FB}$ with the SM prediction superimposed.

The region where the forward-backward asymmetry changes sign, known as zero-crossing point ($q_0^2$), is predicted to lie in the range $[4.0 < q_0^2 < 4.3 \text{ GeV}^2/c^4]$ [13]. LHCb has measured for the first time the zero-crossing point $q_0^2 = 4.9^{+1.1}_{-1.3} \text{ GeV}^2/c^4$, which agrees with the SM predictions (Figure 1).

Figure 1: Forward-backward asymmetry of the di-muon pair (left) and zero-crossing point (right).
6 Isospin asymmetry of $B \to K^{(*)}\mu^+\mu^-$

The isospin asymmetry of the decays $B \to K\mu^+\mu^-$ and $B \to K^{(*)}\mu^+\mu^-$ is defined as:

$$A_I \equiv \frac{B(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_\pm} B(B^\pm \to K^{(*)}\pm\mu^+\mu^-)}{B(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_\pm} B(B^\pm \to K^{(*)}\pm\mu^+\mu^-)},$$

where $\frac{\tau_0}{\tau_\pm}$ is the ratio of lifetimes of the $B^0$ and $B^\pm$ mesons. For the $B \to K^{(*)}\mu^+\mu^-$ case, the SM predicts $A_I$ of $\mathcal{O}(-1\%)$ at low $q^2$ and $\mathcal{O}(1\%)$ at $q^2 \to 0$ [14], while there is no precise prediction of $A_I$ for the $B \to K\mu^+\mu^-$ case. Figure 2 shows the LHCb results on the isospin asymmetries [15]. Theoretical prediction and experimental measurement are in agreement for the $B \to K^{(*)}\mu^+\mu^-$ case, while a precise SM prediction for the $B \to K\mu^+\mu^-$ case is foreseen in order to reveal whether the measured 4.4 $\sigma$ statistical significance deviation from zero can be accommodated in the SM or is a New Physics effect.

![Figure 2: Isospin asymmetry as a function of $q^2$ in the $B \to K^{(*)}\mu^+\mu^-$ (left) and $B \to K\mu^+\mu^-$ systems (right). The blue line corresponds to theoretical predictions.](image)

7 Branching fraction measurement of $B^+ \to \pi^+\mu^+\mu^-$

$B^+ \to \pi^+\mu^+\mu^-$ decays are processes mediated by $b \to d l^+l^-$ transitions never observed before. In the SM, such transitions are suppressed by a factor $|V_{td}/V_{ts}|$ that does not necessarily appear in New Physics models. The LHCb measurement [17], $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (2.4 \pm 0.6_{(\text{stat})} \pm 0.2_{(\text{syst})}) \times 10^{-8}$, is in agreement with the SM prediction of $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (1.91 \pm 0.21) \times 10^{-8}$ [16]. $B^+ \to \pi^+\mu^+\mu^-$ is the rarest $B$ decay ever observed.
8 Conclusions

The LHCb Collaboration has presented measurements of branching fractions of beauty, charm, and tau decays, as well as of angular distribution of $B^0 \to K^{(*)0} \mu^+ \mu^-$ and of the isospin asymmetry of the $B \to K^{(*)} \mu^+ \mu^-$ system. All these measurements are of an unprecedented accuracy and are consistent with the SM predictions. The measured isospin asymmetry of the $B \to K \mu^+ \mu^-$ system shows a $4.4 \sigma$ deviation from zero.

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Heavy-Flavor Results at CMS

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The CMS experiment [1] at the LHC is a multi-purpose detector. Due to its versatility, especially of the trigger system, and to the excellent muon transverse-momentum ($p_T$) resolution, several heavy-flavor physics results have been obtained, using proton-proton data recorded in 2010–11 at a center-of-mass energy of 7 TeV.

1 Quarkonia

From the theoretical point of view, the prompt charmonium cross section is a clean probe of Non Relativistic QCD approaches. Recently, $J/\psi$ and $\psi(2S)$ cross-sections have been computed at Next-to-Leading Order (NLO) in these models, using the long-distance matrix elements as determined in Tevatron data. In the same model, predictions for the ratio of $\chi_c$ over $J/\psi$ production rate, and the analogous for $\chi_c^2$ over $\chi_c^1$, have been obtained. At relatively high $p_T$, a significant fraction of the $J/\psi$ and $\psi(2S)$ comes from $b$-hadron decays and, if it is separated experimentally from the prompt component, provides a direct test of the Fixed-Order Next-to-Leading-Log (FONLL) prediction for the $b \rightarrow \psi$ production cross section.

The differential cross sections can be expressed as:

$$\frac{d^2\sigma}{dp_Tdy}(Q\overline{Q}) \cdot B(Q\overline{Q} \rightarrow \mu^+\mu^+) = \frac{N_{\text{rec}}(Q\overline{Q})}{\int Ldt \cdot \langle A \cdot \varepsilon \rangle \Delta p_T \Delta y} \quad (1)$$

where $N_{\text{rec}}(Q\overline{Q})$ is the $Q\overline{Q}$ yield in a given $p_T$-$y$ bin, $\int Ldt$ is the integrated luminosity, $\langle A \cdot \varepsilon \rangle$ is the average value in the bin of the geometrical acceptance, determined using Monte Carlo (MC) simulations, times the reconstruction efficiency of the di-muon, and $\Delta p_T \Delta y$ is the size of the bin. Multiplication by $1 - f_B$ ($f_B$) yields the prompt (non-prompt) component of the total inclusive cross section. Muon trigger and reconstruction efficiencies are determined in CMS from the data using the “tag-and-probe” method [2], which uses independent $J/\psi$ samples to provide a sample of muons unbiased with respect to the selection under investigation.

The measurement of the $J/\psi$ and $\psi(2S)$ differential cross sections [3] uses a data sample corresponding to an integrated luminosity of 37 pb$^{-1}$. Using a fit to the invariant mass and decay length distributions, production cross sections have been
measured separately for prompt and non-prompt charmonium states, as a function of the transverse momentum in several rapidity ranges (Fig. 1, left). The ratio of the differential production cross sections of the two states, where many systematic uncertainties (e.g. from luminosity and muon efficiency) cancel, is also determined. The branching fraction of the inclusive $B \to \psi(2S)X$ decay is extracted from the ratio of the non-prompt cross sections to be $(3.08 \pm 0.12 \text{ (stat.) } \pm 0.13 \text{ (syst.) } \pm 0.42 \text{ (theor.)}) \times 10^{-3}$.

The $p_T$-differential measurement of the relative prompt production rate of $\chi_{c2}$ and $\chi_{c1}$ is based on a sample of 4.6 fb$^{-1}$ of data [4]. The two states are reconstructed in their radiative decays $\chi_c \to J/\psi + \gamma$, with the photon converting into an $e^+e^-$ pair in the tracker barrel region. A very good signal purity is obtained with this method, as well as a resolution of about 6 MeV/$c^2$, that allows a clear separation of the two states. Results for the cross-section ratio are shown in Fig. 1, right.

![Figure 1: Left: Measured differential cross section for prompt $\psi(2S)$ production as a function of $p_T$ for different rapidity bins. The blue histograms indicate the theoretical predictions from NRQCD calculations. Right: Measured $\chi_{c2}$ over $\chi_{c1}$ cross section ratio as a function of $J/\psi$ $p_T$.](image)

2 $b$-baryons

Precise measurements of the $\Lambda_b$ and $\bar{\Lambda}_b$ cross-sections, as well as searches for new $b$-baryon states have been performed at CMS, using data samples of 1.9-5.3 fb$^{-1}$.

$\Lambda_b$ baryons are reconstructed through their decays to $J/\psi \Lambda \to \mu^+\mu^-p\pi^-$ [5]. A good resolution is obtained with a mass-constrained vertex fit to the 4-particle
candidates, while the request of a large significance of $J/\psi$ and $\Lambda$ vertex displacement rejects background from prompt tracks. Efficiencies are determined from “tag-and-probe” and MC simulation. A slight excess of the total measured cross section with respect to MC@NLO predictions is found, consistent with CMS measurements of other $b$-hadron species. However, unlike other $b$-hadrons, the $p_T$ spectrum falls more rapidly than NLO QCD predictions, and this is attributed to a difference in the hadronization mechanism. The particle over anti-particle cross-section ratio is found to be compatible with 1 at all $p_T$ values.

Among the neutral “cascade” $b$-baryons ($\Xi^0_0$), only the $J^P = \frac{1}{2}^+$ state had been previously observed; however color hyperfine splitting predicts the mass of the $J^P = \frac{3}{2}^+$ state to be large enough for a $\Xi^0_0^* \rightarrow \Xi^- \pi^+$ decay. Therefore the state is searched in this channel [6], profiting of the presence of three weakly decaying particles in the chain ($\Xi_0^-, \Xi^-, \Lambda^0$) which allows reconstruction of three detached vertices to reject background from prompt tracks. The result is an observation with a significance corresponding to 6.9 standard deviations. The measured mass of the new resonance is $5945.0 \pm 0.7 \text{ (stat.)} \pm 0.3 \text{ (syst.)} \pm 2.7 \text{ (PDG)} \text{ MeV}/c^2$, in agreement with theoretical predictions (Fig. 2).

![Figure 2: Q = M(J/\psi \Xi^- \pi^+) - M(J/\psi \Xi^-) - M(\pi^+) distribution in the 0 < Q < 50 MeV/c^2 range, along with the result of the signal-plus-background fit (blue solid curve); the background term is also shown (red dashed curve).](image)

3 Rare decays

In CMS searches for $B_0^0$, $B^0$ and $D^0 \rightarrow \mu^+\mu^-$ decays have been performed. These decays are predicted to be rare in the Standard Model (SM) and, especially in the $B$
sector, a significant enhancement over the SM branching ratios ($B_{SM} \sim 10^{-10} - 10^{-9}$) is predicted in most supersymmetric theories. An observation of a non-SM value of the branching fraction would therefore represent an indirect evidence for new physics.

For the $B_s^0$ and $B^0$ analysis [7], the dataset corresponds to an integrated luminosity of 5.0 fb$^{-1}$. The analysis is performed separately in two channels, at low and high muon pseudo-rapidity, and then combined for the final result. A “normalization” sample of events with $B^+ \rightarrow J/\psi K^+$ decays is used to remove uncertainties related to the $b\bar{b}$ production cross section and the integrated luminosity and reduce uncertainties on efficiencies, which are determined from MC. Selection is based on several types of variables, including high $p_T$, vertex displacement and dimuon isolation, and has been optimized to mitigate the effects of high pileup. A “blind” analysis approach is applied.

An event-counting experiment is performed in dimuon mass regions around the $B_s^0$ and $B^0$ masses. MC simulations are used to estimate backgrounds due to other rare $B$ decays and combinatorial backgrounds are evaluated from the data in dimuon invariant mass sidebands. The observed number of events is consistent with background plus SM signals. The resulting upper limits on the branching fractions are $B(B_s^0 \rightarrow \mu^+\mu^-) < 7.7 \times 10^{-9}$ and $B(B^0 \rightarrow \mu^+\mu^-) < 1.8 \times 10^{-9}$ at 95% CL.

Similar techniques are exploited in the search for $D^0 \rightarrow \mu^+\mu^-$ [8], but the data sample used corresponds to 90 pb$^{-1}$ only, due to the trigger limitations in selecting the normalization sample $D^0 \rightarrow K^-\mu^+\nu_\mu$. The resulting upper limit is $B(D^0 \rightarrow \mu^+\mu^-) < 5.4 \times 10^{-7}$ at 95% CL.

References

New physics signals in top physics

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1 Introduction

Effective Field Theory (EFT) provides a model-independent way to search for new physics if the new degrees of freedom are heavy. The new physics appears then as new interactions between the known particles including modification of the SM vertices. In the Lagrangian, they are written as new operators built from the SM fields and invariant under its symmetries. These operators have dimension higher than four and are suppressed by negative powers of the new physics scale $\Lambda$ to get the required dimension for the Lagrangian. Only the operators with the lower dimension, i.e. dimension-six, can be kept in good approximation since the new physics scale is well above the energies probed by the experiments. Consequently, EFT is valid only below the scale of the new physics. In this region, the unitary bound is never reached and no form factors are needed unlike for anomalous couplings (see [1] for a complete discussion of the advantages of EFT compared to anomalous couplings). EFT is also more predictive due to the symmetries. For example, an operator often contains several vertices with different numbers of legs all depending on its coefficient only. The symmetries also make the EFT Lagrangian renormalizable and allow loop computation. Despite that the number of dimension-six operators that can be added to the SM Lagrangian is large, only a few contribute to a particular process and they can usually be distinguished using several observables. This will be illustrated in the following for top pair production. The complete discussion and list of references can be found in ref. [2]. The only references hereafter are new measurements or computations that have been used to update the results from ref. [2].

2 The effective Lagrangian for top pair production

The observables and the squared matrix elements will be expanded to the same order as the Lagrangian, i.e. $\Lambda^{-2}$. Consequently, the new contributions arise as the interference between the dimension-six operators and the SM, in particular, with the
dominant QCD processes. The operators should contain top quarks, light quarks and/or gluons. Five operators give the largest contributions to top pair production, one operator which modify the interactions of the top and the gluon:

\[ \mathcal{O}_{h_g} = \left( H \overline{Q}_L \right) \sigma^{\mu\nu} T^A t_R G^A_{\mu\nu}, \]

(1)
two operators involving both the right-handed top and the light quarks:

\[ \mathcal{O}_{R v} = \left( \overline{t}_R \gamma^\mu T^A t_R \right) \sum_{q=u,d} \left[ \overline{q} \gamma_\mu T^A q \right] \]
\[ \mathcal{O}_{R a} = \left( \overline{t}_R \gamma^\mu T^A t_R \right) \sum_{q=u,d} \left[ \overline{q} \gamma_\mu \gamma_5 T^A q \right] \]

(2)
and two similar four-fermion operators with the left-handed doublet of heavy quarks. Those four-fermion operators have to be the product of two color-octet current to interfere with the SM and can only affect top pair production by quark annihilation. The full Lagrangian is written as

\[ \mathcal{L}_{\overline{t}t} = \mathcal{L}_{\overline{t}t}^{SM} + \frac{1}{\Lambda^2} \left( c_{h_g} (\mathcal{O}_{h_g} + h.c.) + (c_{R v} \mathcal{O}_{R v} + c_{R a} \mathcal{O}_{R a} + R \leftrightarrow L) \right). \]

3 Phenomenology

The total cross-section at hadron colliders only depends on two parameters \( c_{h_g} \) and \( c_{V_v} = c_{R v} + c_{L v} \). The axial operators \( \mathcal{O}_{R a} \) and \( \mathcal{O}_{L a} \) can only contribute to observables that are odd functions of the scattering angle because the axial current is odd under the exchange of the light quark and anti-quark. They have thus no effect on the total cross-section. The contributions from the two vector operators are identical since the cross-section is not sensitive to the helicity of the top. The constraints from the measurements of the total cross-section at the Tevatron and at the LHC [3] are shown on Fig. 1. The new NNLO results for the top pair production by quark annihilation [4] have allowed to significantly reduce the region allowed by the Tevatron data. The four-fermion operators have a small contribution at the LHC where the dominant production mechanism is gluon fusion. Consequently, the constraints at the LHC in the \( c_{V_v} \) direction is less stringent than at the Tevatron.

Dimension-six operators are also expected to influence the shape of the distributions if the \( \Lambda^{-2} \) is balanced in the numerator by the energies of the process. The contributions of the four-fermion operators have an extra \( s \) factor compared to the SM one. Consequently, they can be further constrained using the the invariant mass distribution. On the contrary, the contribution from the operator \( \mathcal{O}_{h_g} \) has to be proportional to the Higgs vev and to the top mass and mainly affects the overall normalization. While the shape distortion are too small at the LHC so far, the Tevatron strongly constrain the four-fermion operators contribution as shown on Fig. 1.
Figure 1: On the left, the allowed regions from the LHC total cross-section at 7 TeV (red lines) and the Tevatron total cross-section (green region) and invariant mass shape (blue region) in the $c_{Vv}$-$c_{hg}$ plane. On the right, the summary of the present constraints.

The forward-backward asymmetry is an odd function of the scattering angle and allows to constrain the axial operators. In fact, all the measurements related to the asymmetry depend only on $c_{Aa} = c_{Ra} - c_{La}$ as long as the spin of the top quarks are not measured simultaneously. The best value obtained by fitting the total asymmetry measured by CDF [5], $c_{Aa}/\Lambda^2 = 2.04$ TeV$^{-2}$, can then be used to predict the rapidity and invariant mass distributions. As shown on Fig. 2, the predictions are in good agreement with the data. Furthermore, both the forward-backward asymmetry and the invariant mass distribution can be explained as they are affected by independent combinations of operators.

Spin dependent observables are required to disentangle the four-fermion operators with the right-handed top from those with the left-handed top. Fortunately, spin correlation can be observed in top pair production. The parameter sensitive to the amount of top pair produced with the same or opposite helicity has been measured [6] and the precision is close to the expect effects from the dimension-six operators. However, this parameter is only sensitive to $c_{Vv}$ and $c_{hg}$. The other parameters vanish in the SM but are sensitive to the orthogonal combination $c_{Av} = c_{Rv} - c_{Lv}$. Again, those effects due only to the four-fermion operators are small at the LHC.

To sum up, effective field theories provide a model independent way to search for heavy new physics and have many desirable properties. They are also useful for phenomenology at hadron colliders, various dimension-six operators are already constrained by their data. Those constraints can be improved by new measurements and more precise predictions for the SM contributions.
Figure 2: Distributions of the forward-backward asymmetry as a function of the rapidity (left) and invariant mass (right). The SM predictions are in red, the SM and the interference with the dimension-six operators predictions for the value of $c_{Aa}/\Lambda^2$ which gives the best fit for the total asymmetry at the Tevatron are in blue, the data [5] are in black.

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References


Top quark production at ATLAS

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1 Introduction

The top-quark (t-quark) is the heaviest elementary particle (173.2 GeV) [1] among the Standard Model (SM) particles. Owing to its largest mass, there are several theoretical predictions that new physics beyond the SM could appear in both the production or in the decay process of the t-quark. At the LHC, plenty of the t-quarks are produced either as a pair (tt) or singly, enough to test the SM by measuring its production cross-section. Based on the 0.7 fb$^{-1}$ proton-proton (pp) collision data recorded by the ATLAS detector [2], precise measurements have been performed of the tt production cross-section using the single-lepton (tt → ℓνqq b¯b, ℓ = e, μ) [3], and the dilepton (tt → ℓ+ℓ−ντb̄b) [4] channel. The combined cross-section (177±11 pb) is consistent with the theoretical prediction with an uncertainty of 6%, which is smaller than the theoretical accuracy (10%). The tt production cross-section in alternative decay channels and the single-top production cross-section are of primary interest to further investigate new physics effect.

2 Single-top production cross-section

The single-top production cross-section provides a direct probe of the Wtb coupling, and can constrain the absolute value of the CKM quark-mixing matrix element V_{tb} without any assumption on the number of quark generations. The production cross-section for the two leading processes: the t-channel (64.6^{+2.7}_{-2.0} pb) and the Wt associated production channel (15.7±1.1 pb) are presented.

Wt-channel The associated Wt production involves more than 250 GeV in the final state. The production rate at the Tevatron is too small (0.2 pb) to be observed, while it is much higher at the LHC owing to the larger partonic energy.

Using 2.05 fb$^{-1}$ of pp collision data, the analysis exploits the leptonic decays of both the W associated to the t-quark and the W from its decay. Candidate events are extracted by requiring two high-p_T leptons, significant missing transverse momentum ($E_T^{miss}$ > 50 GeV), and at least one jet with p_T > 30 GeV. The remaining Z+jet background is reduced by requiring the sum of the opening angles between leptons and the $E_T^{miss}$, $\sum_{i=1,2} \Delta \phi(\ell_i, E_T^{miss}) > 2.5$ rad, and the dilepton mass ($m_{\ell\ell}$) outside the Z mass window ($m_{\ell\ell} < 81$ GeV or $m_{\ell\ell} > 101$ GeV). The dominant background comes from tt dilepton events.
An approach based on a Boosted Decision Tree (BDT) [5] has been developed to discriminate $Wt$ events from backgrounds, followed by a template fit to the BDT output distribution. The result is incompatible with the background-only hypothesis at the 3.3 $\sigma$ level, and the cross-section, 16.8 $\pm$ 5.7 pb, shows good agreement with the theoretical prediction (3.4 $\sigma$ is the expected value). This is the first evidence of single-top production via the $Wt$ channel, and the result is used to determine $|V_{tb}| = 1.03^{+0.16}_{-0.19}$, assuming that $|V_{tb}| \gg |V_{ts}|, |V_{td}|$ [6].

$t$-channel The $t$-channel has the largest cross-section among the single-top processes, enabling us to measure $|V_{tb}|$, as well as the cross-section separately for the $t$-quark ($\sigma_t$) and the $\bar{t}$-quark ($\sigma_{\bar{t}}$). The ratio $\sigma_t/\sigma_{\bar{t}}$ is sensitive to the two PDFs ($u$-quark and $d$-quark) as the systematic uncertainties are partially cancelled. The enhancement of the ratio may provide an interesting handle to search for new physics.

Based on 1.04 fb$^{-1}$ of $pp$ collision data, events are selected by requiring one high-$p_T$ lepton, $E_T^{miss} > 25$ GeV, and two or three jets, with exactly one of them identified as originating from a $b$-quark. The dominant background consists of $W$+jet events, modeled by the MC simulation and normalized to the data. The cross-section is extracted by fitting the distribution of a multivariate discriminant based on a neural network, and turns out to be 83 $\pm$ 20 pb. Assuming that the $t$-quark related CKM matrix elements obey the relation $|V_{tb}| \gg |V_{ts}|, |V_{td}|$, the coupling strength at the $Wtb$ vertex is determined to be $|V_{tb}| = 1.13^{+0.14}_{-0.13}$. Under the assumption that $|V_{tb}| \leq 1$, a lower limit of $|V_{tb}| > 0.75$ is obtained with the 95% confidence level [7].

The ratio $\sigma_t/\sigma_{\bar{t}}$ is measured using 4.7 fb$^{-1}$ data with a slightly optimized event selection. The cross-section is extracted separately according to the lepton charge by performing a binned maximum likelihood fit to the output distribution of the neural networks. The resulting cross-section is $\sigma_t = 53.2 \pm 10.8$ pb and $\sigma_{\bar{t}} = 29.5^{+7.4}_{-7.5}$ pb, with its ratio measured to be $R_t = 1.81^{+0.23}_{-0.22}$. The measurement is in agreement with the predictions, that vary between 1.86 and 2.07 depending on the assumed PDFs [8].

3 $t\bar{t}$ production cross-section

The measurement of the $t\bar{t}$ production cross-section in different decay channels is of primary importance to test the SM. In particular, the cross-section using final states including a $\tau$-lepton is sensitive to new physics such as the charged Higgs boson, predicted by the supersymmetric model. In the following, the analysis in the $\tau$ plus lepton channel ($t\bar{t} \rightarrow \tau^+\nu_\tau\ell^-\overline{\nu}\overline{\nu}b\overline{b}$) [9], in the $\tau$ plus jet channel ($t\bar{t} \rightarrow \tau^+\nu_\tau q\overline{q}b\overline{b}$) [10], and in the all-hadronic channel ($t\bar{t} \rightarrow q\overline{q} q\overline{q} q\overline{q}b\overline{b}$) [11] are shortly described.

$t\bar{t}$ production in the $\tau$ plus lepton final state Candidate events are extracted from 2.05 fb$^{-1}$ data, by requiring one high-$p_T$ lepton (electron or muon), at least one hadronically decaying $\tau$ candidate, $E_T^{miss} > 30$ GeV, and two or more energetic jets, with at least one of them identified as a $b$-jet. Since the most important background is due to jets mimicking a $\tau$ candidate, multivariate technique based on a BDT is used to reconstruct the
\( \tau \) candidate, relying on its large separation power between signal and background. In order to estimate the number of background events in a data-driven way, the data have been split according to the charge correlation between a lepton and a reconstructed \( \tau \) candidate, followed by the subtraction of the same-sign events from the opposite-sign events to reduce part of the backgrounds. This enables to model the background in a data-driven way, which leads to the reduction of the systematic uncertainty. The cross-section is extracted by the template fitting to the BDT output distribution, which yields \( \sigma_{\tau} = 186 \pm 25 \text{ pb} \). With a total uncertainty of 13\%, the obtained result is consistent with the theoretical prediction \( (164^{+11}_{-10} \text{ pb}) \).

**\( t\bar{t} \) production in the \( \tau \) plus jet final state** Candidate events are selected from 1.67 fb\(^{-1}\) data, by requiring at least five jets, with two of them identified as \( b \)-jets, a large \( E_T^{\text{miss}} \) significance \( (E_T^{\text{miss}}/\sum E_T > 4 \), where \( \sum E_T \) is the scalar sum of the transverse energy released by all the visible particles). One of the remaining jets is selected as the \( \tau \) candidate based on the event topology. The remaining backgrounds come from the QCD multi-jet events.

The cross-section is obtained by fitting the distribution of the number of tracks associated to the \( \tau \) candidate with templates. Signal events produce a peak in correspondence to an odd number of tracks coming from the \( \tau \)'s. The signal template is derived from MC simulation, while the background templates for the multi-jet and the \( t\bar{t} \) combinatorics are constructed in a data-driven way. The obtained cross-section of 200\( \pm 47 \text{ pb} \), is in agreement with the theoretical prediction.

**\( t\bar{t} \) production in the all-hadronic channel** The \( t\bar{t} \) production cross-section in all-hadronic channel is sensitive to new physics including a multi-jets final state, such as the one predicted by the low scale gravity and the weakly-coupled string theory. Although there is the big advantage of a largest branching ratio \( 46\% \) of all \( t\bar{t} \) decays), the analysis is challenging due to the large multi-jet backgrounds.

Candidate events are selected from 4.7 fb\(^{-1}\) data by requiring at least six jets, with at least two of them being identified as \( b \)-jet, and a small \( E_T^{\text{miss}} \) significance less than three. A kinematic likelihood fit is performed to find the correct association of jets that can reconstruct the \( t \)-quark mass. The number of signal events is extracted by using an unbinned likelihood fit to the \( t \)-quark mass. The shape of the background, which consists of multi-jet events, is modeled by the events passing the event selection without the requirement of the presence of \( b \)-tagged jets. The signal is modeled using a MC simulation. The measured cross-section, 168 \( \pm 62 \text{ pb} \), is found to be compatible with the theoretical prediction.

### 4 Summary

Figure 1 shows the summary of the \( t\bar{t} \) and the single-top production cross-section measurements, with the corresponding theoretical cross-sections. All the results are consistent with the theoretical prediction, showing the validity of the perturbative QCD at the LHC energy.
scale. Further improvement on the systematic uncertainty will lead to better measurements which will allow to probe new physics.

Figure 1: Summary of the $t\bar{t}$ and the single-top cross-section measurement.

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Top quark cross section measurements in CMS

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1 Introduction

The most recent results on the measurements of top anti-top quark pair ($t\bar{t}$) and single top production cross sections at 7 TeV are presented. These are obtained using CMS [1] data collected in 2011. The $t\bar{t}$ inclusive cross sections are measured in the lepton+jets, dilepton and fully hadronic channels, including the tau-dilepton and tau+jets modes. The results are combined and confronted with precise theory calculations. In this article also the differential $t\bar{t}$ cross section measurements, the single top cross section measurements and the charge asymmetry measurement are presented.

2 Inclusive cross section measurements

The most suitable channel for precise measurements of the $t\bar{t}$ production cross section is the lepton+jets channel. The analysis is performed by dividing data in different categories of events according to the jet multiplicity and the number of b-tagged jets. The cross section is then extracted with a fit to the mass of the secondary vertex of the jets. One of the main features of this analysis is that the systematic uncertainty are treated as nuisance parameters of the fit. The relative uncertainty in the measurement of the $t\bar{t}$ cross section is $\sim 7\%$ and it is dominated by the uncertainty in modeling of the signal component and by the luminosity measurement. In the remaining channels the $t\bar{t}$ production cross section has been measured by a counting experiment for the dilepton channel, while in the fully hadronic channel a kinematic fit to the distribution of the reconstructed top mass is used. The most recent results are coming from the hadronic tau+jets channel. In this case the measurement is performed using a multivariate analysis. More in details the signal has been extracted from the backgrounds using a fit to a neural network output distribution. The results of the fit is shown in Fig.1 [2]. Overall the results in these channels are compatible with the theoretical predictions but their uncertainties are larger with respect to the measurements in the lepton+jets channel due to systematic effects mainly connected with the jet energy scale or background estimation. In table 1 the results for the $t\bar{t}$ production cross section measurement for the different channels are presented.
### Table 1: Results of the $t\bar{t}$ production cross section measurements in different channels.

<table>
<thead>
<tr>
<th>$t\bar{t}$ channel</th>
<th>cross section measurement result (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton + jets</td>
<td>$164.4 \pm 2.8$(stat.) $\pm 11.9$(syst.) $\pm 7.4$(lumi.)</td>
</tr>
<tr>
<td>dilepton</td>
<td>$169.9 \pm 3.9$ (stat.) $\pm 16.3$ (syst.) $\pm 7.6$ (lumi.)</td>
</tr>
<tr>
<td>dilepton + tau</td>
<td>$148.7 \pm 23.6$(stat.) $\pm 26.0$(syst.) $\pm 8.9$(lumi.)</td>
</tr>
<tr>
<td>hadronic tau + jets</td>
<td>$156 \pm 12$ (stat.) $\pm 33$ (syst.) $\pm 3$ (lumi)</td>
</tr>
<tr>
<td>fully hadronic</td>
<td>$136 \pm 20$ (stat.) $\pm 40$ (syst.) $\pm 8$ (lumi)</td>
</tr>
</tbody>
</table>

3 Differential cross section measurements

Thanks to the large statistics recorded by the CMS experiment in 2011, we are able to provide also the measurements of the differential cross section. Differential measurements were performed in the lepton+jets and dilepton channels after the reconstruction of the $t\bar{t}$ kinematics, unfolded to parton level. The differential cross section is measured after background subtraction and unfolding the observed value. There is a very good agreement between the unfolded data and the simulation within the uncertainty of the measurement. One distribution of particular interest is $p_T^{\ell}$ which is shown in Fig.2 for the dilepton channel [3].

4 Single Top production

Single top quarks can be produced through the s and t-channels and in association with a W boson. The dominant production mode is the t-channel. The most recent result for this channel is $\sigma(t) = 70.2 \pm 11.5$(stat. + syst.) $\pm 3.4$(lumi.) pb obtained
using a fit to the pseudo-rapidity of the recoiling jet. The comparison of the current measure with the Standard Model expectation is presented in Fig.3. The value of the $|V_{tb}|$ coupling has been also derived. Assuming $|V_{td}|, |V_{ts}| \ll |V_{tb}|$ we find $|V_{tb}| = 1.04 \pm 0.09(exp) \pm 0.02(th)$ [4].

Figure 2: Differential cross section measurement with respect to the $p_T$ of the $t\bar{t}$ system, for the dilepton channel. The measurements are compared to the predictions from Madgraph, POWEGH, and MC@NLO Monte Carlo generators.

Figure 3: Comparison of the current measurement for the single top $t$–channel cross section production with the Standard Model expectation.

5 Charge asymmetry measurements

The difference in the angular distributions between top quarks and antiquarks have been measured. In addition to the inclusive measurement, for the first time at the
LHC also differential measurements of the charge asymmetry are performed. The invariant mass, the rapidity, and the transverse momentum of the $t\bar{t}$ system are chosen as differentiating variables since they are sensitive to the different processes contributing to the overall charge asymmetry [5]. The measured inclusive asymmetry of $AC = 0.004 \pm 0.010\text{(stat.)} \pm 0.012\text{ (syst.)}$ and the measured differential asymmetries are consistent with the predictions from the standard model (Fig.4).

![Figure 4: Differential measurements of the charge asymmetry with respect to three different differentiating variables: the transverse momentum, the invariant mass and the rapidity of the $t\bar{t}$ system.](image)

**References**


Recent top physics results from the D0 experiment

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Abstract

We review recent measurements of the properties of the top quark by the D0 experiment: the decay width of the top quark, the CKM matrix element $V_{tb}$, the helicity of the $W$ boson, anomalous couplings at the $Wtb$ vertex, violation of invariance under Lorentz transformations, and the asymmetry of $t\bar{t}$ production due to the strong colour charge. The measurements are performed using data samples of up to 5.4 fb$^{-1}$ acquired by the D0 experiment in Run II of the Fermilab Tevatron $p\bar{p}$ collider at a centre-of-mass energy of $\sqrt{s} = 1.96$ TeV.

PACS 14.65.Ha – Top quarks.

The pair-production of the top quark was discovered in 1995 by the CDF and D0 experiments [1] at the Fermilab Tevatron proton-antiproton collider. Observation of the electroweak (EW) production of single top quarks was presented only 3 years ago [2]. The large top quark mass of 173.2 ± 0.9 GeV [3] and the resulting Yukawa coupling of about 0.996 ± 0.006 suggest that the top quark could play a crucial role in EW symmetry breaking. Precise measurements of the properties of the top quark provide a crucial test of the consistency of the standard model (SM) and could hint at physics beyond the SM. The full listing of top quark measurements by the D0 experiment can be found in Ref. [4].

At the Tevatron, top quarks are mostly produced in pairs via the strong interaction. In the framework of the SM, the top quark decays to a $W$ boson and a $b$ quark nearly 100% of the time, resulting in a $W^+W^-b\bar{b}$ final state from top quark pair production. Thus, $t\bar{t}$ events are classified according to the $W$ boson decay channels as “dileptonic”, “all–jets”, or “lepton+jets”. The EW production of single top quarks is classified via $s$ and $t$ channel, as well as associated $Wt$ production.

We extract the total decay width of the top quark [5] from the partial decay width $\Gamma_{t\rightarrow Wb}$, measured using the $t$-channel cross section for single top quark production [6], and from the branching fraction $B_{t\rightarrow Wb}$, measured in $t\bar{t}$ events [7], from up to 5.4 fb$^{-1}$ of data. This extraction is made under the assumption that the EW coupling in top quark production is identical to that in the decay, and using the next-to-leading order (NLO) calculation of the ratio $\Gamma_{t\rightarrow Wb}^{SM}/\sigma_{t\rightarrow Wb}^{SM}$, i.e. $\Gamma_{t} = \frac{\sigma_{t\rightarrow Wb}}{B_{t\rightarrow Wb}} \times \frac{\Gamma_{t\rightarrow Wb}^{SM}}{\sigma_{t\rightarrow Wb}^{SM}}$. 

Properly taking into account all systematic uncertainties and their correlations among the measurements of $\Gamma_{t\to Wb}$ and $\sigma_{t\to \text{channel}}$, we find $\Gamma_t = 2.00^{+0.47}_{-0.43}$ GeV, which translates into a top-quark lifetime of $\tau_t = (3.3^{+0.9}_{-0.6}) \times 10^{-25}$ s, in agreement with the SM expectation. This constitutes the world’s most precise indirect determination of $\Gamma_t$ to date. Furthermore, we use the $t$-channel discriminant of the above measurement to extract a limit of $|V_{tb}| > 0.81$ at 95% C.L., without the commonly made assumptions that $t \to Wb$ exclusively, or on the relative $s$ and $t$ channel rates.

In the SM, the top quark decays into a $W$ boson and a $b$ quark with a probability of $>99.8\%$, where the on-shell $W$ boson can be in a left-handed, longitudinal, and right-handed helicity state. A NLO calculation in the SM predicts $f_-=0.301$, $f_0=0.698$, and $f_+=4.1 \times 10^{-4}$, respectively. A deviation from the SM expectation could indicate a contribution from new physics. We simultaneously measured the $f_0$ and $f_+$ helicity fractions in the dilepton and $\ell +$ jets final states using 5.4 fb\(^{-1}\) of data [8]. A model-independent fit to the distribution in $\cos \theta^*$, where $\theta^*$ is the angle between the three-momentum of the top quark and the down-type fermion in the $W$ boson rest frame, yields $f_0 = 0.67 \pm 0.10$ and $f_+ = 0.02 \pm 0.05$, in agreement with the SM expectation. The combination with measurements by CDF in the dilepton and $\ell +$ jets final states using up to 4.8 fb\(^{-1}\) yields $f_0 = 0.72 \pm 0.08$ and $f_+ = -0.03 \pm 0.46$ [9].

The SM provides a purely left-handed vector coupling at the $Wtb$ vertex, while the most general and lowest-dimension effective Lagrangian allows a right-handed vector coupling $f_R^V$ as well as tensor couplings $f_T^L$ and $f_T^R$. We extracted limits on those anomalous couplings from single top production in 5.4 fb\(^{-1}\) using both shapes of kinematic distributions as well as the overall and $s$ versus $t$ channel event rates [10]. This was done under the assumption of real, i.e. $CP$-conserving couplings and a spin 1/2 top quark predominantly decaying to $Wb$. The results are shown in Table 1. Furthermore, we exploit that anomalous couplings at the $Wtb$ vertex will alter the rates of the three helicity states of $W$ bosons in $t\bar{t}$ decays, and combine the above analysis with the one in Ref. [8] to obtain improved limits [11], shown in Table 1.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$W$ helicity only</th>
<th>single top only</th>
<th>combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>f_R^V</td>
<td>^2$</td>
<td>0.62</td>
</tr>
<tr>
<td>$</td>
<td>f_T^L</td>
<td>^2$</td>
<td>0.14</td>
</tr>
<tr>
<td>$</td>
<td>f_T^R</td>
<td>^2$</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Table 1: Observed upper limits on anomalous $Wtb$ couplings at 95% C.L. from $W$ boson helicity assuming $f_T^L = 1$, from the analysis of single top events, and their combination, for which no assumption on $f_T^L$ is made, using 5.4 fb\(^{-1}\).

Invariance under Lorentz transformations is a fundamental property of the SM. We performed a search for Lorentz invariance violation (LIV) by examining the $t\bar{t}$
production cross section in $\ell + \text{jets}$ final states using 5.3 fb$^{-1}$ [12]. We quantified LIV in the top sector using in the SM Extension (SME) formalism [13], which parametrises the amount of LIV in terms of bilinear coefficients and results in a $t\bar{t}$ production rate which is modulated in full or half-units of a siderial day due to the rotation of the Earth. Thus, we investigate the $t\bar{t}$ production rate in 12 bins of the siderial phase, normalised by the recorded luminosity per bin. Our results are consistent with the SM hypothesis, and we proceed to set limits on LIV [12].

In the SM, the pair production of top quarks in $p\bar{p}$ collisions, a $CP$ eigenstate, is symmetric at LO under charge conjugation. NLO calculations predict a small forward-backward asymmetry $A_{\text{fb}}$ of the order of 5% in the $t\bar{t}$ rest frame. It is due to a negative contribution from the interference of diagrams for initial and final state radiation, and a (larger) positive contribution from the interference of box and tree-level diagrams. This experimental situation is unique to the Tevatron. A convenient observable for the Tevatron is $A_{\text{fb}} = N_{\Delta y > 0} - N_{\Delta y < 0} / N_{\Delta y > 0} + N_{\Delta y < 0}$, where $y_t$ ($y_{\bar{t}}$) is the rapidity of the $t$ ($\bar{t}$) quark. Another common observable does not depend on a full reconstruction of the $t\bar{t}$ system: $A_{\ell} = N_{q^+y^+} - N_{q^-y^-} / N_{q^+y^+} + N_{q^-y^-}$, where $q_{\ell}$ is the lepton charge.

We measured $A_{\text{fb}}$ in the $t\bar{t}$ rest frame in $\ell + \text{jets}$ final states on a dataset corresponding to 5.4 fb$^{-1}$ using $t\bar{t}$ event candidates fully reconstructed with a kinematic fitter, and found $A_{\text{fb}} = 9.2\% \pm 3.7\%$ at the reconstruction level [14]. Our result, shown in Fig. 1 (a), is about 1.9 standard deviations (SD) away from the MC@NLO [15] prediction of 2.4 $\pm$ 0.7%. After correcting for detector acceptance and resolution we find $A_{\text{fb}} = 19.6 \pm 6.5\%$, 2.4 SD away from the MC@NLO prediction of 5.0 $\pm$ 0.1%. In addition, we measured $A_{\text{fb}}$ in various subsamples defined by $m_{t\bar{t}} \leq 450$ GeV and by $|\Delta y| \leq 1.0$. We do not find any statistically significant dependencies. Furthermore, we have measured the lepton-based asymmetry and find $A_{\ell} = 14.2 \pm 3.8\%$ and $15.2 \pm 4.0\%$ at reconstruction and parton level, respectively, while MC@NLO predicts $A_{\ell} = 0.8 \pm 0.6\%$ and $2.1 \pm 0.1\%$. Our results display some tension with the NLO SM
prediction. This may indicate a contribution from new physics, but may as well be due to contributions at higher orders in $\alpha_s$ within the SM.

I presented recent measurements of key properties of the top quark by the D0 experiment, most in good agreement with SM expectations. The forward-backward asymmetry $A_{fb}$ of $t\bar{t}$ production displays tension between the measurement and the SM NLO calculations. We look forward to updates with the full dataset of 9.7 $fb^{-1}$ in the near future. I would like to thank my fellow D0 collaborators and also the staffs at Fermilab and collaborating institutions, as well as the D0 funding agencies.

References


Measurement of top-quark properties with the ATLAS experiment

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Abstract
Since the start of the LHC physics programme in 2009, a huge number of top quarks have been produced in collisions and recorded by the experiments. In 2011, 4.7 fb$^{-1}$ of data has been collected by the ATLAS experiment \cite{1} at $\sqrt{s} = 7$ TeV. This allows not only for searches of rare processes but for precision measurements of top quark properties. These measurements are especially important since they allow for tests of Standard Model predictions and for searches of new physics processes.

1 Introduction
The top quark decays almost exclusively into a $W$ boson and a $b$ quark. The decay modes of the $W$ boson define three $t\bar{t}$ final states: lepton+jets, dilepton and all hadronic. The measurements summarised here have been performed in one or more of these decay channels using data sets of $1.04 - 4.7$ fb$^{-1}$.

2 Measurements of top-quark properties
Measurement of the top quark mass The top quark mass is a fundamental parameter of the Standard Model that has been measured at the Tevatron to large precision: $m_{\text{top}} = 173.2 \pm 0.6$ (stat.) $\pm 0.8$ (syst.) GeV \cite{2}. The ATLAS experiment has performed several measurements in the lepton+jets and in the fully hadronic channel.
In the lepton+jets channel, two analyses utilize 1.04 fb$^{-1}$ of data each. The first uses a two-dimensional template fit to simultaneously extract the top quark mass and the Jet Scale Factor (JSF). The JSF is a global correction factor that accounts for the differences between the simulated and observed reconstructed $W$ mass $m_{\text{reco}}^{W}$ and is sensitive to the Jet Energy Scale (JES). The top mass obtained from this 2D fit yields: $m_{\text{top}} = 174.5 \pm 0.6$ (stat.) $\pm 2.3$ (syst.) GeV \cite{3}.
The second method performs a one dimensional template fit, using the R32 variable (defined as the ratio of the reconstructed top quark mass and the reconstructed W mass) as the observable. The result is in good agreement with the 2D fit:
\[ m_{\text{top}} = 174.4 \pm 0.9 \text{ (stat.)} \pm 2.5 \text{ (syst.) GeV} \]

The analysis in the all hadronic channel uses 2.04 fb\(^{-1}\) of data. Multijet production is the dominant source of background and is estimated from data. The events are reconstructed using a \(\chi^2\) fit. A one dimensional template fit is performed to the data. The systematic uncertainty is dominated by the JES and by the background modelling. The final result is:
\[ m_{\text{top}} = 174.9 \pm 2.1 \text{ (stat.)} \pm 3.8 \text{ (syst.) GeV} \]

The electromagnetic coupling of the top quark is tested through a measurement of the cross-section for \(t\bar{t}\)-production in association with an additional photon using a data set of 1.04 fb\(^{-1}\). In the analysis, prompt photons have to be distinguished from hadrons that are faking photons. Since prompt photons are in general isolated and those faked by hadrons are not, the photon isolation can be used as an observable in a template fit. Background templates are obtained using data driven techniques. Interference effects between radiative top quark production and decay are taken into account. The \(t\bar{t}\gamma\) cross-section times branching ratio for photons with \(p_T > 8\) GeV has been measured to:
\[ \sigma = 2.0 \pm 0.5 \text{ (stat.)} \pm 0.7 \text{ (syst.)} \pm 0.08 \text{ (lumi) pb} \]

**Charge asymmetry**  A small charge asymmetry in \(t\bar{t}\)-production is expected at NLO due to interferences between initial and final state radiation (ISR/FSR) as well as between Born- and box-diagrams. A deviation from the prediction could be a hint at the existence of new particles such as \(W'\) or \(Z'\) bosons. The Tevatron measurement of \(A_{FB}\) shows an excess as well as a mass dependence of the forward-backward asymmetry. Since the LHC is a pp collider, the charge asymmetry \(A_C\) (defined as \(A_C = \frac{N(\Delta|y|>0)-N(\Delta|y|<0)}{N(\Delta|y|>0)+N(\Delta|y|<0)}\)) is used instead of \(A_{FB}\).

In the lepton+jets channel, the difference of the absolute rapidities between top- and antitop-quark \(\Delta|y|\) is used to determine \(A_C\) in a data set of 1.04 fb\(^{-1}\). A Bayesian unfolding method is applied. The result obtained for \(A_C\) is in good agreement with the SM prediction: \(A_C = -0.019 \pm 0.028 \text{ (stat.)} \pm 0.024 \text{ (syst.)} \). No mass dependence of the result is observed.

In the dilepton channel, the complete 2011 data set of 4.7 fb\(^{-1}\) is used. In addition to the top quark-based asymmetry, the charge asymmetry of the two leptons is studied using the difference of the absolute pseudorapidities. No deviation from the SM prediction is found.
Spin correlation  Since the top quark decays before it can hadronise, the spin information of the top quarks is transferred to its decay products. Therefore the spin correlation between the two top quarks in a top-quark pair event can be measured by studying the leptons and quarks from the decay. The spin correlation has been measured in the dilepton channel in 2.1 fb$^{-1}$ of data [8], using the angular difference between the two charged leptons as observable. The measured spin correlation yields $A_{\text{helicity}} = 0.40_{-0.08}^{+0.09}$ (SM prediction: 0.31) and excludes the no spin correlation hypothesis with a significance of 5.1 $\sigma$. This result is the first observation of spin correlation in $t\bar{t}$-events.

$W$ boson polarization  $W$ bosons from top-quark decays can either be longitudinally, left-handed or right-handed polarized where the right-handed contribution is strongly suppressed by the (V-A) structure of the $Wtb$ vertex. This vertex structure can therefore be tested by comparing the measured $W$-helicity fractions with the SM predictions. Any deviation from the predicted values of $F_0= 0.687(5)$, $F_L= 0.311(5)$, $F_R =0.0017(1)$ [9] could be a hint at non-SM physics processes. In ATLAS, the $W$-helicity fractions have been measured with two different approaches, both using the angular distribution of the charged lepton in the $W$ boson rest frame. The first analysis performs a direct measurement using a template method while the second one measures angular asymmetries and uses them to determine the helicity fractions. Both analyses have been performed in the lepton+jets and in the dilepton channel, using 1.05 fb$^{-1}$ of data. The four results are combined using the BLUE method [10,11]. The combined result is in good agreement with the SM prediction and is the most precise measurement of the $W$-helicity fractions in top quark decays to date: $F_0= 0.67 \pm 0.07$, $F_L= 0.32 \pm 0.04$ and $F_R= 0.01 \pm 0.05$ [12].

Searches for FCNC  The large number of top quarks that are produced at the LHC allows for searches for rare processes such as searches for flavour changing neutral currents (FCNC). Two searches have been performed with one analysis looking for FCNC in single top production and one looking for FCNC in top decays. In the SM, the decay $t \rightarrow qg$ is a rare process that is difficult to separate from the multijet background. Therefore, a search for FCNC in top production is performed ($qq \rightarrow t \rightarrow W(\rightarrow l\nu)b$) using 2.05 fb$^{-1}$ of data. A neural network is used in the analysis [13]. No deviation from SM predictions has been found, therefore limits are set on the branching ratios at 95 % C.L.: BR($t \rightarrow ug) < 5.7 \cdot 10^{-5}$, BR($t \rightarrow cg) < 2.7 \cdot 10^{-4}$.

The second analysis searches for $tt\bar{t}$ events where one of the top quarks decays into $qZ$. Only events with leptonically decaying $Z$ and $W$ bosons are considered. Since no signal is found, a limit is set on the branching ratio at 95 % C.L.: BR($t \rightarrow qZ) < 0.73 \%$ [14].
3 Conclusion and outlook

ATLAS has a wide-ranging programme of top-quark properties studies. Even though the full data set is not used in all the measurements, they already have a comparable or better precision than the corresponding results from the Tevatron. The highlights described here are the most precise measurement of the W-helicity fractions in top-quark decays and the observation of $t\bar{t}$ spin-correlation in the dilepton channel.

References


Measurement of the Top Quark mass and other properties with CMS

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1 Introduction

The top quark, discovered in 1995 at the Tevatron Collider, plays a crucial role in the Standard Model (SM) since it is the heaviest known fundamental particle. As the top quark is expected to couple strongly to particles predicted in Beyond the Standard Model theories, the study of its properties is a key ingredient in the search for new phenomena. In 2011, the Large Hadron Collider delivered a dataset of 5fb$^{-1}$ at a center-of-mass energy of 7TeV to the CMS experiment resulting in a very large sample of top quark pairs. This has allowed CMS to perform precise measurements of the properties of the top quark.

2 The top quark mass

2.1 Top mass measurement in the l+jets channel

In the $\mu$+jets decay channel, the Ideogram method [1] is applied to measure $m_t$ and the Jet Energy Scale (JES) using 4.7fb$^{-1}$ of data. Using the four leading jets in the event, there are 12 unique jet-quark assignments possible. By imposing a b-tagging criterion the number of possible combinations can be reduced. To make the final jet-quark assignment, a kinematic fit of the entire event is used for each possible jet combination where an equal-mass constraint is applied on the two top quarks and two $m_W$ constraints. The kinematic fit returns the fitted top-quark mass $m_{t,i}^{\text{fit}}$ and the fit probability $P_{t,i}^{\text{fit}}$. An event-by-event likelihood function, shown in eq. (1), is constructed and a global likelihood fit to all selected yields a top mass of 172.6 ± 0.6(stat) ± 1.2(syst) GeV is obtained.

$$
\mathcal{L}(\text{event} | m_t, \text{JES}) = \left( \sum_{i=1}^{n} P_{t,i}^{\text{fit}} \cdot P \left( m_{t,i}^{\text{fit}}, m_{W,i}^{\text{true}} | m_t, \text{JES} \right) \right)^{\sum_{i=1}^{n} P_{t,i}^{\text{fit}}} \tag{1}
$$

This is the most precise LHC result where the systematic uncertainty is dominated by the JES of b-jets and the factorization scale uncertainty. The effects of color reconnection and underlying event are still under study.
2.2 Top mass measurement in the di-lepton channel

The top quark mass is measured in the di-lepton channel with the KINb method \[2\] using \(2.3 \, fb^{-1}\) of data. This method consists of solving the kinematic equations multiple times for each jet-quark assignment, each time varying the event kinematics within the experimental resolutions. The top quark mass for each event, \(m_{KINb}\), is then defined as the mean of the gaussian fit to the distribution of the reconstructed top quark mass for all the different solutions of the kinematic equations for the chosen jet-quark assignment. Finally a top mass of \(m_t = 173.3 \pm 1.2(\text{stat})^{+2.5}_{-2.0}(\text{syst})\) GeV is extracted from a likelihood fit to the \(m_{KINb}\) distribution being the most precise top quark mass measurement to date in the di-lepton channel with similar precision to the D0 measurement \[3\].

2.3 Top mass determination from the top quark pair cross section

The top quark mass can also be derived from the measured top quark pair cross section because the event selection used in the cross section analysis introduces a dependence on the top quark mass \[4\]. This derivation is performed using the di-lepton cross section result for \(1.14 \, fb^{-1}\). The dependence of the cross section on the top mass is parametrized by third order polynomials in each di-lepton channel. The cross section can be either related to \(m_t^{\text{pole}}\), which is essentially the quantity measured by the direct reconstruction method, or to \(m_t^{\text{MS}}\). The method yields \(m_t^{\text{pole}} = 170.3^{+7.3}_{-6.7}\) GeV and \(m_t^{\text{MS}} = 163.1^{+6.8}_{-6.1}\) GeV for the pole mass and the \(\overline{\text{MS}}\) mass, respectively.

3 Measurement of the difference in top quark and anti-top quark mass

In the SM, one of the fundamental symmetries is CPT invariance which states that a particle and its anti-particle have equal mass. The analysis is performed using lepton+jets events selected from a data sample corresponding to an integrated luminosity of \(4.96 \, fb^{-1}\). The mass difference between the top quark and its anti quark is measured \[5\]. The charge of the selected lepton in the event is used to distinguish between hadronically decaying top and anti-top quarks. The mass of the hadronically decaying top and anti-top quark is measured using the well established Ideogram method on the two distinct samples. Then the mass difference is calculated by subtracting the masses obtained in each measurement. The subtraction results in significant reduction of systematic errors. The mass difference is measured to be \(\Delta m_t = -0.44 \pm 0.46(\text{stat}) \pm 0.27(\text{syst})\) GeV and is the most precise measurement to date.
4 Other top quark properties

4.1 Measurement of the W boson polarization

In the $t \rightarrow Wb$ decay, the W boson may have a longitudinal, left-handed or right-handed polarization. Measuring the respective helicity fractions ($F_0$, $F_L$ and $F_R$) with great precision will enhance the search for anomalous couplings. The helicity fractions have been measured in the muon+jets channel on a dataset corresponding to an integrated luminosity of $2.2\, fb^{-1}$ [6]. The helicity fractions are extracted from a likelihood fit to the $\cos(\theta^*)$ distribution while a kinematic fit on the entire event is used to improve the Missing Transverse Energy (MET) resolution. The measured fractions $F_0 = 0.567 \pm 0.074$ (stat) $\pm 0.047$ (syst), $F_L = 0.393 \pm 0.045$ (stat) $\pm 0.029$ (syst) and $F_R = 0.040 \pm 0.035$ (stat) $\pm 0.044$ (syst) are in good agreement with SM predictions $F_0 = 0.7$ and $F_L = 0.3$.

4.2 Probing the heavy flavor content in top decays

In the SM with three generations of quarks, the $|V_{tb}|$ CKM-matrix element is expected to be close to unity as a consequence of the unitarity of the CKM matrix and of the measurements of the other elements. This means that the top quark will decay almost exclusively into a W-boson and a b-quark. To test the validity of this theory, the branching fraction of the $t \rightarrow Wb$ decay is measured relative to the one of $t \rightarrow Wq$ decay. Using a di-lepton $tt$ sample, corresponding to an integrated luminosity of $2.2\, fb^{-1}$, the $R = B(t \rightarrow Wb)/B(t \rightarrow Wq)$ variable is measured [7]. A likelihood fit on the b-tag multiplicity distribution, including gaussian smearing terms for experimental effects, yields $R=0.98 \pm 0.04$ consistent with the SM. The dominant systematics in this measurement are the b-tagging uncertainty and the uncertainty on the factorization scale.

4.3 Search for Flavor Changing Neutral Currents (FCNC)

As opposed to the SM prediction that $B(t \rightarrow Wb) \sim 1$, the top quark could decay into a Z-boson and a light quark through a Flavor Changing Neutral Current (FCNC) interaction. In a top quark pair decay, one possible signature is the three-lepton final state from $t\bar{t} \rightarrow Zq + Wb \rightarrow \ell^+\ell^-j + \ell^\pm\nu b$. This particular topology has been searched for using a cut-based analysis technique[8]. Events with three leptons $p_T > 20$ GeV are selected requiring $60 < m_{\ell^+\ell^-} < 120$GeV for same flavor lepton pairs. To enhance the signal yield over background, an extra criterion on HTs = $\sum p_{T\ell} + \sum E_{Tj} + E_T > 250$ GeV and $10 < m_{Wb}, m_{Zq} < 250$ GeV is applied. All backgrounds are estimated from simulation except for the $t\bar{t}$ and Drell-Yan backgrounds which have been estimated from data. For a dataset corresponding to an integrated luminosity
of $4.6 fb^{-1}$, $16.2 \pm 3.9 \text{(stat.)} \pm 2.6 \text{ (syst.)}$ events are expected in the background hypothesis only. In total 11 events where observed resulting in $Br(t \rightarrow Zq) < 0.34\%$ at 95% C.L.

### 4.4 Constraining the top quark charge

In the SM, the top quark has an electric charge of $+2/3e$. However, more exotic charge hypotheses exist. The top quark charge is reconstructed by exploiting the charge correlation between the high $p_T$ muon from the W-boson decay and the soft muons from B-hadron decay inside the b-jet. To discriminate between the expected charge of $+2/3e$ and a more exotic scenario of $-4/3e$, a normalized test statistic ($A$) is constructed such that $A=-1$ corresponds to the $-4/3e$ scenario. The measured value of $A_{\text{meas}} = 0.97 \pm 0.12 \text{(stat)} \pm 0.31 \text{(syst)}$ is in good agreement with the SM $A=1$ expectation ruling out the exotic scenario at 99.9% C.L.

### 5 Summary

With the excellent performance of the Large Hadron Collider and the high data-taking efficiency of the CMS experiment, the exploration of the top quark sector is advancing well. The CMS experiment has measured the top quark mass using a wide range of techniques in different channels resulting in a combined value of $m_t = 172.6 \pm 0.4 \text{(stat)} \pm 1.2 \text{(syst)}$ GeV and is continuing to increase precision. To further test the SM, the CMS experiment has performed many measurements. The difference in the top and anti-top quark mass was measured as well as deviations in the heavy flavor content. Searches were conducted for the existence of FCNC, anomalous couplings, and the existence of top quarks with a non-SM charge. So far no deviations from the SM have been observed.

### References


The data is being recorded at the Large Hadron Collider (LHC) for quite some time. All this data has produced only strong support for the standard model (SM). There does not seem to be any significant evidence for beyond the standard model (BSM) scenarios [1]. Various extensions of the standard model are getting seriously constrained. There also appear to be strong suggestions that the only missing piece of the SM, the Higgs boson exists. However, SM is unsatisfactory in a number of ways. One has to keep looking for any hint for the new physics signal. It would appear that to test the model and look for the directions for the extension, one may need to probe as many SM processes as possible. In particular, one would be looking for the processes that have many particles in the final state or have small cross sections.

At the LHC and proposed hadron colliders such as HE-LHC, one of the features is large gluon luminosity. Therefore, some of the $gg$ scattering processes, which occur at the one-loop level and have many particles in the final state, would be important and observable at the LHC. They can also contribute to the backgrounds to the BSM physics scenarios. We are interested in a particular set of processes $pp \rightarrow VV'g/\gamma X$. Here $V, V' = W, Z, \gamma$. We are particularly interested in the contribution from the gluon-gluon scattering. Since $W, Z, \gamma$ do not couple to the gluons directly, these processes take place at the one-loop.

A selection of the processes of interest are:

\begin{align}
    gg & \rightarrow \gamma\gamma, \gamma Zg, \gamma Z\gamma, \\
    gg & \rightarrow ZZg, ZZ\gamma, ZZZ, \\
    gg & \rightarrow WWg, WW\gamma, WWZ
\end{align}

The process $gg \rightarrow \gamma\gamma g$ has already been examined long ago. Our primary focus would be on the process $gg \rightarrow \gamma Zg$, with some comments on the other processes. The work on some of these processes has been reported in [2]. These generic processes take place at one-loop. The one loop diagrams that make contribution are box-type and pentagon-type diagrams. For the processes involving $W$-bosons, there are also triangle-type diagrams. These diagrams have a quark loop. We have also considered the possibility of a heavy quark in the loop, i.e., the top quark. For the processes (1),
for each quark flavour, there are 24 pentagon-type and 18 box-type diagrams. Only half of these diagrams are independent. Because of the Z-boson, the amplitude for both box-type and pentagon-type diagrams is sum of vector coupling and axial-vector coupling part. In the case of box-type diagrams, the axial-vector coupling pieces add up to zero (Furry’s theorem). So the box-type diagrams contribute only through vector coupling of the Z-boson. The process $gg \rightarrow \gamma Z \gamma$ gets contribution from only pentagon-type diagrams. Furthermore, here vector coupling contributions add up to zero. So there is contribution from axial-vector coupling of the Z-boson only.

Details of our calculation can be found in [2, 3]. For each class of diagrams, we write down the amplitude for a prototype diagram. The amplitude for the rest of the diagrams is generated by appropriate permutations of the external legs. One has to be a bit careful due the presence of $\gamma_5$ in the amplitude. The trace of $\gamma$ matrices is computed in $d$ dimensions using FORM. The amplitude is now written in terms of tensor integrals. The most complicated tensor integral that appears in the calculations is:

$$E_{\mu\nu\rho\sigma\delta} = \int \frac{d^4k}{(2\pi)^d} \frac{k^\mu k^\nu k^\rho k^\sigma k^\delta}{N_0 N_1 N_2 N_3 N_4}. \quad (4)$$

Here, $N_i = k_i^2 - m_q^2 + i\epsilon$ and $k_i$ is the momentum of the $i^{th}$ internal line in the corresponding scalar integrals; $d = (4 - 2\epsilon)$ and $m_q$ is the mass of the quark in the loop. We also examine the effect of non-zero $m_q$.

The tensor integrals are reduced to scalar integrals using the techniques of Oldenborgh and Vermaseren. For massless quarks in the loop, we have computed the scalar integrals and checked with existing results. For the massive quarks in the loop, we use OneLOop library for the bubble, triangle, and box scalar integrals. For the pentagon scalar integrals, we use the result of vanNeerven. One can write pentagon scalar integral in terms of box scalar integrals, $E_0 = \sum_{i=0}^{4} c_i D_0^{(i)}$.

We have made a number of checks on our calculation. The process is UV finite.
Pentagram diagrams are obviously UV finite. But individual box diagram is not. However, when we add box diagrams, the UV divergences cancel. We have checked that the mass singularities which show up as $\log^2(m_q)$ and $\log(m_q)$ also cancel. There is no soft IR divergence, as we will be making $p_T$ cuts on the jets. We have checked the gauge invariance by replacing the polarization vector of $g/\gamma/Z$ bosons with the corresponding momentum vector. The amplitude vanishes when we make this replacement for the photon, gluon and suitably for the Z-boson.

We compute the amplitude numerically, To do the phase space integration, we use a PVM implementation of the VEGAS algorithm (AMCI) and run the code on a cluster of machines. In Fig 2(i), we display cross section as a function of centre-of-mass energy. These results include following kinematic cuts: $P_{T,Z,j} > 50$ GeV, $|\eta^{\gamma,Z,j}| < 2.5$, $R(\gamma,j) > 0.6$. We have also chosen factorization and renormalization scales as $\mu_f = \mu_R = p_T^Z$. Rest of the results are for the center-of-mass (CM) energy of 14 TeV. In Fig 2(ii), we show the cross section as a function of $p_T^{\min}$. Fig 3 displays the $p_T$ and $\eta$ distributions for the gluon-jet and the photon. The plots for the Z-boson are similar to that of the photon. We observe that few hundred such events have already been produced at the LHC by now. Of course, one will have to dig it out of other tree-level processes with the same final state. We note that the photon $p_T$ distribution is harder, as compared to the gluon-jet distribution. It is because the photon is emitted from the quark loop, while the gluon can be emitted from another gluon (in the box diagram). The rapidity distribution of the gluon-jet is also more spread out. The virtue of this is that a cut on $p_T$ and rapidity of a photon can be used to discriminate from the processes where, it is emitted directly as bremsstrahlung, like in quark initiated processes. We find that the top-quark makes negligible contribution to the process. This decoupling of a quark occurs starting around $m_q = 100$ GeV.

The results for the process $gg \rightarrow \gamma\gamma g$ are already in literature for massless quark in the loop. We included heavy-quark, top-quark, in the calculation and found that it made negligible contribution. The typical cross-section for $p_T^{\min} = 30$ GeV, at 14 TeV LHC, is about 642 fb. The cross-section for the process $gg \rightarrow \gamma\gamma Z$ is quite small, as expected. It is about 0.05 fb.

In conclusion, we have presented brief results for the processes $gg \rightarrow \gamma Zg, \gamma Z\gamma$. These are standard model processes and cross sections are large enough so that these processes could be observable at the LHC. More detailed results can be found in [2, 3].

References


Figure 2: (i) Centre of mass energy (ii) $p_T^{\text{min}}$ dependence of the cross section (at 14 TeV) for $gg \rightarrow \gamma Zg$.

Figure 3: (i) $p_T$ and (ii) $\eta$ distributions of the gluon; (iii) $p_T$ and (iv) $\eta$ distributions of the photon.
Diboson cross section measurement at ATLAS and limits on anomalous gauge couplings

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1 Introduction

The diboson measurements using ATLAS pp collisions at $\sqrt{s} = 7$ TeV offer a good opportunity to study the high energy behavior of electroweak interactions in the Standard Model (SM). The measurements not only verify the SM theory but also aim for new physics search by probing the triple gauge-boson vertices through the search for anomalous couplings. Besides, the SM $W^+W^-$ and $ZZ$ productions are the irreducible backgrounds of dibosons produced by the Higgs decay.

2 Diboson measurement

We present measurements of diboson production in ATLAS [1] involving five different electroweak diboson channels ($ZZ$, $WZ$, $WW$, $W\gamma$ and $Z\gamma$). Cross sections are measured with full leptonic decay channels including neutrinos wherever relevant. $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ and $WW \to \ell\nu\ell'\nu$ are measured for exclusive production, namely without the presence of jets, whereas the other channels are measured for inclusive production, with any number of accompanying jets (Throughout this document, $\ell$ and $\ell'$ denote either electron or muon). For each channel, a total cross section is measured. Furthermore, in order to be less sensitive to theoretical uncertainties related to the extension of our measurement to the complete phase space volume, a fiducial cross section is measured within a phase space volume defined on the Monte Carlo generated particles which corresponds to the same kinematic cuts applied by the event selection. Limits on anomalous triple-gauge couplings (aTGCs) are set. Part of the results presented below are based on the full data sample taken in 2011, and correspond to an integrated luminosity of 4.7 fb$^{-1}$. The other results are based on a partial data set taken in the first part of 2011 and correspond to 1.02 fb$^{-1}$.

The $ZZ$ cross section is measured [2] using the leptonic $\ell^+\ell^-\ell'^+\ell'^-$ channels with the full 2011 data set. To extract the $ZZ$ signal, four isolated leptons are considered with a transverse momentum $p_T > 7$ GeV while the leading lepton must have
...candidates are selected by requiring $|m_{\ell^+\ell^-} - m_Z| < 25$ GeV and 62 observed candidates are left. The measured total cross section is $7.2^{+1.1}_{-0.9}$ (stat)$^{+0.4}_{-0.3}$ (syst)$\pm 0.3$ (lumi) pb, consistent with the SM prediction calculated at the Next-to-Leading Order (NLO), $\sigma_{ZZ} = 6.5^{+0.3}_{-0.2}$ pb. The measured fiducial cross section is $21.2^{+3.2}_{-2.7}$ (stat)$^{+1.0}_{-0.9}$ (syst)$\pm 0.8$ (lumi) fb. Limits on the neutral triple-gauge couplings [3] shown in Figure 1 are determined using the total number of observed events with the partial 2011 data set.

The $ZZ$ cross section is also measured [4] using the $\ell^+\ell^-\nu\bar{\nu}$ channels with the full 2011 data set. Neutrinos are detected by the presence of the missing transverse energy $E_T^{miss}$. Candidate events are preselected after requiring exactly two same-flavor opposite-sign (SFOS) leptons with $p_T > 20$ GeV within the $Z$ mass window ($|m_{\ell^+\ell^-} - m_Z| < 15$ GeV). The largest $Z + \text{jets}$ background is suppressed by requiring axial-$E_T^{miss} > 80$ GeV, where axial-$E_T^{miss}$ is the projection of the $E_T^{miss}$ vector along the direction opposite to the reconstructed $Z$ transverse momentum. The remaining $Z + \text{jets}$ and top backgrounds are further reduced by retaining only the events without any reconstructed jets with $p_T > 25$ GeV and $|\eta| < 4.5$. Finally, the signal event candidates are required to satisfy $|E_T^{miss} - p_T^Z|/p_T^Z < 0.6$. The measured total cross section is $5.4^{+1.3}_{-1.2}$ (stat)$^{+1.4}_{-1.0}$ (syst)$\pm 0.2$ (lumi) pb, consistent with the SM prediction, $\sigma_{ZZ}$ (NLO) = $6.5^{+0.3}_{-0.2}$ pb. The measured fiducial cross section is $12.2^{+3.0}_{-2.8}$ (stat)$\pm 1.9$ (syst)$\pm 0.5$ (lumi) fb.

The cross section results of the $W^\pm Z$ leptonic decay channel [5] are extracted using the partial 2011 data set. Events with at least three isolated leptons with $p_T > 15$ GeV are considered. $Z$ bosons are selected by requiring an SFOS lepton pair with invariant mass within 10 GeV of $m_Z$. The third lepton, assigned to the $W$, is required to have $p_T > 20$ GeV. The events must also have $E_T^{miss} > 25$ GeV, and the transverse mass reconstructed from $E_T^{miss}$ and the third lepton $p_T$ is required to exceed 20 GeV. The measured total cross section is $20.5^{+3.1}_{-2.8}$ (stat)$^{+1.4}_{-1.3}$ (syst)$^{+0.9}_{-0.8}$ (lumi) pb, consistent with the SM prediction, $\sigma_{WZ}$ (NLO) = $17.3^{+1.3}_{-0.8}$ pb. The measured fiducial cross section is $102^{+15}_{-14}$ (stat)$^{+6}_{-5}$ (syst)$\pm 4$ (lumi) fb. Limits on aTGCs, which are shown in Figure 1, are calculated using the total number of observed signal candidates.

$WW \rightarrow \ell\ell'\nu\bar{\nu}$ cross section results [6] are based on the full 2011 dataset. Candidate events are required to have exactly two opposite-sign isolated leptons with the leading (subleading) lepton $p_T$ above 25 (20) GeV. The most dominant background of $Z + \text{jets}$ is reduced by requiring $m_{\ell\ell'} > 15$ GeV and $|m_{\ell\ell'} - m_Z| > 15$ GeV for $\ell\ell' = e\mu$ or $\mu\mu$. Besides, the relative $E_T^{miss}$ which is the $E_T^{miss}$ projected onto the direction orthogonal to the closest lepton or jet (if the angle is below $\pi/2$, otherwise, it is simply the $E_T^{miss}$) is required to exceed 50, 55 or 25 GeV for $\ell\ell' = e\mu, \mu\mu$ or $e\mu$ respectively. The remaining dominant background is from top production, which can be reduced by requiring an exclusive final state, rejecting events with jet(s) having $p_T > 25$ GeV and $|\eta| < 4.5$ or jets with $p_T > 20$ GeV containing a b-hadron. The measured total cross section is $53.4 \pm 2.1$ (stat)$\pm 4.5$ (syst)$\pm 2.1$ (lumi) pb, consistent
with the SM prediction, $\sigma_{ZZ}$ (NLO) = 45.1 ± 2.8 pb. The fiducial cross sections vary between different channels, which have different kinematic cuts, and they are listed in [6]. Limits on aTGCs with the partial 2011 data set [7] are obtained using the $p_T$ distribution of the leading lepton. They are shown in Figure 1 and compared with other measurements.

$W\gamma$ and $Z\gamma$ cross section results [8] are based on the partial 2011 data set. W bosons are required to have one isolated lepton with $p_T > 25$ GeV, $E_{T}^{\text{miss}} > 25$ GeV and transverse mass, $m_T > 40$ GeV. Z bosons are required to have two isolated SFOS leptons with $p_T > 25$ GeV and invariant mass $m_{\ell\ell} > 40$ GeV. Isolated photons are required to have transverse energy $E_T > 15$ GeV. The remaining major backgrounds are from $W/Z + jets$. Both inclusive and exclusive cross section results are measured and compared with theoretical NLO predictions as shown in Figure 2. Measurements of the exclusive fiducial cross sections for $W\gamma$ with $E_T^{\gamma} > 100$ GeV and $Z\gamma$ with $E_T^{\gamma} > 60$ GeV are used in aTGCs limit extraction. Results are summarized in Figure 1 and compared with other measurements.

3 Summary

Diboson measurements using the 2011 7 TeV $pp$ collisions at ATLAS are presented. Both total and fiducial cross sections are measured. Limits on aTGCs are determined for the measured diboson productions. The results are competitive with those of LEP and Tevatron, and some are more restrictive than those of the Tevatron.

References

Figure 1: The 95% Confidence Intervals for anomalous couplings from ATLAS, D0, CDF, CMS and LEP for the aTGCs in $ZZ$, $WZ$, $WW$, $W\gamma$ and $Z\gamma$. The luminosities and the values assumed for the cut-off parameter $\Lambda$, which corresponds to a dipole form factor $f(s) = 1/(1+s/\Lambda^2)^2$ needed for unitarity, are indicated.

Figure 2: The measured cross section for $W\gamma(a)$ and $Z\gamma(b)$ production together with the SM prediction in the fiducial region. The measurements are performed in different $E_T$ and jet multiplicity regions. For a better comparison to SM predictions, the events are analyzed both inclusively, with no requirements on the recoil system, and exclusively, requiring there be no hard jet. The lower plots show the ratio between the data and the NLO prediction of the MCFM generator [9].
Measurement of the Drell–Yan differential cross section with the CMS detector at the LHC

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1 Introduction

The production of lepton pairs in hadron-hadron collisions via the Drell–Yan (DY) process is described in the standard model (SM) by the $s$-channel exchange of $\gamma^*/Z$. Theoretical calculations of the differential cross section $d\sigma/dM$ and the double-differential cross section $d^2\sigma/dMdY$, where $M$ is the dilepton invariant mass and $Y$ is the absolute value of the dilepton rapidity, are well established up to the next-to-next-to-leading order (NNLO). Comparisons between calculations and precise experimental measurements provide stringent tests of perturbative quantum chromodynamics (QCD) and constraints on the parton distribution functions (PDFs). Furthermore, the production of DY lepton pairs constitutes a major source of background for various physics analyses, such as $t\bar{t}$ and diboson measurements, as well as for searches for new physics beyond the standard model, such as production of high mass dilepton resonances. We present measurements of the differential DY cross section $d\sigma/dM$ in the dimuon and dielectron channels and the double-differential cross section $d^2\sigma/dMdY$ in the dimuon channel. The measurements are performed with the full 2011 dataset corresponding to an integrated luminosity of 4.5 fb$^{-1}$ of proton-proton collisions collected with the Compact Muon Solenoid (CMS) [1] detector at the Large Hadron Collider (LHC) at a centre-of-mass energy of $\sqrt{s} = 7$ TeV.

2 Analysis

The analysis is based on data samples selected by di-lepton triggers. The events in the dimuon channel are triggered by two muons, where each muon track is matched to a silicon tracker track. Asymmetric muon $p_T$-thresholds of 8 and 13 GeV are applied. Muons are required to pass the standard CMS muon identification and quality criteria, based on the number of hits found in the tracker, the response of the muon chambers, and a set of matching criteria between the muon track parameters as determined by the inner tracker section of the detector and as measured in the muon chambers.
In order to reduce the fraction of muon pairs from (different) light-meson decays a common vertex for the two muons is fitted and the event is rejected if the dimuon vertex $\chi^2$ probability is smaller than 2. The events in the dielectron channel are triggered by two electrons with minimum $E_T$ requirements of 17 GeV for one of the electrons and 8 GeV for the other. Energy-scale corrections are applied to individual electrons and each electron candidate is required to be consistent with a particle originating from the primary vertex in the event. Electron identification criteria based on shower shape and track-cluster matching are applied to the reconstructed candidates. Electrons originating from photon conversions are rejected by eliminating those electrons for which a partner track consistent with a conversion hypothesis is found, and requiring no missing hits in the pixel detector. Isolation requirements are imposed on muons and electrons.

The differential $d\sigma/dM$ cross section measurements are performed in 40 mass bins. The double-differential cross section measurement is performed in 6 dimuon invariant mass bins. For each mass bin, 24 bins of absolute dimuon rapidity are defined, except for the highest mass bin, where only 12 absolute dimuon rapidity bins are used.

The main backgrounds at high dilepton invariant masses are caused by $t\bar{t}$ and diboson production, while at invariant masses below the $Z$ peak, DY production of $\tau^+\tau^-$ pairs becomes the dominant background. At low dimuon invariant masses, most background events are QCD multijet events. At low dielectron invariant masses, most background events are from $\tau^+\tau^-$ and $t\bar{t}$, whilst the contribution from QCD is small. For the dimuon channel, the electroweak and $t\bar{t}$ backgrounds are evaluated through simulation studies, expected to provide a good description of the real contributions. In contrast, the QCD background is evaluated from data. The background estimation is performed with the same methods [2]. There are two categories of dielectron backgrounds: the first category contributes candidates composed of two genuine electrons and the second contributes candidates in which at least one particle is a misidentified electron. We estimate the contribution from these processes with a sample of $e^{\pm}\mu^{\pm}$ events having the same physical origin. The genuine dielectron background from $WZ$ and $ZZ$ production is estimated from simulation. The misidentified electron backgrounds originate from QCD multijet and $W$+jet events.

The reconstructed dilepton invariant mass spectra are first corrected for acceptance (in case of the $d\sigma/dM$ measurement) and detector efficiencies. Then the corrected spectra are altered by a bin-by-bin final state electromagnetic radiation (FSR) correction factor which relates the yields before and after the FSR takes place. The effects of the detector resolution on the observed dilepton spectra are corrected through an unfolding procedure [2]. The trigger, reconstruction and identification efficiency is estimated using clean samples of muon pairs in the $Z$ peak. To describe the observed efficiency variations between data and simulation, efficiency correction factors are obtained in bins of $p_T$ and $\eta$ as the ratio of the efficiencies measured with data and with the simulated events.
3 Results

In order to reduce systematic uncertainties, the Drell-Yan differential cross section is normalized to the cross section in the $Z$ peak region ($60 < M < 120$ GeV). The result of this measurement in the full phase space is presented in Fig. 1. The $d\sigma/dM$ measurement is in agreement with the NNLO theoretical predictions, as computed with FEWZ [3] using the MSTW2008 PDFs.

![Figure 1: The Drell-Yan invariant mass spectrum, normalized to the Z resonance region, as measured and as predicted by NNLO calculations, for the full phase space in the dimuon channel (left) and the dielectron channel (right).](image)

The result of the double-differential cross section measurement within the detector acceptance is presented in Fig. 2. The measurement is compared to the POWHEG NLO [4] prediction calculated with CT10 PDFs and the NNLO theoretical predictions as computed with FEWZ [3] using the MSTW2008 PDFs.

References

Figure 2: The Drell-Yan rapidity-invariant mass spectrum within the detector acceptance in the dimuon channel, normalized to the $Z$ resonance region.
ATLAS measurements of photons, jets and subjets

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Abstract

Comprehensive measurements of inclusive and dijet cross sections are presented, spanning the dijet mass range from 70 GeV to 4 TeV. Inclusive photons and diphotons have also been measured over a wide range of mass and pT. These measurements constitute precision tests of QCD in a new energy regime, and show sensitivity to the parton densities in the proton. In addition, charged particles, subjets and jet shapes have been measured, to investigate jet fragmentation and to study new variables developed to reduce sensitivity to soft QCD and pileup, and to improve the identification of boosted heavy particles decaying to hadrons.

1 Introduction

Measurements of prompt photons and jets at the LHC provide precision tests of perturbative QCD and help constrain the parton densities in the proton in a new kinematic regime. For example, photon production with an associated jet is particularly sensitive to the gluon content and photon fragmentation function. Quantifying the detector response to photons and jets not only improves the calibration, but aids understanding of backgrounds to key channels such as Higgs ($\gamma\gamma$), and to searches for new physics beyond the Standard Model. The composite nature of jets formed by two- and three-body decays enables boosted objects to be identified from their jet substructure, which differs to that from quark and gluon initiated jets. These proceedings begin with a synopsis of the reconstruction methods before summarizing the latest ATLAS measurements of photon and jets, and finally recent studies of jet substructure are reviewed.

2 Photon and jet reconstruction and calibration

Photons are reconstructed in ATLAS [1] using a finely segmented, multi-layer liquid argon-lead sampling calorimeter, in which the lateral and longitudinal shower shapes allow suppression of hadronic background. Converted and unconverted photons are distinguished using nine discriminating variables. Prompt photons deposit energy in a tight radial cone enabling identification using an isolation requirements of
$E_T^{ISO} < 3 \text{ GeV}$. Jets are reconstructed as four-vector summations of noise-suppressed three dimensional calorimeter clusters, grouped by the anti-$k_T$ or Cambridge-Aachen clustering algorithm [2]. The jet energy scale uncertainty is $< 5\%$ after corrections for the non-compensating calorimeter, dead material, out-of-cone effects and pile-up, and is validated in-situ using the $Z(\text{ee}) + \text{jet}$ direct transverse momentum balance [3, 4].

3 Measurements

3.1 Photons

The kinematic reach of prompt photon measurements has been extended from a photon $E_T$ of 15–100 GeV [5] to the range 45–400 GeV [6, 7]. The measurements are consistent in overlap bins, though show some discrepancies below 25 GeV for central photons, which has helped to constrain the gluon pdfs [8].

Differential diphoton cross-section measurements [9] generally agree well with the NLO model, except for a discrepancy at low $\Delta \phi_{\gamma\gamma}$, as shown in Fig 1. The discrepancy is improved by $\gamma\gamma$NNLO calculations [10].

Figure 1: Differential diphoton cross-section as a function of $m_{\gamma\gamma}$, $p_T^{\gamma\gamma}$ and $\Delta \phi_{\gamma\gamma}$ [9].

In a recently published analysis [11] of the first 37 pb$^{-1}$ recorded by ATLAS, the cross section for production of an isolated photon associated with jets is calculated in six different angular configurations of the jet and photon rapidity. This division of the phase space enables access to regions of differing fragmentation contributions and parton momentum fractions. NLO pQCD predictions are found to be in fair agreement with the data, except for $E_T^\gamma \leq 45$ GeV, where theory overestimates the measured cross section, again indicating that NNLO predictions are necessary.
3.2 Jets

Existing ATLAS measurements of inclusive and dijet jet cross sections [12] have been extended [13] to include jet rapidities up to $|y| < 4.4$ and to span jet transverse momenta from 20 GeV to 1.5 TeV and dijet masses from 70 GeV to 5 TeV. Comparisons with NLO pQCD predictions show good agreement over many orders of magnitude, covering $7 \times 10^{-5} < x < 0.9$ in the parton momentum fraction.

The 2011 data corresponding to $4.8 \pm 0.2$ fb$^{-1}$ were used to measure the dijet double-differential cross section [14] as a function of dijet mass, $m_{12}$ and half the absolute separation between the two jets, as shown in Fig 2. In general there is good agreement between data and NLO pQCD predictions including non-perturbative corrections, while a negative trend emerges in data at large $y^*$ and $m_{12}$.

![Figure 2: Dijet double-differential cross section as a function of dijet mass, binned in half the absolute rapidity difference between the two leading jets, $y^* = \frac{|y_1 - y_2|}{2}$. The results are shown for jets identified using the anti-$k_T$ algorithm with $R = 0.6$. [14].](image)

3.3 Subjets

When a heavy object decays hadronically the Lorentz boosted products are typically so tightly collimated that they are reconstructed as a single merged jet in ATLAS. The mass and internal substructure of composite jets can be exploited to identify boosted
objects of interest, while suppressing hadronic background. Recent measurements [15] of the jet mass were made in the $p_T$ range $200 – 600$ GeV and are shown in Fig 3 for a restricted window of $300 – 400$ GeV. While Pythia tends to be too soft and Herwig++ too hard, applying splitting and filtering [16] recovers the constituent subjets and improves the agreement with the prediction.

A deeper insight into jet properties has been gained by direct measurements [17] of subjet characteristics and simulation studies of correlations between the key variables, including: angularity, planar flow, eccentricity, width, $p_T$ and mass. The studies show that splitting and filtering largely eliminates the dependence of the jet mass on pile up interactions.

Figure 3: Normalised cross-section as a function of mass of Cambridge-Aachen jets with $R = 1.2$, before (left) and after (right) splitting and filtering [15].

4 Conclusion

Comprehensive measurements of photons, jets and subjets provide precision tests of perturbative QCD in a new kinematic regime. The photon and diphoton cross sections have helped constrain the gluon pdfs and indicate NNLO calculations are necessary to best describe the data. Measurements of inclusive and dijet cross sections agree well with NLO pQCD over many orders of magnitude, while constraining parton shower tunes for high mass dijets. Jet substructure observables have been measured leading to improved understanding of jet substructure techniques, which are useful for identifying boosted hadronic topologies in searches for new physics.
References

Higgs boson search at ATLAS

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1 Introduction

The 2011 run of the Large Hadron Collider (LHC) at CERN was very successful, with experiments accumulating nearly 5 fb\(^{-1}\) of data. Of particular interest was the search for a Standard Model (SM) Higgs boson, the remaining component of the SM that has not yet been definitively observed. This note summarizes the status of this search at the ATLAS experiment [1] using the full 2011 data set of (4.6–4.9) fb\(^{-1}\).

2 Higgs boson search channels

The Higgs boson search is carried out for many different final states. At the LHC, the dominant production mode for a Higgs boson is gluon-gluon fusion \((gg \rightarrow H)\). For a Higgs boson with mass \(m_H\) above about 135 GeV, the dominant decay is into a pair of \(W\) or \(Z\) gauge bosons; such decays that include leptons in the final state are distinctive enough to search for directly. For lower Higgs boson masses, the dominant decay is into two \(b\)-quarks. The very large heavy-flavour multijet background makes it infeasible to search for this decay directly. One can look for rarer but more distinctive decays of the Higgs boson, such as \(H \rightarrow \gamma\gamma\) or \(H \rightarrow \tau\tau\), for diboson decays in which one of the gauge bosons is off-shell, or for a Higgs boson produced in association with a \(W\) or \(Z\) boson. The best sensitivity for \(m_H \approx 125\) GeV is obtained from \(H \rightarrow \gamma\gamma\), followed by \(H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell\).

2.1 \(H \rightarrow \gamma\gamma\) channel

The diphoton decay of the Higgs boson is relatively rare (with a branching ratio \(\sim 0.2\%\)). In order to have good sensitivity in this channel [2], one must have very good \(m_{\gamma\gamma}\) resolution as well as good control over non-photon backgrounds. ATLAS achieves a mass resolution of about 1.7% at \(m_H = 120\) GeV, and the fraction of non-photon background is less than 30%.

To optimize the expected sensitivity, the analysis is split into nine subchannels with differing mass resolution and expected signal fraction, depending on the kinematics of the photons and whether they converted. The background is modeled with...
an exponential fit to the data. Results are shown in Figure 1. The $m_H$ regions (113–115) GeV and (134.5–136) GeV are excluded at 95% CL. A small excess is seen around $m_H = 126.5$ GeV, with a local significance of $2.8\sigma$, or a global significance of $1.5\sigma$ when the look-elsewhere effect is taken into account over the $m_H$ range (110–150) GeV.

Figure 1: Results from the $H\rightarrow\gamma\gamma$ channel [2]. Left: Invariant mass distribution for the entire sample, overlaid with the fitted total background. The expectation for a $m_H = 125$ GeV SM Higgs boson is also shown. Right: Local probability $p_0$ for the background to fluctuate to the observed number of events or higher. The dashed line shows the expected median local $p_0$ for the signal hypothesis when tested at $m_H$.

2.2 $H\rightarrow ZZ^{(*)}\rightarrow\ell\ell\ell\ell'$ channel

In this channel [3], one looks for two pairs of opposite-sign, same-flavour leptons ($e$ or $\mu$), with one pair having an invariant mass close to the $Z$ boson mass. This channel has a quite small background and a fully-reconstructed Higgs boson decay, which allows it to have good sensitivity over a wide range of Higgs boson masses, from 600 GeV down to 110 GeV. The background is primarily $ZZ$ diboson production, with smaller contributions from $Z +$ jets and $t\bar{t}$.

The results are shown in Figure 2, Row 1. The $m_H$ regions (134–156) GeV, (182–233) GeV, (256–265) GeV, and (268–415) GeV are excluded at 95% CL. Small excesses are seen around 125 GeV, 244 GeV, and 500 GeV with local significances of $2.1\sigma$, $2.2\sigma$, and $2.1\sigma$, respectively. The excess at 125 GeV corresponds to three events that cluster within the $m_H$ mass resolution of 2%: two $2e2\mu$ events at 123.6 and 124.3 GeV, and one $4\mu$ event at 124.3 GeV.

2.3 $H\rightarrow WW^{(*)}\rightarrow\ell\nu\ell\nu$ channel

This channel [4] is also sensitive over a wide mass range. The event selection requires two isolated, opposite-sign leptons and a large missing transverse energy ($E_T^{\text{miss}}$). The
Figure 2: Selected results. Left two columns: data compared with expected background for (Row 1) $m_{4\ell}$ from the $H \rightarrow ZZ^{(*)} \rightarrow \ell\ell'\ell\ell'$ channel for 100 GeV < $m_H$ < 250 GeV and for the complete range [3]; (Row 2) $m_T$ from the $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$ channel with 0/1 jets [4]; (Row 3) $m_{bb}$ from the $ZH$ and $WH$ channels [5]; (Row 4) $m_{\tau\tau}$ from the $H \rightarrow \tau\tau\tau\ell$ and $H \rightarrow \tau\tau\ell\ell$ channels [6]. An example of the expected signal is also shown (scaled up for some channels to make it more visible). Right: Corresponding exclusion plots, showing the expected (dashed) and observed (solid) 95% CL upper limits on SM Higgs boson production. The dark (green) and light (yellow) bands indicate the expected limits with ±1σ and ±2σ fluctuations, respectively.
analysis is divided into subsamples with 0, 1, and $\geq 2$ jets, as the background composition is quite different for these cases: for the 0-jet case, the background is dominated by the $WW$ and $Z +$ jets processes, while for the 2-jet case, $t\bar{t}$ dominates. As there are two neutrinos in the final state, the Higgs boson mass cannot be reconstructed; the transverse mass $m_T$ is used instead. Results are shown in Figure 2, Row 2. No excess is seen, and the $m_H$ region (133–261) GeV is excluded at 95% CL.

2.4 Other low-$m_H$ channels

Two additional channels are sensitive to a low-mass Higgs boson. In the $V(H\to b\bar{b})$ channel [5], one searches for a Higgs boson produced in association with a vector gauge boson, with the Higgs boson decaying into a $b\bar{b}$ pair. The event selection for this channel requires a gauge boson decay to leptons/neutrinos (one of $W\to \ell\nu$, $Z\to \ell\ell$, or $Z\to \nu\nu$) and exactly two $b$-tagged jets. The analysis is subdivided in bins of $p_T(V)$. The $H\to \tau\tau$ analysis [6] is divided into 2$\ell\nu\nu$, 2$\ell\tau\nu$, and 2$\tau\nu\nu$ subchannels; these are then further subdivided according to the number of extra jets in the event. Since there are multiple neutrinos in the final state, the invariant mass $m_{\tau\tau}$ is estimated either using the collinear approximation (assuming the neutrino to be collinear with the visible decay products) or the “missing mass calculator” technique (incorporating the probability distribution for the opening angle in $\tau$ decays).

Selected results are shown in Figure 2, Rows 3 and 4. Exclusion limits for these channels range from about 2.5 to 12 times the SM Higgs boson production cross section over the $m_H$ range (100–150) GeV.

2.5 Other high-$m_H$ (diboson) channels

The remaining diboson channels are sensitive to higher Higgs boson masses. For the $H\to ZZ\to \ell\ell\nu\nu$ channel [7], events with a $Z\to \ell\ell$ decay and large $E_T^{\text{miss}}$ are selected. Different selection requirements are made for $m_H$ above or below 280 GeV. For $H\to ZZ\to \ell\ell qq$ [8], events are selected with one $Z\to \ell\ell$ decay, one $Z\to jj$ decay, and small $E_T^{\text{miss}}$. As the fraction of heavy-flavour in the final state is quite different for signal and background, this channel is divided into “tagged” (with two identified $b$-jets) and “untagged” subchannels. The principal backgrounds for these two channels are $Z +$ jets, $t\bar{t}$, and ZZ. For the $H\to WW\to \ell\nu qq$ channel [9], events are selected with an isolated lepton, large $E_T^{\text{miss}}$, and a $W\to jj$ decay. This analysis is divided into subchannels according to the number of additional jets in the event.

Results are shown in Figure 3. The $ZZ\to \ell\ell\nu\nu$ channel excludes at 95% CL the $m_H$ range (320–560) GeV, while the $ZZ\to \ell\ell qq$ channel excludes the ranges (300–322) GeV and (353–410) GeV. Exclusions from the $WW\to \ell\nu qq$ channel are 2–10 times the SM cross section.
Figure 3: Selected results from the remaining diboson channels. Top: data and expected background for $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$, showing $m_T$ [7] (left); $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$, showing $m_{\ell\ell\ell\ell}$ for the high-$m_H$, tagged subchannel [8] (middle); and $H \rightarrow WW \rightarrow \ell\ell\nu\nu$, showing $m_{\ell\nu\ell\nu}$ for the 0-jet subchannel [9] (right). The expectations for a Higgs boson of $m_H = 350$ GeV are also shown. Bottom: Corresponding exclusion plots (see Figure 2).

3 Combination of all channels

For the final results, all these channels are combined [10]. Systematic uncertainties are taken to be either 100% correlated or uncorrelated between channels. The results are shown in Figure 4. The $m_H$ ranges (111.4–116.6) GeV, (119.4–122.1) GeV, and (129.2–541) GeV are excluded at 95% CL, and the $m_H$ range (130.7–506) GeV is excluded at 99%. An excess is seen around $m_H = 126$ GeV, with a local significance of 3.0$\sigma$. The global significance is approximately 15% over the full range (100–600) GeV and (5–7)% over the range (110–146) GeV, corresponding to the range at low-$m_H$ not excluded by the previous LHC SM Higgs boson combined search at 99% CL [11]. If the excess is interpreted as a SM Higgs boson, the corresponding cross section ratio at $m_H = 126$ GeV is $\mu = \sigma_{\text{obs}}/\sigma_{\text{SM}} = 1.1 \pm 0.4$, consistent with the SM value of 1.0. The excess is observed only in the $H \rightarrow \gamma\gamma$ and $H \rightarrow \ell\ell\ell'$ channels; however, none of the other channels are inconsistent with a SM Higgs boson at this mass.

4 Summary

From the 2011 data, ATLAS excludes at 95% CL the $m_H$ range (111.4–541) GeV, except for the regions (116.6–119.4) GeV and (122.1–129.2) GeV. An excess is seen in the $H \rightarrow \gamma\gamma$ and $H \rightarrow \ell\ell\ell'$ channels at $m_H \approx 126$ GeV which is consistent with a
Figure 4: Left, middle: Combined exclusion limits for the full mass range and for $m_H < 150$ GeV [10] (see Figure 2). Right: Local probability $p_0$ for the background to fluctuate to the observed number of events or higher, by channel, for $m_H < 150$ GeV. Dashed lines show the expected median local $p_0$ for the signal hypotheses at $m_H$.

SM Higgs boson. The chance of this being due to a background fluctuation is 15% over the full mass range, or (5–7)% over (110–146) GeV.

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References

Higgs searches in CMS

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1 Introduction

The search for the scalar boson of the Brout-Englert-Higgs mechanism [1, 2] is one of the most important aspects of the program of the Large Hadron Collider. The boson has been excluded at 95% confidence level (CL) by direct searches at LEP [3] for masses smaller than 114.4 GeV and at Tevatron [4] for masses around 160 GeV.

In the context of the Standard Model (SM) indirect constraints from precision electroweak measurements favour a low mass Higgs boson, with the upper limit $m_H < 169$ GeV at 95% CL from the standard fit and $m_H < 143$ GeV at 95% CL including direct searches before LHC. The dominant Higgs production mode at LHC is the gluon-gluon fusion, followed by vector boson fusion (VBF) and associated production with a vector boson (VH) which have smaller cross sections but cleaner final states. The search channels as well as their optimization vary as function of the Higgs mass. The most sensitive decay at low mass, below approximately 130 GeV, is the one into two photons; between $\sim 130$ and 200 GeV the WW channel is the most sensitive, and above $\sim 200$ GeV the various ZZ channels take over.

A detailed description of the CMS detector can be found in [5]. The analyses described in the following use up to 5 fb$^{-1}$ of data collected during 2011 by CMS at a center-of-mass energy of 7 TeV, with an average of 9 pile-up interactions per bunch crossing. Results of searches for the Higgs in the Standard Model and beyond (SUSY and other BSM scenarios) are discussed.

2 Low mass SM channels

2.1 $H \to \gamma\gamma$ channel

The Higgs boson branching ratio for the decay into two photons is approximately $2 \times 10^{-3}$ between 110 and 150 GeV. The diphoton mass resolution is very good,
around 1-2%, and the signature in this channel is two high $E_T$ isolated photons. A signal would appear as a small, narrow peak above a large background smoothly falling. After the final selection, the dominant background is the irreducible $\gamma\gamma$ QCD production, followed by events in which at least one of the two identified photons is a jet faking a photon. Events produced via VBF are selected requiring two extra jets at large $\Delta\eta$. The signal to background ratio in the di-jet tag class is relatively large, bringing to an improvement on the exclusion sensitivity of approximately 10% in cross section [6, 7]. For the limit and significance calculation, the background is estimated by fitting with a polynomial the full mass range. We found that the possible bias in the background estimation is always less than 20% of the statistical error. The expected 95% CL exclusion limit on the cross-section varies between 1.2 and 2 times the SM prediction, while data exclude at 95% CL the mass ranges 110.0-111.0 GeV, 117.5-120.5 GeV, 128.5-132.0 GeV, 139.0-140.0 GeV and 146.0-147.0 GeV. We observe the largest excess around 125 GeV with a local significance of $2.9\sigma$. The global significance is $1.6\sigma$ when taking into account the look elsewhere effect (LEE) estimated in the full mass range 110-150 GeV.

2.2 $H \rightarrow \tau\tau$ and $H \rightarrow bb$ channels

The $H \rightarrow \tau\tau$ and $H \rightarrow bb$ channels are the only Higgs boson decays into fermions detectable at LHC. They are less sensitive than the $H \rightarrow \gamma\gamma$ channel, but would be important to measure the couplings to leptons and quarks. In both channels the background for the inclusive search is huge and the sensitivity is improved by requesting additional tags.

For the $\tau\tau$ channel we exploit the VBF production as well as a boosted topology. The mass reconstruction is not very precise (around 20%) due to the presence of neutrinos in the decay. The search is performed in the mass range between 110 and 150 GeV [8] and the expected exclusion limit at 95% CL is approximately 3 times the SM prediction, without any significant excess in data.

To study the Higgs decays to bb we exploit the VH associated production with W and Z decaying leptonically [9]. We require the bb system to be boosted to improve both the background rejection and the mass resolution, which is about 10%. We perform the search in the mass range between 110 and 135 GeV and the expected sensitivity for exclusion ranges from 3 to 6 times the SM. Also in this channel we see no significant excess in data.
3 SM channels sensitive in the full mass range

3.1 $H \to WW \to 2\ell 2\nu$ channel

The $H \to WW \to 2\ell 2\nu$ channel is the most sensitive one approximately in the mass range 125-200 GeV. The final state consists of two isolated high $p_T$ leptons and large missing transverse energy due to the presence of the two undetected neutrinos, which are also responsible for the poor mass resolution (of the order of 20%). The most important backgrounds are the irreducible WW production and the reducible W plus jets, Z plus jets, ttbar and di-bosons productions. Most of them are estimated from data.

The analysis [10] is performed in the full mass range from 110 to 600 GeV, in exclusive jet multiplicities (0, 1 and 2-jet bins) and flavour ($\text{ee}$, $\mu\mu$, $e\mu$) categories because of the different sensitivities and background contributions. The 2-jet bin corresponds to the VBF topology and the search exploits characteristics such as the presence of jets at large $p_T$, $\Delta\eta$ and di-jet invariant mass. Two types of searches are carried out: a cut-and-count analysis for all the sub-channels and a multivariate analysis which is applied to the 0 and 1-jet bins only. In both cases a mass dependent selection is used. We observe no significant excess in the full mass range though a small excess is observed at low mass. The 95% C.L. expected exclusion is for $m_H$ between 127 and 270 GeV, while the range 129-270 GeV is excluded at 95% CL in data.

3.2 $H \to ZZ \to 4\ell$ channel

The $H \to ZZ \to 4\ell$ channel has the cleanest final state, which is characterized by the presence of four isolated leptons. For high Higgs mass both pairs of opposite charge and same flavour leptons are consistent with Z decays, while for lower Higgs masses at least one pair has lower mass. The mass resolution is very good and ranges between 1 and 2%. The Higgs branching ratio for this channel is rather small but the background is almost negligible. It mainly consists of irreducible continuum ZZ production and, to a lesser extent, Z plus jets and Zbb. The $p_T$ of the lower $p_T$ lepton is rather small and one of the most challenging issues of the analysis is the achievement of high lepton selection efficiency down to very low $p_T$. The analysis is carried out in the full mass range, from 110 to 600 GeV [11]. We do not observe any significant excess in data and we exclude at 95% CL the SM Higgs boson with $m_H$ in the 134-158, 180-305 and 340-465 GeV regions. The most significant excess is given by an accumulation of 3 events at a mass of approximately 119.5 GeV. It has a local significance of 2.5$\sigma$ and a global significance of 1.0$\sigma$ in the full mass range and 1.6$\sigma$ in the mass range 100-160 GeV.
4 High mass SM channels

The SM Higgs boson almost exclusively decays into WW and ZZ for masses above approximately 200 GeV. The search in the previously described H→ WW → 2ℓ2ν and H→ ZZ → 4ℓ channels have been performed in CMS up to m_H 600 GeV. For the high mass region searches have been performed also in the ZZ channels where one Z decays into ν [12], quark [13] and τ pairs [14]. The first one has high sensitivity for m_H > 250 GeV, resulting in a 95% CL exclusion of Higgs masses in the 270-440 GeV region. The second channel a little lower sensitivity, while the last one has a sensitivity of about 4 times the SM. The search in the channel H→ WW → qqlν has been also performed, which has good sensitivity for high masses resulting in a 95% CL exclusion of m_H in the range 327-415 GeV.

5 Combination of all SM channels

Eleven SM decay channels have been studied in CMS using up to 5 fb⁻¹ of 7 TeV collision data and they are combined to obtain the final exclusion and discovery confidence levels. The combination is carried out using the CLs method. The values of cross sections and branching ratios and their theoretical uncertainties are taken from the LHC cross section working group [15]. More details on the present combination, which includes preliminary results, can be found in [16]. An overall signal strength multiplier \( \mu = \sigma / \sigma_{SM} \) is introduced and limits on its value are derived.

Figure 1 on the left shows the SM exclusion confidence level as function of the Higgs boson mass. The SM Higgs boson is excluded by our search at 95% confidence level in the range 127.5–600 GeV and at 99% confidence level in the range 129–525 GeV. The expected 95% exclusion is 114.5–543 GeV. The observed upper limit on the Higgs boson mass is higher than expected in case of no signal because of the excess that is observed in the data in the region between 115 and 128 GeV. Figure 1 on the right shows the local p-value as a function of the Higgs boson mass, which quantifies the probability that a background-only fluctuation is more signal-like than the observation. The minimum combined p-value is observed at a mass of 125 GeV with a local significance of 2.8σ. A similar significance is expected in presence of a 125 GeV Higgs boson signal. When taking into account the look elsewhere effect estimated in the mass range 110-600 GeV (110-145) we obtain a global significance of 0.8σ (2.1σ). The fitted value of the signal strength multiplier \( \mu = \sigma / \sigma_{SM} \) of the excess near 125 GeV is consistent with the SM scalar boson expectation and several channels show some excess, though most of it comes from the \( H \rightarrow \gamma \gamma \) channel.
Figure 1: Exclusion confidence level for the combined SM Higgs search in the full mass range 110–600 GeV (left) and combined local p-value for the SM Higgs search (right).

6 Non Standard Model Higgs searches

While the Standard Model describes very precisely the experimental measurements some open points still arise like the dark matter origin and the hierarchy problem. Theories have been proposed to answer some of these questions, such as supersymmetry or other scenarios beyond the standard model (BSM). In the Minimal Supersymmetric Standard Model (MSSM), the standard scalar Higgs boson is replaced by three neutral (h, H, A) and two charged (H±) Higgs particles, and all decays to down-type fermions are enhanced by a factor tanβ. The MSSM neutral Higgs bosons are searched in CMS in the ττ final state and a large fraction of the MSSM Higgs parameters space is constrained [8]. Charged MSSM Higgs bosons are searched in the top decays $t \rightarrow bH^\pm$ with τ final states $H^+ \rightarrow \tau \nu$ [17]. Higgs studies in the context of the next-to-minimal-supersymmetric extensions of the Standard Model [18] or the see-saw model [19] are also carried out. Finally, searches for the Higgs boson in extensions of the Standard Model including a fourth generation of fermions (SM4) or with a Fermiophobic Higgs are performed [16]. No excess is found in any of these searches with 2011 data, and limits are set.

7 Conclusions

The search for the SM Higgs boson in different final states, using CMS data at $\sqrt{s} = 7$ TeV, has been presented. The SM Higgs boson is excluded at 95% CL in the mass range 127.5–600 GeV, and an excess of events above the expected SM background is observed at the lower end of the explored mass range. The largest excess, with a local significance of 2.8 standard deviations, is observed for a Higgs boson mass hypothesis of 125 GeV. In addition, a broad program of BSM Higgs searches has been performed, showing no evidence for BSM Higgs bosons.
References


Electroweak and Hints of New Phenomena at the Tevatron

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1 Introduction

The CDF and D0 experiments at Fermi National Accelerator Laboratory Tevatron collider have carried out a diverse program of electroweak measurements which test the predictions of the standard model. Many of these tests are also sensitive to alternative theories that enhance the standard model at high energies. In addition to these searches, the Tevatron experiments have performed extremely precise measurements of the W mass, which along with the top mass provide a constraint on the allowed mass of the Higgs boson within the standard model. These measurements are made at a center of mass energy of $\sqrt{s}=1.96$ TeV in proton-antiproton collisions, utilizing between 2.1-8.6 fb$^{-1}$ of integrated luminosity.

2 Searches for New Phenomena

2.1 $Z \rightarrow ee$

The dielectron final state is one of the best measured topologies at the Tevatron as both experiments have excellent electron resolution. The CDF experiment has produced a new measurement of the $Z$ $p_T$ distribution [1] (the invariant mass range selected is $66 < M_{ee} < 115$ GeV), which utilizes the same well understood 2.1 fb$^{-1}$ dataset as an earlier measurement of the $Z$ angular coefficients [2]. At low transverse momentum the $Z$ $p_T$ is sensitive to the effects of soft gluon emission, while at high $p_T$ the distribution tests higher order QCD effects. The shape of the distribution at low $p_T$ is also an important ingredient in describing the shape of the W $p_T$ distribution, needed for precision measurement of the W mass. The measured differential cross section is shown in Figure 1. When compared to the RESBOS [3] theoretical prediction, there appears to be general agreement over the full range of $p_T$.

Also utilizing the dielectron final state, the D0 experiment has produced a measurement of the $e^+e^-$ forward-backward asymmetry, and extracted the corresponding
value of $\sin^2\theta_W$ in the vicinity of the Z resonance ($70 < M_{ee} < 130$ GeV), using 5 fb$^{-1}$. If an additional heavy resonance were being produced and decaying to dielectrons, the forward-backward asymmetry would deviate from the standard model prediction in that invariant mass range (see Figure 2). No such deviation is observed.

D0 extracts a value of $\sin^2\theta_W = 0.2309 \pm 0.0010$ and also uses this measurement to set limits on the u- and d-quark vector and axial couplings [4]. CDF has also produced a preliminary measurement corresponding to $\sin^2\theta_W = 0.2320 \pm 0.008^{+0.001}_{-0.0009}$ using 2.1 fb$^{-1}$. With the full Run II dataset utilizing CDF and D0 combined, the precision of this result will have a substantial impact on the world average.

2.2 Diboson Final States

Diboson production provides an excellent test of the standard model. Since the trilinear gauge couplings are specified exactly (with no room for tuning), each measurement is also a search for new physics, particularly at high boson transverse momentum.

The D0 experiment has performed a measurement of the differential cross section for $Z\gamma$ production as a function of photon transverse momentum using 6.2 fb$^{-1}$ of integrated luminosity (electron and muon decays of the Z are used) [5]. In multiboson final states often a parametrized lagrangian is used to detail consistency with the standard model couplings. In this particular case however, models of gauge mediated supersymmetry breaking would also give rise to additional events with a photon and a Z boson. In these models, the next-to-lightest supersymmetric particle (NLSP)
decays to a neutral gauge boson and the gravitino, which results in a final state with missing transverse energy (the escaped gravitino) and multiple gauge bosons. The typical final state which is used in these searches is two photons and missing transverse energy, but a complementary channel is when one NLSP decays to a $Z$ boson and the other decays to a photon. No excess in the missing transverse energy is observed and limits are set on the production cross section [6].

Likewise, measurements of the $WZ$ and $ZZ$ cross sections have been made by the D0 experiment. The $WZ$ cross section is measured in the $ee\nu\nu$, $e\mu\nu\nu$, $e\mu\mu\nu$ and $\mu\mu\nu\nu$ decay modes using $8.6\ \text{fb}^{-1}$. The same dataset is used to measure the $ZZ$ cross section in the $ee\nu\nu$ and $\mu\mu\nu\nu$ decay modes. No discrepancy with the standard model prediction is observed.

In an inclusive search for new physics with multiple leptons, CDF examines final states using trileptons in events where there are two electrons, or two muons, and one additional reconstructed lepton ($e$, $\mu$ or $\tau$) or an isolated track. This search makes use of $5.8\ \text{fb}^{-1}$ of integrated luminosity. All backgrounds are measured in data control regions of dilepton invariant mass, jet multiplicity and missing transverse energy. After ascertaining that the backgrounds are well modeled by using the control regions, specific kinematic requirements particular to supersymmetry are crafted. No excess is observed, and cross section limits are set.

In a separate search for new physics with leptons, CDF has performed a dedicated analysis searching for a heavy resonance decaying to $Z$ boson pairs. Initially, an excess was observed in the four charged lepton channel (see Figure 3, left panel). Additional searches in the dilepton plus missing transverse energy, and dilepton plus
dijet topologies, which should have larger branching fractions, revealed no additional excess events (see Figure 3, center panel and right panel), and cross section limits were set [8].

3 Precision Measurement of the W Mass

A full description of the precision measurement of the W mass by the Tevatron experiments is beyond the scope of these proceedings. The basic method used is to build detailed parametrized simulations of the experiment response, and then generate template shapes corresponding to different values of the W mass. These templates are then used to fit the data distributions. The differences in the individual experimental designs manifestly affect the performance of each detector, as well as how these descriptions were developed. A brief description of the characterization of the lepton energy scales and resolutions is included here.

Measurement of the W mass with the CDF detector begins with precision tracking. The alignment of the individual detectors is verified using cosmic muon events. Then, using inclusive samples of $J/\psi \rightarrow \mu\mu$ events, the momentum scale and linearity of the tracking is verified, and cross checked using $Z \rightarrow \mu\mu$ events (yielding an independent measurement of the Z mass). With the tracking momentum scale verified, the E/p distribution for electrons is used to set the energy scale for the calorimeter. The radiative tail of this distribution is also used to verify the energy loss and radiative components of the calorimeter response. The calorimeter energy scale for electrons is then cross checked using $Z \rightarrow ee$ events (yielding a similarly unbiased estimate of the Z mass). With the lepton energy scale verified, and the recoil distributions modeled using Z events, the lepton transverse momentum, missing transverse energy and transverse mass are used to measure the W mass. Taking into account the correlations between these distributions, the measured value of the W mass using 2.2 fb$^{-1}$ in both the electron and muon channels from CDF is $M_W=80387\pm19$ MeV [9].

Measurement of the W mass with the D0 detector is done differently, the precision
of the tracking is not sufficient to carry out the same momentum scale determination and transfer. The electron channel alone is used, utilizing only the central calorimeter ($|\eta|<1.1$). In order to model the amount of material prior to the active layers of the sampling calorimeter, the energy scale of each layer of the electromagnetic part of the calorimeter along with the material is allowed to vary and is fit to the longitudinal shower profile from $Z \rightarrow ee$ events in data. These $Z$ events must be split into categories according to the rapidity of each electron, since different impact angles will encounter different amounts of material. The individual layers are independently varied in order to check the robustness of the description. The energy scale and offset are then set using the $Z$ mass, using the corrected material distribution, and verified in different ranges of instantaneous luminosity in order to check for pileup dependent effects. After taking into account the correlations between the lepton transverse momentum, the missing transverse momentum and transverse mass, only the transverse momentum and transverse mass distributions contribute to the final value (combined with the earlier D0 measurement), yielding $M_W=80375\pm23$ MeV [10].

With the combination of the Run II W mass measurements from CDF and D0 (along with the Run 0/I measurements), the Tevatron measurements of the W mass now dominate the world average (as shown in Figure 5). It is worth noting that there is still a significant amount of the uncertainty which can be reduced by additional statistics, and by higher precision parton distribution function fits when available.

4 Summary

A limited set of results from electroweak measurements and their implications for searches for new phenomena have been presented. The precision measurement of the
Figure 5: Summary of W mass measurements and new world average.

W mass at the Tevatron now dominates the world average, which along with the top mass constrains the allowed standard model value of the Higgs mass.

References

1 Introduction

A brief report on supersymmetry (SUSY) and other beyond-SM (BSM) searches in \( \sqrt{s} = 7 \text{ TeV} \) pp collisions using up to 4.7 fb\(^{-1}\) of ATLAS [1] data at the LHC is presented. The shown results correspond to the status as of June 2012.

2 Supersymmetry searches

SUSY searches within ATLAS are grouped into R-parity conserving (RPC), and R-parity violating (RPV) together with long-lived particle models. Searches for RPC models are further divided into inclusive searches for strong production, searches for third generation squarks (direct and indirect production), and electroweak production (\( \tilde{\chi}^\pm, \tilde{\chi}^0, \tilde{\ell} \)). In the following, results with less than 1.0 fb\(^{-1}\) of data are omitted.

Table 1 lists the most relevant inclusive SUSY searches. Long cascade decays are searched for both with and without leptons. Exclusion limits of the all-hadronic search are shown in Fig. 1. The most stringent limits exclude squark and gluino masses up to 1.4 TeV (for \( m_{\tilde{q}} \approx m_{\tilde{g}} \)). The signature of GMSB models is to a large extent determined by the next-to-lightest-SUSY-particle (NLSP). Depending on its nature taus, photons, or Z bosons are emitted, which defines the corresponding searches.

Table 2 lists SUSY searches for third generation squarks. A light \( \tilde{t} \) is motivated by naturalness arguments. Exclusion limits for a gluino-mediated \( \tilde{t} \) model and a direct \( \tilde{t} \) production scenario are shown in Fig. 2. In the first scenario gluino masses are excluded up to about 900 GeV for \( m_{\tilde{\chi}^0_1} < 200 \text{ GeV} \), and a very-light \( \tilde{t} \) is excluded by the second search up to a mass of about 135 GeV.\(^1\)

Table 3 lists ATLAS searches for electroweak production. In a \( \tilde{\chi}^\pm_1-\tilde{\chi}^0_2 \) production model where each decay proceeds via a \( \tilde{\ell} \) thus giving rise to large lepton multiplicities, gaugino masses are excluded up to 300 GeV [15].

Table 4 lists searches for RPV and long-lived scenarios. These searches typically exploit experimentally challenging signatures, e.g. a displaced vertex, a disappearing track, or a stable massive particle, or energy deposits in unpaired bunches. The search for disappearing tracks [18] excludes non-prompt chargino masses up to 118 GeV.

\(^1\)These values are derived from the \( -1 \sigma_{\text{theory}} \) observed limit contours.
signature | model(s) | L | ref.
--- | --- | --- | ---
0-lep + $E_T^{\text{miss}} + \geq (2-6)$ jets | medium to large mass splittings | 4.7 fb$^{-1}$ | [2]
0-lep + $E_T^{\text{miss}} / \sqrt{H_T} + \geq (6-8)$ jets | long decay chains, or multi-jets from e.g. $t\bar{t}$ decays | 4.7 fb$^{-1}$ | [3]
$\geq 1$-lep + $E_T^{\text{miss}} + \geq (3,4)$ jets | decays with intermediate $\tilde{\chi}^\pm, \tilde{\chi}^0, \tilde{\ell}$ | 4.7 fb$^{-1}$ | [4]
$\geq 1$ tau + jets + $E_T^{\text{miss}}$ | GMSB with stau NLSP | 2.1 fb$^{-1}$ | [5]
$\geq 2$ tau + jets + $E_T^{\text{miss}}$ | GMSB with stau NLSP | 2.1 fb$^{-1}$ | [6]
2-photons + $E_T^{\text{miss}}$ | GMSB with bino-like neutralino | 1.0 fb$^{-1}$ | [7]
$Z \to \ell\ell +$ jets + $E_T^{\text{miss}}$ | GMSB with higgsino-like neutralino | 1.0 fb$^{-1}$ | [8]

Table 1: Inclusive searches for RPC strong SUSY production. The word lep denotes an isolated electron or muon, and tau a hadronic tau decay.

Figure 1: Exclusion plots in the MSUGRA/CMSSM (left) and squark-gluino-neutralino (right) models from Ref. [2].
signature: model(s) | L | ref.
--- | --- | --- | ---
0-lep + \(E_T^{\text{miss}}\) + \(\geq(4,6)\) jets + \(\geq3\) bjets | gluino-mediated \(b\) or \(t\) | 4.7 fb\(^{-1}\) | [9]
(0,1)-lep + \(E_T^{\text{miss}}\) + \(\geq(3,4)\) jets + \(\geq(1,2)\) bjets | gluino-mediated \(\bar{b}\) or \(\bar{t}\) | 2.1 fb\(^{-1}\) | [10]
2-lep same-sign + \(E_T^{\text{miss}}\) + \(\geq4\) jets | gluino-mediated \(b\) or \(t\) | 2.1 fb\(^{-1}\) | [11]
2-lep + \(E_T^{\text{miss}}\) + \(\geq1\) jets | direct very-light \(\tilde{t}\) | 4.7 fb\(^{-1}\) | [12]
\(Z \rightarrow \ell\ell + E_T^{\text{miss}}\) + \(\geq2\) jets + \(\geq1\) bjet | direct \(\tilde{t}\) in GMSB | 2.1 fb\(^{-1}\) | [13]
0-lep + 2 bjets + MCT | direct \(\tilde{b}\) | 2.1 fb\(^{-1}\) | [14]

Table 2: Third generation searches for RPC strong SUSY production. The word \(\text{lep}\) denotes an isolated electron or muon, and \(\text{bjet}\) a b-tagged jet.

Figure 2: Exclusion limits in a gluino-mediated \(\tilde{t}\) [9] (left) and a direct \(\tilde{t}\) with \(\tilde{t} \rightarrow b\tilde{\chi}^{\pm}\) [12] (right) model.

signature: model(s) | L | ref.
--- | --- | --- | ---
3-lep + \(E_T^{\text{miss}}\) + Z rich/depleted | \(\tilde{\chi}_1^\pm - \tilde{\chi}_0^0\), decay via \(\ell\) | 2.1 fb\(^{-1}\) | [15]
4-lep + \(E_T^{\text{miss}}\) + (Z depleted) | \(\tilde{\chi}_1^\pm - \tilde{\chi}_0^0\), and RPV | 2.1 fb\(^{-1}\) | [16]
2-lep + \(E_T^{\text{miss}}\) + (jets) | \(\tilde{\chi}_1^\pm - \tilde{\chi}_2^0\), decay via \(\tilde{\ell}\) | 1.0 fb\(^{-1}\) | [17]

Table 3: Searches for RPC electroweak SUSY production. The word \(\text{lep}\) denotes an isolated electron or muon, Z rich (depleted) describes a requirement (veto) on a lepton pair that has an invariant mass compatible with the Z boson.
signature & model(s) & L & ref. \\
\hline
Disappearing track + jets + $E_T^{\text{miss}}$ & AMSB scenarios & 4.7 fb$^{-1}$ & [18] \\
el-mu continuum & t-channel exchange of RPV $\tilde{t}$ & 4.7 fb$^{-1}$ & [19] \\
long lived particle & R-hadron (Pixel) & 2.1 fb$^{-1}$ & [20] \\
el-mu resonance & RPV $\tilde{\nu}_\tau$ (s-channel) & 1.1 fb$^{-1}$ & [21] \\
\hline
\end{tabular}

Table 4: RPV and long-lived SUSY searches.

Figure 3: Comparison of exclusion limits in a leptophobic $Z'$ model using the boosted (left) [23] and resolved (right) [24] $t\bar{t}$ resonance searches.

3 Other beyond-SM searches

There is some overlap between SUSY and BSM searches. However, many BSM final states are not covered by SUSY searches, including e.g. signatures with resonances, monojets, and in general signatures with small to medium $E_T^{\text{miss}}$. A complete list of non-SUSY BSM searches can be found in Ref. [22]. A few selected results are presented here.

A new search for heavy $t\bar{t}$ resonances specifically takes advantage of the boost by using "fat jets" to collect all collimated decay products in a single jet. Figure 3 shows the exclusion limits for one benchmark model (leptophobic $Z'$). The comparison with the corresponding resolved (not using "fat jets") search shows the gain for a heavy resonance.

Figure 4 shows results of the search for high-mass dilepton resonances. The sequential-SM $Z'$ model is excluded up to a mass of 2.2 TeV.

Di-jet signatures are powerful probes of new physics, e.g. excited quarks ($q^*$) or contact interactions. $q^*$ are excluded up to masses of 3.35 TeV [26].
Figure 4: Invariant di-electron mass (left) and combined electron+muon exclusion limits for a sequential-SM $Z'$ model using the di-lepton resonance search [25].

4 Summary

ATLAS is mining its data for the expected and unexpected. There is a strong and diverse program for BSM searches: SUSY and non-SUSY; generic and inclusive searches, as well as dedicated searches (e.g. direct $\tilde{t}$ production). New techniques are implemented (e.g. boosted top), and new phase-space is explored (e.g. 3-bjets). No excess has been observed. ATLAS will keep looking, thanks to the excellent LHC and detector performance.

References


Contextualizing the Higgs at the LHC

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Abstract

Recent excesses across different search modes of the collaborations at the LHC seem to indicate the presence of a Higgs-like scalar particle at 125 GeV. Using the current data sets, we review and update analyses addressing the extent to which this state is compatible with the Standard Model, and provide two contextual answers for how it might instead fit into alternative scenarios with enlarged electroweak symmetry breaking sectors.

1 Introduction

A central issue to be addressed by the LHC is that of determining the dynamics that UV completes the theory of massive weak vector bosons, which by itself is consistent and predictive only below scales $\mathcal{O}(4\pi m/g)$, with $m$ the vector’s mass and $g$ the gauge coupling.

There are three possibilities for such a completion that we will consider here:

1. The Higgs is an elementary state in the UV. The nonlinear sigma model of interacting longitudinally-polarized vectors is linearized by this single state, granting the theory safe access to arbitrarily high scales in the absence of gravity.

2. The longitudinal components of the $W/Z$ states are composite, arising as Goldstone bosons of a strong dynamics that confines at a scale $\Lambda_c \sim 4\pi f$ with $f = 246$ GeV, breaking a global symmetry in the pattern $G/H \sim SO(4)/SO(3)$. There is no light Higgs boson in this minimal symmetry-breaking structure.

3. The longitudinal modes of the vectors are arranged into an enlarged coset space arising from a non-minimal symmetry breaking structure, e.g. $SO(5)/SO(4)$. The Higgs can thus be realized itself as a (pseudo) Goldstone state.
The final case above interpolates between the first two. The Higgs VEV and couplings depend on $\Lambda_c$ and a vacuum alignment angle, $\theta = \arcsin(v/f)$, determined by symmetry-breaking spurions; case (1) corresponds to $\theta \to 0$ and case (2) to $\theta \to 1$. We thus find it convenient to parameterize the low-energy physics of the Higgs boson in a fully generic way, as in [1]. We restrict our study to interactions of $\mathcal{O}(\partial^2)$ and $\mathcal{O}(\partial^4)$, corresponding respectively to the first two terms in the chiral Lagrangian

$$\mathcal{L} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \ldots$$

In unitary gauge, we have explicitly:

$$\mathcal{L}^{(2)} = \frac{1}{2} (\partial \mu h)^2 - \frac{1}{2} m_h^2 h^2 - \sum_{\psi=u,d,l} m_{\psi(i)} \bar{\psi}^{(i)} \psi^{(i)} \left( 1 + c_\psi \frac{h}{v} + \ldots \right) - \left( m_W^2 W_\mu W^\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right) \left( 1 + 2 a \frac{h}{v} + \ldots \right);$$

$$\mathcal{L}^{(4)} = \frac{\alpha_{em}}{4\pi} \left( \frac{c_{WW}}{s_W^2} W_\mu^+ W_\nu^- + \frac{c_{ZZ}}{s_W^2 c_W^2} Z_\mu^+ Z_\nu^- \right) \frac{h}{v} + \frac{\alpha_s}{4\pi} c_{gg} G_\mu^2 \frac{h}{v}. \quad (3)$$

In what follows, we update current exclusion limits [2, 3] in this parameter space and apply them first to the SM and composite Higgs scenarios with flavor-universal Yukawa rescalings ($c_\psi = c$), and second to the minimal supersymmetric Standard Model (MSSM) where up and down-type Yukawas are rescaled independently. Explicit expressions for the overall rescaling functions of each search channel can be found for instance in the appendix of [4].

## 2 Higgs Status: The SM and Compositeness

We first consider the case of flavor-universal rescalings to the SM Yukawa couplings, and examine the space spanned by the couplings $a$ and $c$ of Eq. (2). For both ATLAS and CMS, we use best fit values for the signal strength modifier, $\mu$, to construct exclusions for all channels except those involving $h \to WW$. For the latter, we find it more appropriate to apply the likelihood (re)construction techniques detailed in [3], which at present is the only way in which we can incorporate all subchannel information. For the CMS searches, we reconstruct likelihoods from the expected and observed exclusion limits provided in [5], while for ATLAS we construct likelihoods using the event numbers marginalized over signal and background uncertainties quoted in [6].

The results are shown separately for ATLAS [7] and CMS [8] in Figure 1. The overall picture is consistent with the SM at the $1\sigma$ level, but the peak likelihood in the neighborhood of the SM point is found to lie at $(a \simeq 0.98, c \simeq 0.58)$ with CMS data and $(a \simeq 1, c \simeq 0.73)$ with that from ATLAS. This is suggestive of non-SM
dynamics, though more data will be needed in order to draw concrete conclusions in this direction.

\[ m_h = 125 \text{ GeV} \]

68% CL
90% CL
95% CL
\( \sigma \) SM
0.0 0.5 1.0 1.5 2.0
-3
-2
-1
0
1
2
3

Figure 1: Exclusion contours drawn from current ATLAS and CMS data.

We note here the importance of including information of exclusive search modes, as this serves crucially to determine even the qualitative features of the likelihood isocontours. An important reason for the differences in constraints coming from CMS and ATLAS, for instance, can be traced to the fact that individual limits are quoted for five separate categories of the \( \gamma \gamma \) [9] final states in CMS, while only a combined limit for this channel is quoted in the ATLAS searches. Treating a particular search mode at the level of exclusive subchannels should however include information regarding cut efficiencies for each category. These can have a non-negligible impact on the effect of \( \gamma \gamma \) final states in particular, and have thus been included in our fits using the estimates of [4]. For further details and concrete demonstrations of these effects, cf. [10].

3 Higgs Status: Supersymmetry

In the MSSM, up and down-type Yukawa couplings vary independently. In the interest of providing model-independent results, we show in Figure 2 likelihood contours generated in the three-dimensional space \((a, c_t, c_b = c_\tau)\) by projecting over different regions of the vector coupling \(a\), with likelihoods derived by generalizing the methods described above. We refer to [11] for further details.

An interesting feature of Figure 2 is that for several values of the vector coupling, a preference for enhanced up-like Yukawa couplings is identified; this is not possible
for the tree-level MSSM at $\tan \beta > 1$, and is atypical even at loop-level with SUSY breaking effects included. At present, the best fit point for the space accessible to the tree-level MSSM lies at the decoupling limit, where all couplings take their SM values. This conclusion is however dominated by $h \to \gamma\gamma$, whose excesses would in fact prefer $a > 1$. The best fit within MSSM priors is thus found at the maximal value $a = 1$, with Yukawa couplings consequentially dragged to their decoupling values.

If the $\gamma\gamma$ excesses should decrease or if there are in fact new states contributing to these decay modes such that a larger rate will continue to be observed, then it is helpful to examine separately the information from the $VV$ channels. From these channels, we see a preference for substantial suppression in $a$: this is due to the fact that the rescaling factor of the $WW + 2j$ final state—which observes a significant reduction compared to the SM—is sensitive predominantly to $a$. In order to accommodate this channel while maintaining more SM-like rates for the remaining inclusive $VV$ modes, the decrease in production via vector boson fusion due to $a < 1$ is offset by an increase in the top contribution to gluon fusion, i.e. $c_t > 1$ and thus $c_b < 1$.

![CMS Combined Likelihoods [4.9 fb^{-1} @ 7 TeV]](figure)

Figure 2: 3D likelihoods, projecting two ranges of vector coupling onto the plane of Yukawas for top and bottom quarks. Regions I and II are accessible for any value of $\tan \beta$ in a generic type-II 2HDM; at tree-level in the MSSM, region II is inaccessible for any $\tan \beta < 1$.

4 Conclusions

The current excesses observed by the ATLAS and CMS collaborations are found to be consistent with the SM taking all data combined, though room for significant
deviations obviously remains. The statistics of the available data is still sufficiently low that we expect these conclusions to remain very much in flux during the coming months. In this note, we have reviewed ways in which model-independent fits can be constructed in generic parameter spaces, and provided contextual answers for whether the current situation allows for the hinted Higgs-like state to emerge from a larger EWSB sector. The likelihoods in the context of flavor-universal composite Higgs peak at suppressed Yukawa couplings which could be indicative of relatively low-scale compositeness, while an interesting shallow direction exists in the MSSM fit which could cause tension for minimality and therefore suggest some other new SUSY dynamics to be relevant for weak-scale physics.

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References

Search for the SM Higgs in the two photon and tho Z to four lepton decay channels at CMS

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Results are presented on the search for the Standard Model Higgs decaying into two photons or into two Z bosons, with each Z boson decaying into a pair of charged leptons. The full data sample of 4.7/fb of pp collisions collected in 2011 with the CMS experiment at the LHC have been analysed. The search results are translated into 95% exclusion limits for the Higgs boson, as function of the Higgs mass.

1 Introduction

The Standard Model (SM) of particle physics is an extremely accurate description of the fundamental particles and their interactions. Although the predictions of the SM have been experimentally verified to extreme precision, the mechanism by which the W and Z bosons acquire mass while the photon remains massless is unknown. One proposed mechanism by which this is achieved in nature is through spontaneous electroweak symmetry breaking through the introduction of a complex scalar field. In addition to supplying a mechanism by which the W and Z gain mass, the theory predicts the existence of a fundamental scalar boson, the SM Higgs boson. The mass of this particle, \(m_H\), is not predicted by the theory although direct searches [1] and precision electroweak measurements [2] suggest a range \(114 < m_H < 152\) GeV. The two decay channels \(H \to \gamma\gamma\) and \(H \to ZZ \to 4l\) provide very clean final states with a fully reconstructible mass peak making them very sensitive at low \(m_H\). This document describes the search performed using data recorded at CMS corresponding to \(4.7 fb^{-1}\) of pp collisions at \(\sqrt{s} = 7\)TeV.

2 \(H \to \gamma\gamma\) decay channel

The search for the Higgs boson decaying to two photons is described in detail in [3]. Although this decay channel has a relatively low branching ratio of around \(10^{-3}\), such events can be selected online readily by the presence of two high \(p_T\) photons. The main SM backgrounds are prompt photons from hard QCD interactions (around 70%) and fakes from narrow jets and \(\pi^0\)’s. Since these backgrounds are non-resonant, the main strategy is to search for a narrow mass peak on a smoothly falling background in the invariant mass, \(m_{\gamma\gamma}\), spectrum.
2.1 Event Selection and Classification

Cuts of $p_T/m_{\gamma\gamma} > 1\frac{1}{3}$ are applied to the photons. The cuts are designed to reduce inefficiencies in triggering and to avoid shaping the background spectrum.

A boosted decision tree (BDT) is trained at the per photon level to discriminate against fake photons. In addition to variables describing the shower shape and isolation of the two photons, the number of vertices in the event is included in order to maintain the efficiency in high pileup conditions. A second event-level BDT is trained to rank the vertices of the event using information from tracks and the diphoton system and select the vertex that most likely produced the Higgs. The efficiency for selecting the correct vertex is measured using $Z \rightarrow \mu\mu$ events in data and found to be around 80%.

For low $m_H$ the width of the signal peak is dominated by the resolution of the electromagnetic calorimeter (ECAL). A regression BDT is used to correct the energy of the photons using information from the ECAL to improve the resolution of the signal mass peak. The resolution in data is measured using $Z \rightarrow ee$ events. The uncertainty in this measurement is the dominant source of systematic.

A final BDT is used to categorize the events based on their resolution and kinematic properties of the diphoton system. The number of categories and the range in BDT output covered is optimized to produce the lowest expected limit.

One additional category is formed from events in which at least two jets with $E_T > 30/20$ GeV are identified. This category exploits vector-boson fusion production of the Higgs which accounts for around 10% of the signal. The requirement of two jets greatly improves the signal to background ratio for these events and increases the overall sensitivity of the search by 10%.

2.2 Results

A shape analysis in $m_{\gamma\gamma}$ is used in order to statistically interpret the data. The background in each category is modelled using a polynomial whose number of degrees of freedom is chosen to provide negligible bias in the result while the signal is modelled using MonteCarlo simulation which is tuned to data. The largest excess in the data is found around 125 GeV and corresponds to a local significance of $2.9\sigma$. The results are translated into exclusion limits on SM Higgs production in the range $110 < m_H < 150$ at the 95% confidence level. The expected exclusion is less than $2\times$ SM across this range.

3 $H \rightarrow ZZ \rightarrow 4l$ decay channel

The search for the SM Higgs boson in the four lepton decay channel is described in detail in [4]. The four lepton decay mode provides a very clean, fully reconstructible
final state. The channel is particularly sensitive as the ratio of signal to background exceeds 1. The largest of the backgrounds is from the ZZ continuum from QCD while the remaining backgrounds are largely from $Zbb$ and $t\bar{t}$ production.

The search is performed in three categories, $\mu^+\mu^-\mu^+\mu^-$, $\mu^+\mu^-e^+e^-$ and $e^+e^-e^+e^-$ in order to exploit the varying levels of signal to background from the different final states.

### 3.1 Object Identification

Since there is very little contamination from background, the four lepton search is designed to maximise the efficiency of the signal selection. Electrons and muons can be reconstructed with transverse momenta as low as 7 and 5 GeV within the detector acceptance respectively with both the electron and muon identification remaining $> 85\%$ efficient for $p_T > 10$ GeV. Selection of the signal requires two opposite signed, same flavour combinations of the identified leptons with invariant masses $50 < m_{Z1} < 120$ and $12 < m_{Z2} < 120$ with the leptons satisfying $p_T > 20/10$ GeV.

The contribution from background processes is measured using data-driven techniques. The ZZ production rate is estimated from single Z production in a control region and propagated to the signal region using theoretical calculations for the ratio of single to two Z production cross-sections and efficiencies for lepton identification measured in data. The $Z + X$ background is determined by measuring the lepton mis-identification rate in a $Z + l$ sample in data. A 30\% systematic is included on this background to account for uncertainty in the $p_T$ dependence of the mis-identification rate.

### 3.2 Results

A total of 13 events were observed in the range $110 < m_{4l} < 160$ GeV while $9.5 \pm 1.3$ were expected from SM backgrounds. A shape analysis in $m_{4l}$ were performed to statistically interpret the data. The backgrounds are modelled using polynomials whereas the signal is modelled using a parametric fit to signal MonteCarlo. The largest local excess in the range of Higgs masses tested corresponds to a significance of $2.5\sigma$ near 119 GeV. Exclusions on the production of a SM Higgs bosons are placed in the range 134 to 158 GeV at the 95\% confidence level.

### 4 Combined Results

The two searches in the decay channels $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ were combined statistically to calculate exclusion limits and local significances of the data as shown in figure 1. The data exclude the production of the SM Higgs with a mass in the
Figure 1: Combined results from the $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ \rightarrow 4l$ searches in the low mass region, $110 < m_H < 145$ GeV. Upper panel: Exclusion limits are on the production of the SM Higgs given the data observed. Lower panel: Local significances of excesses in data. The dashed blue line in the lower panel shows the expected local p-value should a Higgs boson with mass $m_H$ exist while the solid shows the observed p-values.

ranges $128 < m_H < 134$ GeV and $137 < m_H < 145$ GeV at the 95% confidence level. The largest excess observed is at 125 GeV corresponding to a local significance of $2.8\sigma$. This is reduced to $1.6\sigma$ when accounting for the look-elsewhere effect.

References


[2] [ALEPH and CDF and D0 and DELPHI and L3 and OPAL and SLD and LEP Electroweak Working Group and Tevatron Electroweak Working Group and SLD Electroweak and Heavy Flavour Groups Collaborations], arXiv:1012.2367 [hep-ex].


Higgs Searches at CDF

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1 Introduction

The standard model of particles physics incorporates a Higgs field in order to pro-vide a mechanism for spontaneous symmetry breaking in the electroweak sector[1]. One of the consequences of this field is the presence of a massive, scalar boson, the Higgs boson. Current electroweak precision fits prefer a Higgs mass of less than 152 GeV/c$^2$ [2] at 95% confidence level. Direct searches at the LEP-II[3] and LHC experiments[4, 5]provide a 95% confidence exclusion limits on the Higgs mass for the regions below 117 GeV/c$^2$, between 119 GeV/c$^2$ and 122 GeV/c$^2$, and above 127 GeV/c$^2$. These proceedings report on direct searches for a standard model Higgs boson at the Tevatron with the CDF II detector[6].

At the Tevatron, the dominant production mechanism for a SM Higgs is through gluon fusion. But for a low mass Higgs ($m_H < 135$ GeV/c$^2$) where the $H \rightarrow WW$ decay is no longer dominant, the production of a Higgs boson in association with a vector boson and subsequent decay to a $b\bar{b}$ pair is the most sensitive search channel for a light SM Higgs. In these proceedings, emphasis is placed on improvements in analysis techniques in searches for Higgs production in association with $W/Z$ bosons in the mass range $100 < m_H < 150$ GeV/c$^2$ and final states containing $b\bar{b}$ candidates. The results of searches utilizing up to $10 fb^{-1}$ of integrated luminosity are presented when combining all search channels at CDF. As well, the details of the numerous search channels can be found in several publications[7].

2 Improved CDF b-tagging

Several different b-quark identification algorithms have been developed by the CDF Collaboration, but previous techniques had not been optimized specifically for direct Higgs searches with $H \rightarrow bb$ final states. The Higgs Optimized B Identification Tagger (HOBIT) was developed to utilize information information from previous algorithms, combine this information within a Neural Network discriminant, and then tune the performance of selection thresholds for maximum Higgs sensitivity. Using the
TMVA[8] framework, the HOBIT Neural Network was trained with 25 input variables that help distinguish b-quark jets from non-b jets and is fully described in [9]. The HOBIT response to b-quark and light-quark jets in simulated data was calibrated in a top enriched sample and in a sample of dijets event containing an electron from the semi-leptonic decay of a b-quark. For the tight (loose) HOBIT threshold, the measured b-quark jet identification efficiency is 42% (70%) with a misidentification rate of light-quark jets of 0.89% (8.9%). The increase in sensitivity for the $WH \rightarrow \ell \nu b\bar{b}$[10] analysis with the HOBIT tagger is compared with the previous tagging strategy[11] in Table 1.

3 Improved Multivariate Discriminants

New multivariate techniques were developed for the $WH \rightarrow \ell \nu b\bar{b}$ and $ZH \rightarrow \ell \ell b\bar{b}$ analyses using several MVA discriminants trained specifically for a single background. The analysis ordered the backgrounds to reject the most efficiently rejected backgrounds first, and then subsequent discriminants trained on the remaining samples. Within the $ZH \rightarrow \ell \ell b\bar{b}$ analysis at CDF[12], the discriminants were developed to reject backgrounds in the order: top-quark production, then $Z + q\bar{q}$ to includes charm, then diboson production, and the final discriminant enhancing the $ZH$ signal over all remaining backgrounds and is shown in Figure 1. The new MVA techniques improved sensitivity by 10% over previous single discriminants.

4 Full Combination of CDF Higgs Searches

A combined search for standard model Higgs production is performed using up to 10 $fb^{-1}$ of data. The channels considered are $WH \rightarrow \ell \nu b\bar{b}$, $VH \rightarrow \nu \nu b\bar{b}$, $ZH \rightarrow \ell \ell b\bar{b}$, $H \rightarrow \gamma \gamma$, $VH \rightarrow jj b\bar{b}$, $H \rightarrow WW$, $H \rightarrow \tau \tau + 2\text{jets}$, $H \rightarrow ZZ \rightarrow \ell \ell \ell \ell$, two

<table>
<thead>
<tr>
<th>Tag Category</th>
<th>Old Taggers S/$\sqrt{B}$</th>
<th>HOBIT S/$\sqrt{B}$</th>
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<tr>
<td>SecVtx+SecVtx</td>
<td>0.228</td>
<td>0.266</td>
</tr>
<tr>
<td>SecVtx+JetProb</td>
<td>0.160</td>
<td>0.200</td>
</tr>
<tr>
<td>SecVtx+Roma</td>
<td>0.103</td>
<td>0.143</td>
</tr>
<tr>
<td>Single SecVtx</td>
<td>0.146</td>
<td>0.053</td>
</tr>
<tr>
<td>Sum</td>
<td>0.331</td>
<td>0.369</td>
</tr>
</tbody>
</table>

Table 1: The signal divided by the square-root of background in several tagging categories in the $WH \rightarrow \ell \nu b\bar{b}$ analysis along with the sum in quadrature of the several categories for the previous analysis and with the HOBIT tagger.
searches for $ttH$ production, and a search for associated production of $WH$ or $ZH$ utilizing tau selection. The 95% C.L. upper limits on Higgs boson production are 2.17, 2.67 and 0.41 times the SM cross section for Higgs boson masses of $m_H=115$, 125, and 165 GeV/c$^2$, respectively and are shown in Figure 2. CDF excludes, at the 95% C.L., the region $148.8 < m_H < 175.2$GeV/c$^2$ and $m_H < 96.9$GeV/c$^2$, with an expected exclusion region of $m_H < 94.2$GeV/c$^2$, $96.1 < m_H < 106$GeV/c$^2$ and $153.8 < m_H < 176.1$GeV/c$^2$. The largest excess at $m_H = 120$GeV/c$^2$ has a local p-value corresponding to a local significance of $2.6\sigma$. The global significance for such an excess anywhere in the full mass range is approximately $2.1\sigma$. We perform an exclusive combination of searches for $H \rightarrow b\bar{b}$ and find that the global probability of the background to fluctuate to produce the $2.9\sigma$ excess observed in the data at any mass in the $H \rightarrow b\bar{b}$ search region is estimated to be $2.7\sigma$.

I would like to thank the Fermilab Accelerator Division for the exceptional performance of the Tevatron, and the entire CDF Collaboration for the excellent dataset, analyses, and results.

References

Figure 2: The ratio of the 95% confidence level Higgs cross-section limit from combining all search channels at CDF divided by the SM Higgs cross-section for potential Higgs masses between 100 and 200 GeV/c$^2$. The solid line shows the observed limit with the dotted line showing the expected limit. The green and yellow bands show the 1σ and 2σ variation respectively on the 95% CL expected limit.

Search for a Light Higgs Boson at ATLAS

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1 Introduction

The Higgs boson is predicted by the Standard Model (SM) as a natural explanation of the electroweak symmetry breaking that originates the mass of the $W$ and $Z$ bosons. Previous results from LEP, Tevatron and LHC had excluded the range up to 114.4 GeV and between 141 and 476 GeV \cite{1, 2, 3}. Indirect limits of $m_H < 158$ GeV at 95% confidence level (CL) have been set using global fits to precision electroweak results \cite{4}.

For the reasons mentioned above, the SM prefers the Higgs boson with relatively light mass. This note describes the results of search for a light mass Higgs boson using full data about 5 fb$^{-1}$ collected in 2011 at $\sqrt{s} = 7$ TeV with ATLAS detector\cite{5}.

2 Higgs boson search in the low mass region

The strategy of search for the Higgs boson depends on its production process and decay mode. The dominant Higgs boson production is via gluon-gluon fusion process, next vector-boson-fusion process and then the associated production with a $W/Z$ boson. In the low mass region, the Higgs boson predominantly decays into $b\bar{b}$ ($m_H < 135$ GeV) and $WW$ ($m_H > 135$ GeV). While $\gamma\gamma$, $ZZ$ and $\tau\tau$ decay modes are not dominant, these decay modes are also promising for the Higgs boson search since the final state can be selected requiring high $p_T$ photons or leptons. In this section, the results of the Higgs boson search in the low mass region are described.

2.1 $H \rightarrow \gamma\gamma$ channel

The branching ratio of diphoton decay is very small, but a narrow Higgs mass peak can be observed over the background thanks to good photon energy resolution.

To optimize the sensitivity, the selected diphoton events are separated into nine mutually exclusive categories depending on whether the photon is converted or unconverted, the pseudorapidity of the photon and $p_T$. This categorization extracts

\[ p_T = \frac{|(p_T^1 + p_T^2) \times (p_T^1 - p_T^2)|/|[p_T^1 - p_T^2]|}{|p_T^1 - p_T^2|}, \]

where $p_T^1$ and $p_T^2$ are the transverse momenta of the two photons.
the region having better diphoton mass resolution and signal-to-background ratio, S/B. Finally, all nine categories are combined. The background model is obtained for each category by fitting diphoton invariant mass, \( m_{\gamma\gamma} \) in the range 100-160 GeV with an exponential function with free slope and normalization parameters. Figure 1(left) shows \( m_{\gamma\gamma} \) distribution summed over all categories. Figure 1(right) shows the observed and expected 95\% CL upper limit on the cross section, divided by the SM prediction, as a function of Higgs boson mass. Two small regions, 113-115 GeV and 134.5-136 GeV are excluded. One interesting excess is observed around 126 GeV. The largest significance is 2.8 \( \sigma \) at 126.5 GeV (1.5 \( \sigma \) when the look-elsewhere-effect in the interval 110-150 GeV is considered) [6].

Figure 1: Left: diphoton mass distribution summed over all categories [6]. Solid line represents the background model fitted by an exponential function. Dashed line represents the signal shape of \( m_H = 120 \) GeV. Right: The observed and expected 95\% CL upper limit on the cross section, divided by the SM prediction, as a function of \( m_H \).

2.2 \( H \to ZZ \to 4\ell \) channel

This channel is very clean and provides good S/B thanks to the requirement of four isolated leptons (4e, 4\( \mu \) or 2e2\( \mu \)). The dominant backgrounds are non-resonant \( ZZ \to 4\ell \), \( Z + \text{jets} \) and \( t\bar{t} \) background in the low mass region. Four lepton invariant mass, \( m_{4\ell} \), resolution is good (1-2\%) and a narrow Higgs mass peak can be observed over a continuous background.

Figure 2 shows \( m_{4\ell} \) distribution (left) and the observed and expected 95\% CL upper limit on the cross section, divided by the SM prediction, as a function of Higgs boson mass (middle). The excluded region is 134-156 GeV. Rightmost plot in figure 2 shows the local \( p_0 \) value which is the probability that the background fluctuates to the observed number of events or higher. An interesting small \( p_0 \) value, corresponding to 2.1\( \sigma \), is observed at 125 GeV. However it is no more significant when the look-elsewhere-effect is considered [7].
Figure 2: Left: $m_{4l}$ distribution [7]. Middle: The observed and expected 95% upper limit, divided by the SM prediction, as a function of the Higgs mass. Right: local $p_0$ as a function of the Higgs mass. The observed local $p_0$-value (solid line) and expected median local $p_0$-value for the signal hypothesis when tested at $m_H$ (dashed line).

2.3 $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ channel

This is the most sensitive channel in the wide mass range of 120-200 GeV. The signal yield is relatively high and the background yield is acceptable thanks to dilepton ($ee, e\mu$ and $\mu\mu$) plus high missing transverse energy, $E_T^{\text{miss}}$, requirement. In this analysis, the event selections are optimized according to the presence of jets because the signal and background composition is different depending on jet multiplicity. It is not possible to reconstruct the invariant mass due to two neutrinos in the final state. Hence the transverse mass, $m_T$, defined in [8] is used as a final discriminant. Figure 3 shows $m_T$ distribution and the observed and expected 95% CL upper limit on the cross section, divided by the SM prediction, as a function of the Higgs boson mass. No significant excess is observed [8]. The excluded region is 133-261 GeV.

Figure 3: Left: $m_T$ distribution in 0-jet events [8]. Right: The observed and expected 95% CL upper limit on the cross section, divided by the SM prediction, as a function of the Higgs mass.


\subsection*{2.4 $H \rightarrow \tau\tau$ and $H \rightarrow b\bar{b}$ channels}

In $\tau\tau$ channel, two leptonic $\tau$, one leptonic $\tau$ plus one hadronic $\tau$ and two hadronic $\tau$ channels are studied separately. Each decay channel is further subdivided into different categories according to the presence of jets. In all channels, no significant excess is observed. Combining all channels, 95\% CL upper limit on the cross section is 3.2 times higher than the SM prediction at 125 GeV \[9\].

In $b\bar{b}$ channel, $WH \rightarrow \ell\nu b\bar{b}$, $ZH \rightarrow \ell\ell b\bar{b}$ and $ZH \rightarrow \nu\nu b\bar{b}$ final states are studied separately. Each final state is subdivided depending on boson momentum, $p_T^V$, or $E_T^{\text{miss}}$ to optimize sensitivity because the boosted category with high $p_T^V$ or high $E_T^{\text{miss}}$ gives better S/B. Combining all channels, 95\% CL upper limit on the cross section is 3.5 times higher than the SM prediction at 125 GeV \[10\].

\section*{3 Summary}

ATLAS has searched for the SM Higgs boson, exploring in particular the low mass region, with the 2011 full data which corresponds to approximately 5fb$^{-1}$. Almost all low mass region is excluded except for small region around 125 GeV mass. In particular, for the $H \rightarrow \gamma\gamma$ and $ZZ \rightarrow 4\ell$ decay modes about 2 $\sigma$ excess in local $p_0$ is observed around 125 GeV. The excess is consistent with the SM prediction.

\section*{References}

[2] CDF, D0 Collaborations, FERMILAB-CONF-12-065-E.
Combined results of SM Higgs searches at CMS

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1 Introduction

The Higgs boson being the last missing piece of the Standard Model is searched in many experiments for at least last three decades. The direct lower limit on the Higgs boson mass comes from electron-positron collision data at LEP, and is $m_H > 114.4 \text{ GeV}/c^2$ at 95% CL [1]. Recent results from Tevatron with up to 8.6 fb$^{-1}$ of $p\bar{p}$ data exclude also a mass window of $156 < m_H < 177 \text{ GeV}/c^2$ [2]. The Higgs boson search, within both Standard Model and its extensions, is also in the centre of the CMS experiment physics program [3]. In this contribution we present results combining searches for SM Higgs boson in most sub-channels explored by the CMS. The results are based on 5 fb$^{-1}$ of data collected in 2010 and 2011. We present significance of observed excesses, and in absence of statistically significant excess we show exclusion limits as a function of $m_H$ [4].

2 Search channels

The SM Higgs boson, with direct coupling to all massive particles of SM, has large number of decay modes with the decay pattern heavily dependent on its mass. The CMS Collaboration pursued Higgs boson search in all the most sensitive decay channels: $H \rightarrow \gamma\gamma, H \rightarrow \tau\tau, H \rightarrow b\bar{b}, H \rightarrow WW^{(*)} \rightarrow 2l2\nu, H \rightarrow ZZ^{(*)} \rightarrow 4l, H \rightarrow ZZ \rightarrow 2l2\nu, H \rightarrow ZZ^{(*)} \rightarrow 2l2q, H \rightarrow ZZ \rightarrow 2l2\tau$. Each of those modes is usually further split in sub-channels to profit from better S/B ratio in different production modes, e.g. vector boson fusion (VBF) vs. gluon-gluon fusion, leading to around 50 sub-channels in total.

3 Statistical analysis

The statistical analysis of the data in the Higgs boson searches is done using the CL$_s$ method with profiled likelihood ratio used as a test statistics. In the combination
all statistical and systematic uncertainties and their correlations are accounted for by introducing nuisance parameters ($\theta$) in the likelihood function [5]. Depending on the mass range the number of sources of systematic uncertainties ranges from 156 to 222, including those fully correlated between different search channels. The statistical analysis is done using a signal strength modifier $\mu$ which multiplies the expected SM Higgs boson cross section: $\sigma = \mu \cdot \sigma_{SM}$.

In the case of exclusion of possible signal the test statistics for each assumed value of parameter $\mu$ is defined as:

$$q_\mu = -2 \ln \frac{\mathcal{L}(\text{data}|\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}, \quad 0 < \mu < \hat{\mu}$$

where $\mathcal{L}(\text{data}|\mu, \hat{\theta}_\mu)$ is the likelihood function maximised with respect to nuisance parameters under the hypothesis of a signal strength $\mu$, while $\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})$ is the likelihood function maximised with respect to both nuisance parameters, and signal strength parameter.

The analysis of observed excesses over the expected background uses similar test statistics function, but assuming $\mu = 0$:

$$q_0 = -2 \ln \frac{\mathcal{L}(\text{data}|0, \hat{\theta}_0)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}, \quad \mu \geq 0$$

An excess is usually quantified in terms of the probability to obtain a value of $q_0$ greater or equal to the one observed in data ($q_{\text{obs}}$) assuming background-only hypothesis: $p_0 = P(q_0 \geq q_{\text{obs}}|b)$. The probability value is then translated into one-sided p-value of the Gaussian distribution, usually denoted a significance $Z$. According to classical hypothesis testing procedure the threshold on $Z$ marking the discovery limit, has has to be defined before looking at the data. A common value used in High Energy Physics is $Z=5$, which corresponds to $p_0 = 2.8 \cdot 10^{-7}$. Since the search is made over a wide mass region the $p_0$ calculated for given mass hypothesis has to be corrected for the so called look elsewhere effect (LEE) [6]. This correction always reduces the $Z$ value, and also depends on the search range.

4 Results

Exclusion limits for the CMS combination of SM Higgs boson searches is presented on Fig. 1. The mass range of 114.5 – 543 GeV/$c^2$ was expected to be excluded basing on detailed Monte Carlo simulations assuming no Higgs boson signal contribution, but the observed exclusion range is 127.5 – 600 GeV/$c^2$ with some excess around mass of 125 GeV/$c^2$. The local p-value of observed excesses is presented on Fig. 2 with the largest excesses, coming mainly from $H \rightarrow \gamma\gamma$ channel, observed around
Figure 1: The 95% CL upper limits on the signal strength parameter $\mu$ for the SM Higgs boson hypothesis as function of the Higgs boson mass in full search range (left), and for low mass range (right). The observed values are shown by the solid line. The dashed line indicates the expected median of results for the background only hypothesis, while the green (dark) and yellow (light) bands indicate the ranges that are expected to contain 68% and 95% of all observed excursions from the median, respectively. The mass ranges first excluded by LEP, Tevatron and this measurement are shown as hatched areas.

mass of 125 GeV/$c^2$. The p-value of this excess corresponds to $Z=2.8$ before applying the LEE correction. After applying the LEE correction the significance is reduced to 2.1, assuming search range 110 – 145 GeV/$c^2$, or 0.8 for the full range of 110 – 600 GeV/$c^2$.

5 Conclusion

The CMS Collaboration analysed almost 5 fb$^{-1}$ of data collected at $\sqrt{s}=7$ TeV in 2010 – 2011 searching for SM Higgs boson using number of decay and production modes. After combination of all modes no statistically significant excess was observed, yielding 95% CL exclusion in range 127.5 – 600 GeV/$c^2$. The largest excess, observed at $m_H=125$ GeV/$c^2$ has significance of $Z=2.1$ for search range 110 – 145 GeV/$c^2$.

6 Acknowledgements

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Figure 2: The observed local p-value $p_0$ as a function of the SM Higgs boson mass in the range 110 – 145 GeV/$c^2$, for the full combination and the two sub-combinations. The global significance of the observed maximum excess (minimum local p-value) for the full combination in this mass range is 2.1$\sigma$. The dashed line shows the expected local p-values $p_0(m_H)$ for the combination, should a Higgs boson with a mass $m_H$ exist.

References


1 Introduction

The Higgs mechanism is the source of electroweak symmetry breaking in the Standard Model of particle physics (SM), providing mass to the $W$ and $Z$ vector bosons. The Higgs boson is a physical manifestation of the scalar Higgs field. Global fits to electroweak measurements provide indirect constraints on the unknown mass of the Higgs boson ($m_H$), predicting $m_H = 94^{+30}_{-23}$ GeV [1]. A high mass Higgs boson, $m_H \geq 200$ GeV, is therefore highly disfavoured by indirect constraints however such measurements should be complemented by direct searches. Direct Higgs boson searches made at LEP excluded $m_H \leq 114.4$ GeV [2], while the combined Tevatron searches exclude the ranges $100$ GeV $\leq m_H \leq 106$ GeV and $147$ GeV $\leq m_H \leq 179$ GeV [3]. The high mass range therefore remains the domain of the LHC experiments. The search for high mass Higgs boson with the ATLAS detector with data up to 4.8 fb$^{-1}$ of data taken at $\sqrt{s} = 7$ TeV at the LHC is discussed.

2 The ATLAS Detector

The ATLAS Detector [4] is a large multi-purpose detector at the LHC. ATLAS has a forward-backwards cylindrical geometry, providing comprehensive coverage around the interaction point. The high granularity inner tracking detector (ID) immediately surrounds the interaction point, covering $|\eta| < 2.5$. The ID is contained within a thin superconducting solenoid providing a 2 T axial magnetic field. A lead/liquid-argon (LAr) sampling electromagnetic calorimeter encloses the solenoid. The hadronic calorimeters follow, comprised of LAr calorimeters in the end-cap and forward regions and iron/scintillating tile calorimeters in the barrel. The muon spectrometer encompasses the whole detector contained inside the magnetic field of three large toroidal magnets. A three level trigger system selects events to be recorded for offline analysis.
3 Individual Search Channels

Higgs boson searches at ATLAS make use of varied production and decay channels. In the high mass regime, the dominant decay processes are to two on-shell vector bosons. The following search channels were analysed with the data corresponding to 4.7-4.8 fb\(^{-1}\) of 7 TeV ATLAS data.

3.1 \(H \rightarrow ZZ \rightarrow llll\)

The decay channel to four leptons provides a striking and low background environment in which to search for the Higgs boson. The search has been performed by looking for a resonant peak in the \(m_\ell\) distribution. This channel has sensitivity to the full Higgs mass range of 110 GeV to 600 GeV. In the high mass range, the limits from this channel, shown in Figure 1, show two deviations from the background: a 2.2\(\sigma\) deviation at 244 GeV and a 2.1\(\sigma\) deviation at 500 GeV. Neither excess remains significant after the look-elsewhere effect is taken into account. In high Higgs mass regions this channel excludes at 95 % C.L. a SM Higgs mass in three ranges: 182 GeV < \(m_H\) < 233 GeV, 256 GeV < \(m_H\) < 265 GeV and 268 GeV < \(m_H\) < 415 GeV [5].

3.2 \(H \rightarrow ZZ \rightarrow ll\nu\nu\)

The presence of two neutrinos in the final state leads to the distinctive signature of large missing transverse energy, \(E_T^{\text{miss}}\), combined with two high \(p_T\) leptons. As the final state cannot be fully reconstructed, the search is performed by searching for an excess in the transverse mass distribution. Separate selections are made in the low and high mass regions. In the high mass region where the \(Z\) bosons become partially boosted, an additional cut is made on the maximum opening angle between the two leptons. The results for this channel, ranging from 200 GeV to 600 GeV, show no significant excesses and exclude at 95 % C.L. a SM Higgs in the range 319 GeV < \(m_H\) < 558 GeV [6].

3.3 \(H \rightarrow ZZ \rightarrow llq\bar{q}\)

The complete final state can be reconstructed in this channel, an excess of events in the \(m_{lljj}\) distribution is searched for. A cut on the opening angle between the leptons once again takes advantage of the moderately boosted \(Z\) bosons present in the high mass region. The analysis is split into samples containing \(\geq 2\) \(b\)-tagged jets and < 2 \(b\)-tagged jets. In the former a large reduction in the \(Z+\)jets background is observed. No significant excesses are seen and this channel excludes at 95 % C.L. a Standard Model Higgs in two small ranges: 300 GeV < \(m_H\) < 310 GeV and 360 GeV < \(m_H\) < 400 GeV [7].
3.4 $H \rightarrow WW \rightarrow ll\nu\nu$

The full mass range is covered by this channel, however the presence of the neutrinos in the final state causes it to have a poor mass resolution. The analysis uses the transverse mass of the $ll\nu\nu$ system to search for an excess of events and is split into 0, 1 and $\geq 2$ associated jet categories. This channel excludes at 95 % C.L. a SM Higgs boson with $133 \text{ GeV} < m_H < 261 \text{ GeV}$ [8]. A multivariate boosted decision tree (BDT) analysis has been performed which extends the exclusion in the high mass regime to $130 \text{ GeV} < m_H < 281 \text{ GeV}$ [9].

3.5 $H \rightarrow WW \rightarrow llqq$

This analysis searches for an excess in the $m_{llqq}$ invariant mass distribution. It covers a mass range above 300 GeV using three separate jet channels: 0, 1 or $\geq 2$ associated jets. The expected sensitivity of this channel is around two times the SM Higgs production cross section; no excesses of events are observed in the data [10].

Figure 1: The 95 % C.L. limits on $\sigma/\sigma_{SM}$ for the $H \rightarrow ZZ \rightarrow llll$ (left), $H \rightarrow ZZ \rightarrow ll\nu\nu$ (middle) and $H \rightarrow ZZ \rightarrow llqq$ (right) channels.

Figure 2: The 95 % C.L. limits on $\sigma/\sigma_{SM}$ for the $H \rightarrow WW \rightarrow ll\nu\nu$ BDT (left), $H \rightarrow WW \rightarrow llqq$ (right) channels.
4 Combination

The search channels presented here have been combined to provide an overall ATLAS Higgs search result. The combined limits exclude the SM Higgs boson at 95 % C.L. in the mass range $129 \text{ GeV} < m_H < 539 \text{ GeV}$[11].

5 Summary

Searches for a high mass SM Higgs boson in various diboson decay channels based on $4.7-4.8 \text{ fb}^{-1}$ of data recorded by the ATLAS detector at $\sqrt{s} = 7 \text{ TeV}$ during the 2011 run have been presented. Individually, the $H \rightarrow ZZ$ channels and the $H \rightarrow WW \rightarrow l\nu l\nu$ channel exclude parts of the SM Higgs mass range above 200 GeV. When combined, the SM Higgs boson is excluded at the 95 % C.L. in the mass range $129 \text{ GeV} < m_H < 539 \text{ GeV}$. This represents a significant exclusion of the presence of a high mass SM Higgs boson. The largest upward deviations from the background-only hypothesis are observed in the $H \rightarrow ZZ \rightarrow llll$ channel, for $m_H = 244 \text{ GeV}$ and 500 GeV with local significances of 2.2 and 2.1 standard deviations, respectively. Once the look-elsewhere effect is considered, neither of these excesses are significant.

References

[3] CDF and D0 Collaborations, FERMILAB-CONF-12-065-E
Tracking, vertexing and b-tagging performance at ATLAS

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1 Introduction

The ATLAS experiment [1] is a general purpose experiment that records collision events produced by the Large Hadron Collider (LHC) [2] at CERN. Surrounding the interaction point, the experiment is equipped with an Inner Detector (ID) tracking system embedded in a 2 T axial magnetic field. The ID consists of two silicon-based detectors (a Pixel detector and a microstrip detector, SCT) closest to the interaction point surrounded by a transition radiation tracker (TRT). The electromagnetic and hadronic calorimeters are located outside the ID solenoid, and are both based on sampling techniques. Finally a muon detector system immersed in a toroidal magnetic field occupies the outermost region of the detector.

The LHC started its operations late 2009, and during 2010 and 2011 it has produced proton-proton collisions at 7 TeV. The integrated luminosity recorded by ATLAS amounts to approximately 40 pb$^{-1}$ in 2010 and 5 fb$^{-1}$ in 2011.

2 Track Reconstruction

Tracks are reconstructed within the full ID acceptance ($|\eta| < 2.5$) using a $\chi^2$ fitter. The pattern recognition [3] works primarily inside-out, starting with a seed in the silicon-based detectors and extrapolating outwards to also include measurements in the TRT. To recover e.g. tracks from secondary interactions there is also an outside-in tracking, which uses TRT track segment seeds and extrapolates inwards. The track candidates are finally required to fulfill a set of quality criteria, based e.g. on the number of silicon hits and the transverse and longitudinal impact parameters with respect the beam spot.

The high instantaneous luminosity of the LHC leads to a large number of additional proton-proton collisions per event (pileup) and thus a relatively high occupancy in the ID. This in turn increases the rate of fake tracks reconstructed from random combinations of ID measurements. To limit the rate of fake tracks, a robust track
reconstruction configuration has been developed which makes more stringent hit requirements [5]. Fig. 1 (left) shows the fraction of fake tracks in three pileup scenarios with the default and robust track reconstruction configuration.

To allow for a precise measurement of the track parameters, a track-based alignment of the ATLAS ID is carried out through a $\chi^2$ minimization of the track-hit residuals. In addition, constraints from the invariant masses of e.g. $K^0_s$ mesons and $Z$ bosons are used, as well as the ratio of the energy of electrons measured in the calorimeters and the corresponding momentum measured in the ID ($E/p$). Fig. 1 (middle) shows the difference between the reconstructed and true $K^0_s$ mass as a function of the azimuthal angle $\phi$ in 2010 and 2011, highlighting the much reduced bias of the track parameters achieved by an improved alignment of the ID in 2011. Fig. 1 (right) shows the data-to-simulation comparison of the transverse impact parameter, $d_0$, of tracks in the forward region. The resolution reaches the design value for low $p_T$ tracks while it is slightly worse than predicted for high $p_T$ tracks due to residual misalignments present in the data.

3 Primary Vertex Reconstruction

Measured tracks are used to reconstruct the hard scatter interaction point as well as the positions of additional proton-proton collisions occurring in the same bunch crossing. The ATLAS primary vertex reconstruction [8] uses an iterative algorithm starting with a vertex finding step in which tracks are associated to a primary vertex followed by a $\chi^2$-based vertex fit. The vertex fitter includes a beam-spot constraint.

The primary vertex resolution is extracted using data driven methods based on split vertex techniques. It is about 23 $\mu$m in the transverse plane and about 40 $\mu$m in
the longitudinal plane for vertices with 70 tracks. The expected vertex reconstruction efficiency is about 95% for non-diffractive events.

4  b-tagging Algorithms and Performance

The identification of jets originating from $b$-quarks is an important part of the LHC physics program. Several algorithms to identify jets originating from $b$-quarks, referred to as $b$-tagging, have been developed ranging from those based on the reconstruction of an inclusive secondary vertex or the presence of tracks with large impact parameters to combined tagging algorithms making use of multi-variate discriminants. The expected performance of various $b$-tagging algorithms is shown in Fig. 2. The most commonly used $b$-tagging algorithm in ATLAS is the multi-variate algorithm MV1 which provides the best rejection of light-flavour jets for a given $b$-jet efficiency.

![Figure 2: The rejection of light-flavour jets as a function of the $b$-jet efficiency for various $b$-tagging algorithms in a sample of simulated $t\bar{t}$ events [9].](image)

To use $b$-tagging in physics analyses, the efficiency $\epsilon_b$ with which a jet originating from a $b$-quark is tagged by a $b$-tagging algorithm needs to be measured, as well as the probability of mistakenly tagging a jet originating from a $c$-quark or a light-flavour parton ($u$-, $d$-, $s$-quark or gluon $g$) as a $b$-jet, referred to as the $c$-tag efficiency and mistag rate respectively. Several methods have been developed to measure the $b$-tag efficiency, the $c$-tag efficiency and the mistag rate in data [9, 10, 11]. The $b$-tag efficiency has been measured with two methods in an inclusive sample of jets which contain muons. The $c$-tag efficiency has been measured in an inclusive sample of jets associated to $D^*$ mesons while the mistag rate has been measured with two complementary methods in an inclusive jet sample. The calibration results are presented as scale factors, defined as the ratio of the efficiency (or mistag rate) in data to that
in simulation. The scale factors for the MV1 algorithm at the operating point corresponding to a 70% \( b \)-tag efficiency in simulated \( t\bar{t} \) events are shown in Fig. 3. For this algorithm and operating point all scale factors are consistent with unity within uncertainties.

Figure 3: The data-to-simulation scale factors for the \( b \)-tag efficiency (top) [9], the \( c \)-tag efficiency (bottom left) [10] and the mistag rate (bottom middle and right) [11] as a function of \( p_T^{\text{jet}} \) for the MV1 algorithm at the operating point corresponding to a 70% \( b \)-tag efficiency in simulated \( t\bar{t} \) events. The light green band in all figures indicates the total uncertainty, while the dark green band in the top figure indicates the statistical uncertainty only. In the top figure the error bars indicate both statistical and total uncertainties while the error bars in the bottom plots show statistical uncertainties only.

5 Conclusions

The ATLAS detector is designed to reconstruct tracks and vertices with high precision. A wide range of studies carried out with the 2011 data set confirm an excellent performance of the tracking, vertexing and \( b \)-tagging. This is achieved e.g. through improved alignment and track reconstruction optimized for high-pileup conditions as well as new multi-variate algorithms which have boosted the \( b \)-tagging performance.
References


Search the SM Higgs boson to $bb$, $\tau\tau$, $WW$, $ZZ$ with 4.7 fb$^{-1}$ of CMS data

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1 Introduction

The Standard Model (SM) of particle physics is the theory of the strong and electroweak interactions. It has been soundly confirmed by a variety of direct and indirect measurements performed over the last decades. By introducing a certain number of scalar degrees of freedom, the mass of the gauge bosons and of the fermions can be generated via the Brout–Englert–Higgs (BEH) mechanism. In its minimal version, the BEH mechanism implies the existence of one physical neutral boson with $J^{CP} = 0^{++}$, the so–called “Higgs boson”, whose mass ($M_H$) is a free parameter of the theory. Theoretical arguments constrain $M_H$ to be bounded from above by about 700 GeV (see e.g. Ref. [1]). Assuming the SM predictions of the electroweak observables, the precision measurements hint at a rather light Higgs boson, $M_H \approx 100$ GeV. Direct searches at LEP2 measure a 95% CL lower bound on $M_H$ at 114.4 GeV [2]. Depending on its mass, the Higgs boson decays predominanlty to $b$–quarks and $\tau$–leptons ($M_H \lesssim 135$ GeV) or to a pair of massive gauge bosons ($M_H \gtrsim 135$ GeV).

At the LHC, the main production mechanisms, ordered by importance, are gluon–gluon fusion (GGF), vector–boson fusion (VBF), and associated production with a gauge boson ($VH$), or heavy quarks ($bbH$, $ttH$).

A detailed description of the CMS apparatus can be found in Ref. [3]. A particle–flow technique is deployed for the offline reconstruction of collision events. The list of reconstructed “particle–flow particles” is then used to build higher–level objects, like jets, $b$–tag discriminators, or the semileptonic decays of tau leptons ($\tau_h$). The missing transverse energy ($E_T^{miss}$) is defined as the negative vector sum of all particles transverse momenta.

The analyses presented in this talk are based on up to 4.7 fb$^{-1}$ of LHC data collected throughout 2011 at a center–of–mass energy of 7 TeV, with a peak instantaneous luminosity of $3.5 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$, and an average of 9 pile–up interactions per bunch crossing.
2 Higgs searches

2.1 $H \rightarrow b\bar{b}$

A search for the SM Higgs boson decaying to a pair of $b$–quarks, and produced in association with a gauge boson $V = W, Z$, is documented in Ref. [4]. Events are selected online requiring electron/muon triggers, or large $E_T^{\text{miss}}$, depending on which of five exclusive final state of the vector $V$ is tagged. A pair of $b$–tagged jets is required offline. The di–jet system is required to have transverse momentum in excess of 150 GeV. The main SM backgrounds consist of $V + bb$ (dominant), $V +$ light quarks, di–boson, and $t\bar{t}$. They are normalized from background–enriched sidebands. The interpretation of the results is performed using a multivariate analysis (“BDT”), cross–checked with a cut–based one. A counting experiment of events with a score of the BDT above a given threshold is used to set exclusion limits. No evidence of a signal over the SM background is found. The observed (expected) exclusion limit at 95% CL on the cross–section of a SM–like Higgs boson is 4.3 (5.7) times the SM prediction for $M_H = 125$ GeV.

2.2 $H \rightarrow \tau^{+}\tau^{-}$

For $M_H \lesssim 145$ GeV, the decay into a pair of tau leptons [5] provides an important discovery channel for the SM Higgs boson, allowing in principle for a direct measurement of the Higgs coupling to leptons. Three final states are considered: when both taus decay leptonically, one into a muon plus neutrinos and the other into an electron plus neutrinos ($\tau_e\tau_\mu$), or when one tau decays leptonically and the other semileptonically ($\tau_e\tau_h$, $\tau_\mu\tau_h$). Depending on the jet content, events are classified into a “VBF”–like, a “Boosted”, and a “0/1–jet” category. The dominant background ($Z \rightarrow \tau\tau$) is estimated from $Z \rightarrow \mu\mu$ data events, where the muons are replaced with simulated tau leptons. The second largest source of background comes from events where a jet is misidentified as a tau ($W +$ jets, QCD). The di–tau mass is reconstructed from the visible tau momenta and $E_T^{\text{miss}}$, using a likelihood–based technique; the resulting di–tau mass resolution is at most 20%. A binned shape analysis of the di–tau mass spectrum is performed for the statistical interpretation of the results. The observation is consistent with the background–only hypothesis. The observed (expected) exclusion limit at 95% CL on the cross–section of a SM–like Higgs boson is 3.6 (2.3) times the SM prediction for $M_H = 125$ GeV.

2.3 $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^–\nu$

A search for the SM Higgs boson decaying to $W$ bosons in the fully–leptonic final state is documented in Ref. [6]. Events with a pair of opposite–charge, isolated and high–
$p_T$ leptons (electrons or muons) are considered. The Drell–Yan and $t\bar{t}$ backgrounds are reduced by a cut on the “projected” $\vec{E}_T^{\text{miss}}$ and a $b$–tag veto, respectively. The largest background comes from the $WW$ continuum, whose contribution is calibrated from sidebands or normalized to the theoretical NLO cross–section, depending on the value of $M_H$ under test. Subleading backgrounds come from $t\bar{t}$, $W$+jets and Drell–Yan, and are estimated from sidebands. Events are further split into a 0–jet, 1–jet and 2–jets category, the latter optimized for the VBF production mode. For the first two categories, a BDT classifies events as signal or background like, depending on the event kinematics. The output of the BD Ts is used in a shape analysis. The SM Higgs boson is ruled out in the range $[129, 270]$ GeV, compared with an expectation of $[127, 270]$ GeV in the background–only hypothesis.

2.4 $H \rightarrow ZZ \rightarrow \ell^+\ell^- q\bar{q}$

The final state $H \rightarrow ZZ \rightarrow \ell^+\ell^- q\bar{q}$, with $q = u, d, c, s, b$, has the largest branching ratio among the $H \rightarrow ZZ$ decays [8]. To enhance the statistical power, events are categorized depending on the number of $b$–tagged jets. To reduce the dominant $Z$+jets background, the analysis exploits an angular likelihood and a quark/gluon likelihood discriminator. A shape analysis of the four–body mass spectrum is performed, with a data–driven parametrization of the background template. Two separate analyses are optimized for the $[130, 164]$ GeV and for the $[200, 600]$ GeV range. The observed limit is consistent with the background–only expectation in the full search range.

2.5 $H \rightarrow ZZ \rightarrow \ell^+\ell^- \nu\nu$

A search for the Higgs boson in the $H \rightarrow ZZ \rightarrow \ell^+\ell^- \nu\nu$ final state is documented in Ref. [7]. In addition to a pair of isolated and opposite–sign electrons or muons, the $E_T^{\text{miss}}$ is required to be in excess of 70 GeV. The largest background comes from events with genuine leptons and missing energy, namely $t\bar{t}$ and $WW$, followed by $WZ$, $ZZ$ and Drell–Yan di–lepton production with instrumental $E_T^{\text{miss}}$. The dominant backgrounds are estimated from data sidebands with opposite–flavor leptons. A binned shape analysis of the transverse mass distribution of the di–lepton and $E_T^{\text{miss}}$ allows to exclude the SM Higgs boson at 95% CL in the range $[270, 440]$ GeV.

2.6 $H \rightarrow ZZ \rightarrow \ell^+\ell^- \tau^+\tau^-$

A search for the Higgs boson decaying to a pair of $Z$ bosons in the $2\ell2\tau$ final state is documented in Ref. [9]. A total of eight independent channels from combinatorial association of the two $Z$ boson final states are simultaneously analyzed. The dominant background is represented by the $ZZ$ continuum, which is normalized to the measured inclusive $Z$ cross–section, scaled by the $\sigma(ZZ)/\sigma(Z)$ theoretical ratio. The residual
backgrounds come from misidentified leptons and are estimated from data using the fake rate method. A binned shape analysis of the visible four–body mass is used to set limits. The upper limit on the cross section is approximately between a factor four and seven larger than the SM cross section in the range $[190, 500]$ GeV, consistent with the background–only expectation.

3 Conclusions

A search for the SM Higgs boson in six different final states, using up to $4.7 \, \text{fb}^{-1}$ of CMS data at $\sqrt{s} = 7$ TeV, has been presented. The analyses presented here target the “low mass resolution” channels. The SM Higgs boson is excluded at 95\% CL over large intervals of $M_H$ in both the intermediate and high mass range. A moderate excess in the low–mass range, with a maximal local significance of about $2\sigma$, is observed from the combination of the $\ell^+\nu\ell^-\nu$, $b\bar{b}$, and $\tau^+\tau^-$ channels.

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SUSY confronts LHC data

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1 SUSY at the LHC

There are many reasons why to expect Supersymmetry (SUSY) at the TeV scale: it solves the hierarchy problem, it provides a natural dark matter candidate, allows for gauge coupling unification, etc. Up to now the direct searches for SUSY, mainly based on missing transverse energy signatures have shown no significant excess over the SM backgrounds [1]. While the actual bounds depend on many details, it is fair to say that the gluinos and the squarks of the first and second generation have to be heavier than 1 TeV, while the third generation squarks will be heavier than 200-300 GeV. The stop searches \(^2\) will play a crucial role in determining if SUSY is indeed a natural solution to the hierarchy problem. For recent strategies for stop searches, see [3].

Actually, the only requirements from naturalness [4] are a light stop (\(m_{\tilde{t}} \leq 400 - 500\) GeV) and light \(\mu\) (\(\leq 200 - 300\) GeV). Such an scenario, dubbed as ”Natural SUSY” [5] is still an open possibility. This suggests the existence of two scales, \(m_{\tilde{g}, \tilde{b}} \geq 1\) TeV, and \(m_{\tilde{t}, \tilde{\chi}} \sim 200-400\) GeV (see Ref. [6] for single-scale Natural SUSY).

The Higgs boson provides an indirect way of searching for SUSY, and the recent discovery of a 125 GeV Higgs [7] with an enhanced diphoton rate, constrain even more the parameter space. We recall that in the Minimal Supersymmetric Standard Model (MSSM) at tree level the lightest Higgs mass fulfills \(m_h^0 \leq m_Z|\cos(2\beta)|\). The upper bound is zero for low \(\tan\beta\) (\(\approx 1\)), but it saturates for \(\tan\beta > 10\). In order to avoid LEP constraints [10], large radiative corrections to the Higgs mass are needed. These corrections depend strongly on several supersymmetric parameters, particularly on the stop mass and mixing angle, and prefer large \(\tan\beta\) and \(m_A > 300\) GeV. The upper bound on \(m_h\) in the MSSM is about 135 GeV [11].

Much theoretical work has been focused in a 125 GeV Higgs in supersymmetric theories (see e.g [8]). In brief, it is possible to obtain such a Higgs mass in the MSSM,

\(^1\)work done in collaboration with Marcela Carena and Eduardo Pontón.

\(^2\)After this talk was given, the LHC collaborations have presented results of their stop searches [2], that do not alter the conclusions of the present discussions.
but this only happens for specific values of the soft parameters (e.g. large stop mixing, large $\tan \beta$, large $m_A$). The other important question is whether such a 125 GeV Higgs boson could have the observed rates to $\gamma \gamma$ and $ZZ$. This can be achieved, for instance, by having a light stau in the spectrum [9].

However, the Higgs can be pointing us toward more generic SUSY scenarios. On one hand the large $\tan \beta$ region is excluded by $\tau^+\tau^-$ searches and, on the other hand, is excluded due to the upper bound on $m_h$. This does not need to be the case in general extensions of the MSSM, and thus the Higgs sector provides information about beyond the MSSM (BMSSM) dynamics.

2 Going Beyond: the BMSSM

Extending the MSSM Higgs sector with dimension 5 operators, one finds [12]

$$W = \mu H_u H_d + \frac{\omega_1}{2M} (1 + \alpha_1 X) (H_u H_d)^2,$$

where $\alpha_1$ and $\omega_1$ are dimensionless, order one parameters, $X = m_s \theta^2$ is the so called ”spurion superfield”, that parameterizes SUSY breaking. In this talk we take $\mu = m_s = 200$ GeV and $M = 1$ TeV, and we choose $A_t = 0$ (no mixing in the stop sector). The consequences of Eq. (1) for the Higgs potential have been studied in [13].

At order $1/M^2$, one has many more new operators [14, 15]. The collider phenomenology of dimension-six operators was studied in detail in Refs. [16, 17, 18]. Here we will show a few selected results.

In Fig. 1 we show our scan restricted to $m_h \in [123 - 127]$ GeV, for $\tan \beta = 2$. In the left panel we show the $m_h - m_H$ plane, while in the right panel we present the rates (cross section times branching ratio) into $\gamma \gamma$ and $ZZ$. From the left panel we see that a Higgs boson $h$ being tested in the diphoton channel could be accompanied by a 150 GeV $H$ boson, and thus there is no need for large $m_A$. Of course this $H$ boson would be mostly gaugephobic, and thus it might be very hard to test it at the LHC. From the right panel we see that the $ZZ$ and $\gamma \gamma$ branching fractions are highly correlated, and that we can not achieve a rate to photons larger than in the SM case.

In Fig. 2 we show the same plot as in Fig. 1, but for $\tan \beta = 20$. We see that now points where $h$ is tested by the diphoton channel require $m_H > 200$ GeV, while for the MSSM one would have $m_H > 300$ GeV. In this case one can obtain rates into the diphoton channel that are larger than in the SM. The two channels are, again, highly correlated since the main contribution to $h \rightarrow \gamma \gamma$ in the SM comes from the $W$ loop.

In Refs. [19] a 125 GeV Higgs in the BMSSM framework was studied with a larger detail, scanning over $\tan \beta$ and taking also into account the large stop mixing case. It was found that the $\gamma \gamma$ and $ZZ$ channel are correlated, but the large stop mixing case changes the slope between the two rates. Hence a rate to $ZZ$ consistent with the SM allows for an enhancement of the $\gamma \gamma$ rate of about 1.5 times the SM one.
To sum up we have seen that while the MSSM can accommodate a 125 GeV Higgs boson, this requires large stop mixing, large values of \( m_A \) and large \( \tan \beta \). The BMSSM allows for more freedom in the supersymmetric parameter space, and in particular opens up the low \( \tan \beta \) region. We have also seen that the SUSY soft parameters are crucial to disentangle the \( ZZ \) and \( \gamma \gamma \) channels, if this excess becomes
significant in the future.

I am grateful to PLHC 2012 organizers for the invitation to present this material, and for a very nice atmosphere during the conference.

References


Search for SUSY in Hadronic Final States at CMS

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1 Introduction

We present the results of searches for SUSY production at CMS [1] in events containing hadronic jets and missing energy, with or without isolated photons or heavy flavor particles, using the full data-set collected in 2011 at 7 TeV in the centre of mass. The results are interpreted in the context of the Constrained Minimal Supersymmetric Standard Model (cMSSM), and of a number of “simplified models”.

Results from four distinct analyses have been presented. Three of them target a final state with missing transverse momentum and multijets, whereas one searches for SUSY adding also one or two photons in the event topology.

2 Jets + $\not{E}_T$ Final States

The analyses that do not have photons in the final states have similar backgrounds that can be listed as follow: from jet energy mismeasurement in multijets events (often called QCD background), from W and $t\bar{t}$ semi-leptonic processes where the charged lepton ($\ell^\pm$) is lost due to detector acceptance, kinematic cuts or identification efficiency, and finally the irreducible background from $Z$ boson decay into neutrinos.

The first presented analysis is based on the $M_{T2}$ variable [2], which is a generalisation of the transverse mass for decay chains with two unobserved particles, as typical in SUSY events. $M_{T2}$ assumes values close to zero for back-to-back events, with no genuine missing energy. This feature naturally suppress the background arising from jet energy mismeasurement in multijets events. Together with the $H_T = \sum_i p_{T,i}$ variable $M_{T2}$ provides a good discriminating power between Standard Model (SM) processes and SUSY-like events. This analysis has also a cut flow that makes usage of b-tagging requirement aiming to cover complementary SUSY signal topologies.

Another analysis pursued by the CMS collaboration is an inclusive search with jets and missing transverse momentum [6], aimed to fully characterise the background kinematic in the search regions, achieved with a detailed data-driven modelling of the background [4]. We perform the analysis binning the phase space in $H_T$ and
The analysis $[5]$ based on the so called Razor variables, $R$ (dimensionless, related to the missing transverse energy $\not{E}_T$) and $M_R$ (an event-by-event indicator of the heavy particle mass scale), aims to fully characterise the data-sets collected by the CMS experiment. The events are divided in 6 exclusive boxes, defined by the number of leptons in the final state (0, 1 or 2) and lepton type (electron or muon). In both simulation and data, the distributions of SM background events are seen to have an exponential dependence $R$ and $M_R$ over a large fraction of the $R^2-M_R$ plane. The analysis uses simulated events to understand the shapes of the SM background distributions and the number – and initial values – of independent parameters needed to describe them. For each of the main SM backgrounds, a control sample is then defined from a subset of the data that is dominated by this particular background in

$$M_T = | - \sum_i \vec{p}_{T,i}^\text{jet} |.$$ QCD is estimated via the “rebalance and smearing” technique, where the particle level $p_T$’s are restored from the detector level inclusive multijets data using a kinematic fit subject to the constraint $M_T = $ soft-particles (i.e., those particles not associated with jets that have a $p_T > 50$ GeV). The obtained set of momenta is subsequently smeared using the jet resolution functions, including non-Gaussian tails. The background from $W$ and $t\bar{t}$ semi-leptonic decay, where the $\ell^\pm$ is lost, is estimated from a muon control sample, correcting for the lepton isolation and identification efficiencies (also modelling the case when an electron is lost). The special case where a $\tau$ is produced and decays in hadrons is handled using a muon control sample where a template of the detector response to the visible energy of the $\tau$ decays is used to smear the muon momentum and thus simulate a $\tau - \text{jet}$. Finally, the $Z \rightarrow \nu\bar{\nu}$ background is estimated using a $\gamma + \text{jets}$ sample exploiting the commonalities of the processes that lie beneath the production of prompt-isolated photon and $Z$ bosons.

Figure 1: 95% C.L. upper limit on signal cross section in Simplified Models: $pp \rightarrow g\bar{g}, g \rightarrow q\bar{q} \tilde{\chi}^0$ (left), $pp \rightarrow g\bar{g}, g \rightarrow q\bar{q} \tilde{\chi}^0$ (centre), derived with the inclusive jet + missing transverse momentum analysis; $pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow bb\tilde{\chi}^0$ (right), measured with $M_{T2}$ based analysis.
order to obtain a data-driven description of the shapes of the background components. A full SM background representation is thus built using statistically independent data samples; this is used as input for a global fit to the remaining data. The fit is performed in the corner of low $M_R$ and small $R^2$ (with information shared across different boxes); the model is then extrapolated on an orthogonal region of the $R^2-M_R$ plane defined to be the search region.

All analyses did not measure any statistically significant deviation from the SM prediction. The results therefore were used to excludes the existence of beyond-SM processes in a portion of the cMSSM plane (Fig. 2) and in several Simplified Models [7], a selection of which is shown in Fig. 1.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Observed limits from several 2011 CMS SUSY searches plotted in the cMSSM ($m_0,m_{1/2}$) plane.}
\end{figure}

3 Photon(s) + Jets + $E_T$ Final States

This type of analyses are motivated by the exploration of the General Gauge Mediation (GGM) models, where the gravitino is the lightest stable particle (LSP). The phenomenology of these models is driven by the NLSP (next-to-LSP) particle type. Two different scenarios have been investigated: (I) Bino-like neutralino, where the neutralino is the NLSP; (II) Wino-like neutralino/chargino, where both charginos and neutralinos are NLSP. The charginos mostly decays in a $W$ boson and a gravitino, in contrast to neutralino that decays into a photon and a gravitino, therefore the two sub-analyses looks for at least 1 jet and 2 photons (I) or at least 2 jets and 1 photon (II). The dominant background arises from QCD processes and it is estimated using an orthogonal sample of non-isolated photons. The subdominant background from Electroweak processes is estimated from $e^-e^-$, $e^-\gamma$ and single-$e^-$ samples, reweighting for the probability to misreconstruct an electron as a photon.
Also for this set of analyses we did not find any deviation from the SM background expectation, therefore we set limits for the aforementioned models. Fig 3 shows the exclusion limits at 95 % C.L. for the Bino-like and Wino-like neutralino models.

![Figure 3: 95% C.L. exclusion contours in gluino-squark mass space for bino-like (left) and wino-like (centre) neutralinos for the di-photon (left) and single photon (centre) analysis. Rightmost plot shows the 95% C.L. exclusion contours in gluino-bino mass space for bino-like neutralinos di-photon analysis.](image)

References


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Inclusive searches for supersymmetric signatures with the ATLAS detector

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1 Introduction

A brief summary of recent results on inclusive searches for supersymmetry (SUSY) and of searches for SUSY signatures involving long-lived massive particles is presented. The reported results use up to 4.7 fb$^{-1}$ of data from $pp$ collisions at center-of-mass energy of $\sqrt{s} = 7$ TeV recorded in 2011 by ATLAS[1] at the LHC.

Strong SUSY production is searched in events with large jet multiplicities and large missing transverse momentum, with and without leptons. SUSY with $\tilde{\tau}$ as next to lightest SUSY particle (NLSP) is searched in events with one or more $\tau$ leptons and missing transverse momentum. SUSY with meta-stable charginos is searched in events with missing transverse momentum and a disappearing track. Table (1) lists the searches presented.

<table>
<thead>
<tr>
<th>Signature</th>
<th>Model</th>
<th>$\int \mathcal{L} dt$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-lep + $E_T^{\text{miss}} + \geq (2-6)$ jets</td>
<td>medium to large mass splittings</td>
<td>4.7 fb$^{-1}$</td>
<td>2</td>
</tr>
<tr>
<td>0-lep + $E_T^{\text{miss}} / \sqrt{H_T} + \geq (6-9)$ jets</td>
<td>long decay chains, $\tilde{g} \rightarrow t \tilde{t} \tilde{\chi}^0$</td>
<td>4.7 fb$^{-1}$</td>
<td>3</td>
</tr>
<tr>
<td>$\geq$ 1-lep + $E_T^{\text{miss}} + \geq (3,4)$ jets</td>
<td>decays with intermediate $\tilde{\chi}^\pm, \tilde{\chi}^0, \tilde{\ell}$</td>
<td>4.7 fb$^{-1}$</td>
<td>4</td>
</tr>
<tr>
<td>2-lep (S.S.) + $E_T^{\text{miss}} + \geq 4$ jets</td>
<td>$m_{\tilde{g}} \sim m_t + m_t + m_{\tilde{\chi}^0}$</td>
<td>2.1 fb$^{-1}$</td>
<td>5</td>
</tr>
<tr>
<td>$\geq$1-tau + $E_T^{\text{miss}} +$ jets</td>
<td>GMSB with $\tilde{\tau}$ NLSP</td>
<td>2.1 fb$^{-1}$</td>
<td>6</td>
</tr>
<tr>
<td>$\geq$2-tau + $E_T^{\text{miss}} +$ jets</td>
<td>GMSB with $\tilde{\tau}$ NLSP</td>
<td>2.1 fb$^{-1}$</td>
<td>7</td>
</tr>
<tr>
<td>Disappearing track</td>
<td>AMSB with meta-stable $\tilde{\chi}^\pm$</td>
<td>4.7 fb$^{-1}$</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 1: SUSY searches performed by ATLAS. The word lep denotes an isolated electron or muon, S.S. denotes same-sign leptons, tau denotes hadronically decaying $\tau$. 
2 Searches with jets and $E_T^{\text{miss}}$

The (2-6) jets search [2] is motivated by strong SUSY production of gluinos and squarks that subsequently decay to quarks and neutralinos. Events are selected based on a jet+$E_T^{\text{miss}}$ trigger, applying a lepton veto, requiring from (2-6) jets, $E_T^{\text{miss}} > 160$ GeV, and azimuthal separation between the $E_T^{\text{miss}}$ and reconstructed jets to reject multi-jet backgrounds. Events are analysed in five signal regions, based on jet multiplicity, and in eleven channels based on the five signal regions and $m_{\text{eff}}$ (incl.), defined to be the scalar sum of the transverse momenta of jets with $p_T > 40$ GeV and $E_T^{\text{miss}}$. Fake $E_T^{\text{miss}}$ and $Z \rightarrow \nu \nu + \text{jets}$ backgrounds are estimated directly from data, other backgrounds are estimated using control regions to extrapolate Monte Carlo (MC) to the signal regions.

The (6-9) jets search [3] is motivated by SUSY models with long decay chains, and models with a gluino decaying to a top quark pair and a neutralino. To avoid overlap with the (2-6) jet search, the trigger used to select events for this search is based on multiple jets instead of $E_T^{\text{miss}}$. Events are selected using a lepton veto, requiring six to nine jets and $E_T^{\text{miss}}$ significance, $E_T^{\text{miss}}/\sqrt{H_T} > 4$ GeV$^{1/2}$. Multi-jet backgrounds are estimated from data by extracting the shape of the $E_T^{\text{miss}}/\sqrt{H_T}$ from a control region with lower jet multiplicity and normalising it according to a control region with the same jet multiplicity but $E_T^{\text{miss}}/\sqrt{H_T} < 1.5$ GeV$^{1/2}$.

The 1-lepton search [4] is motivated by models with SUSY decay chains with intermediate $\tilde{\chi}^{\pm}, \tilde{\chi}^0, \tilde{\ell}$, for which an isolated lepton is a clean signature. Within this search ATLAS performs a soft-lepton analysis which enhances the sensitivity of the search (between twenty to thirty times) in the difficult kinematic region where the neutralino and gluino masses are close to each other. Events with an isolated lepton are selected according to jet multiplicity, $E_T^{\text{miss}}, m_{\text{eff}}$, and $E_T^{\text{miss}}/m_{\text{eff}}$. Backgrounds are determined in a simultaneous Profile Likelihood (PL) fit with nuisance parameters, which allow the determination of some theoretical uncertainties directly from data. Notable uncertainties determined from data are: the relative normalization of W+jets and Z+jets MC samples with different parton multiplicities, the uncertainty in the cross section of the vector boson plus heavy flavor production, the uncertainty on the $p_T^Z$ distribution, and the uncertainty in the normalization of the W +jets and Z +jets 0-1 parton MC due to uncertainties in renormalization and factorization scales.

The two same charge (hereafter called ‘same sign’) lepton search [5] is motivated by the equal probability of the majorana gluino to produce events with same sign and opposite sign leptons. A same sign lepton pair offers a clean signature, and enhances the sensitivity where the gluino mass is close to the combined mass of a top pair and the mass of the lightest neutralino. Events having two leading leptons with the same charge are selected based on jet multiplicity, $E_T^{\text{miss}}$, and $m_T$ for one of the signal regions.

Limits for strong SUSY production are set in the absence of deviations from the
Figure 1: Top left - Exclusion plot in the MSUGRA/CMSSM [2]. Top right - exclusion plot for simplified model (6-9) jet search [3]. Bottom left - Limits on GMSB models based on ≥1,2 tau searches [7]. Bottom right - Limits on meta-stable charginos based on the disappearing track search [8].

Standard Model (SM) predictions. Figure (1 - top left) illustrates the limits set under the MSUGRA/CMSSM framework. Squarks with masses below 1.4 TeV are excluded, and gluinos are excluded with masses below 800 GeV. Results are also interpreted under simplified model assumptions, Figure (1 - top right) illustrates the interpretation of the 6-9 jets result under the assumption of a simplified model where $\tilde{g}\tilde{g}$ are always produced, and each $\tilde{g}$ decays to $t\bar{t} + \chi^0$.

3 Searches with tau leptons, jets and $E_T^{\text{miss}}$

Two SUSY searches motivated by GMSB models with a $\tilde{\tau}$ NLSP are performed. Events are selected based on hadronically decaying $\tau$ leptons identified using Boosted decision trees (BDTs). One search [6] selects events with at least one $\tau$ lepton. Another search [7] selects event with at least two $\tau$ leptons. Signal regions are defined according to $E_T^{\text{miss}}$, $m_{\text{eff}}$, and $m_T(E_T^{\text{miss}}, \tau)$. Since no deviation from the SM is seen, limits on contributions from new phenomena are set. Figure (1 - bottom left) illustrates the interpretation of the result of these two searches under the assumption of GMSB with $m_{\text{mess}} = 250$ TeV, $N_5 = 3$, $\mu > 0$, $C_{\text{grav}} = 1$. 


4 Search with a disappearing track

The search for SUSY with a disappearing track is motivated by AMSB models where the chargino can live long enough to be detected. The search aims at detecting a chargino that decays within the inner detector volume. Since the chargino and the neutralino are very close in mass in these models, the charged particle(s) from the decay of this chargino are too soft to be reconstructed, therefore a disappearing track is expected. Events are selected based on $E_T^{\text{miss}}$, jet multiplicity and a lepton veto. Chargino candidates are selected requiring a good track quality before the TRT (outer part of the inner detector with a radius between 56 to 108 cm) and less than five hits in the TRT’s outer module. Charginos with masses between 90 and 120 GeV are excluded for lifetimes above $10^{-1}$ ns and below $10^2$ ns. Figure (1 - bottom right) illustrates the limits obtained for the chargino.

5 Conclusion

ATLAS has a thriving community with a strong and broad program searching for SUSY. No evidence for SUSY has been found by ATLAS in the 4.7 fb$^{-1}$ recorded by ATLAS in 2011. ATLAS will continue to look for evidence of SUSY.

References


1 Introduction

The Compact Muon Solenoid (CMS) [1] is a multi-purpose detector designed to exploit the high discovery potential provided by the Large Hadron Collider (LHC). Muons are a distinctive signature for many of the most interesting physical processes at CMS.

The performance of muon reconstruction and identification in CMS has been studied on data collected in pp collisions at $\sqrt{s} = 7$ TeV at the LHC at CERN during 2010. During that period the experiment recorded a sample with an integrated luminosity of 40 pb$^{-1}$. We present measurements of muon reconstruction and trigger efficiencies, misidentification, and momentum scale and resolution [2].

2 Muon Reconstruction and Identification

In the standard CMS reconstruction for pp collisions, tracks are first reconstructed independently in the inner tracker (tracker track) and in the muon system (standalone-muon track). Based on these objects, two reconstruction approaches are used: Global Muon reconstruction (outside-in) and Tracker Muon reconstruction (inside-out).

For the former case, for each standalone-muon track, a matching tracker track is found by comparing parameters of the two tracks propagated onto a common surface. A global-muon track is fitted combining hits from the tracker track and standalone-muon track, using the Kalman-filter technique; for the latter case, all tracker tracks with $p_T > 0.5$ GeV/c and total momentum $p > 2.5$ GeV/c are considered as possible muon candidates and are extrapolated to the muon system taking into account the magnetic field, the average expected energy losses, and multiple Coulomb scattering in the detector material, and matched to locally reconstructed segments in muon detectors.

The combination of different algorithms provides robust and efficient muon reconstruction. We study the performance of three basic muon identification algorithms: Soft Muon selection, which requires the candidate to be a Tracker Muon, with a
tighter requirement on the matched muon segment; *Tight Muon selection*, for which the candidate must be a Global Muon with the $\chi^2$/d.o.f. of the global-muon track fit less than 10, additional quality requirements for the track and transverse impact parameter $|d_{xy}| < 2$ mm with respect to the primary vertex; finally, the *Particle Flow Muon selection*, based on the CMS particle-flow [3] event reconstruction, which combines the information from all subdetectors to identify and reconstruct individually particles produced in the collision.

We present here data to simulation comparisons for an inclusive sample of intermediate and high-$p_T$ muons collected with the single-muon trigger. In Figure 1 we show the distributions of transverse momentum and pseudorapidity for Tight Muons with $p_T > 20$ GeV/c, comparing data to Monte Carlo (MC) simulation (include the simulation of QCD processes, quarkonia production, electroweak processes such as $W$ and $Z$ boson production, non-resonant Drell-Yan processes, and top-pair production.), broken down into its different components. For momentum higher than 50 GeV/c, the leading processes are $W$ and $Z$ production, occasionally associated with hard jets. In this region, the data agree with the predictions within 10%. Given the known experimental and theoretical uncertainties, the agreement between the data and simulation is satisfactory over the entire momentum range of $p_T < 200$ GeV/c.

![Figure 1: Distributions of transverse momentum (left) and pseudorapidity (right) for Tight Muons with $p_T > 20$ GeV/c, comparing data (points with error bars) to MC.](image)

**2.1 Efficiency and Misidentification**

We study exclusive samples of prompt muons, pions, kaons, and protons in data to determine the probability that such a particle is reconstructed and identified as a muon. The efficiency to reconstruct a muon in the inner tracker was measured previously [4] and found to be 99% or higher within the whole tracker acceptance, in good agreement with the expectation from simulations. We evaluate the efficiencies...
for different selection algorithms, already presented, for prompt muons, by applying a tag-and-probe technique to muons from J/Ψ and Z decays. Figure 2 shows the efficiency for the Soft Muon selection for muons with $p_T$ up to 100 GeV/c. The tag-and-probe results in data and in simulation agree within the statistical uncertainties of the measurement almost everywhere, with some discrepancies that are understood from a small difference in the widths of the track-to-segment pulls in data and in simulation. Identification efficiencies, for muons with $p_T$ larger than a few GeV/c, are above 95% for all selections studied. Misidentification from pions, kaons and protons from resonances is also measured, being lower than 1% for the loosest selection and below 0.1% for the tightest. Concerning the trigger efficiencies, the plateau efficiencies are about 99% for the Level-1 trigger in the barrel region and for the High Level Trigger in the whole studied pseudorapidity range, for the Soft Muon selection.

3 Muon Momentum Scale and Resolution

The momentum scale and resolution of muons are studied using different approaches in the range $20 < p_T < 100$ GeV/c, where the momentum measurement is provided by the tracker. Figure 3 shows the comparison of muon transverse momentum resolution versus $\eta$ obtained with two different method after correcting for biases in the momentum scale, for both data and simulation. The average bias in the muon momentum scale was measured with a precision of better than 0.2% and was found to be consistent with zero. The relative $p_T$ resolution is between 1.3% to 2.0% for muons in the barrel and better than 6% in the endcaps, in good agreement with simulation.
Figure 3: Relative transverse momentum resolution $\sigma(p_T)/p_T$ in data and simulation measured with two different methods for muons produced in the decays of Z bosons and passing the Tight Muon selection.

4 Conclusions

The performance of muon reconstruction, identification, and triggering in CMS has been studied extensively using 40 pb$^{-1}$ of data collected in pp collisions at $\sqrt{s} = 7$ TeV at the LHC in 2010. These data were used to study several representative muon selections, chosen as benchmarks covering a wide range of physics analysis needs.

Apart from the results summarized here, other studies were performed. For example, algorithms to identify cosmic and beam-halo backgrounds among collision events were developed and successfully used in physics analyses of 2010 data. At high momenta, the best measurement of muon $p_T$ is obtained by selective use of information from the muon system in addition to that from the inner tracker, with $p_T$ resolution better than 10% up 1 TeV/c. Also, the muon trigger efficiency for isolated muons is better than 90% over the full $\eta$ range.

The good performance and detailed understanding of the muon reconstruction, identification, and triggering provides the necessary confidence in all elements of the chain from muon detection to muon analysis.

References

The results of searches for extensions of the Standard Model in the framework of Supersymmetry (SUSY) at the CMS [1] experiment are presented, concentrating on final state signatures containing one or multiple leptons in combination with hadronic activity and missing transverse energy ($E_T^{\text{miss}}$). All presented analyses are based on the full 2011 LHC dataset of 7 TeV pp collisions, corresponding to an integrated luminosity of 4.98 fb$^{-1}$. No excesses above expectations are observed and the results are interpreted as constraints on the parameter space of the Constrained Minimal Supersymmetric Standard Model (CMSSM) and of signature specific “simplified model scans” (SMS).

1 Opposite-Sign Dilepton Channels

Selecting events with opposite-sign dileptons, jets, and $E_T^{\text{miss}}$, yields a sample dominated by the $t\bar{t} + \text{jets}$ and $Z + \text{jets}$ processes. In SUSY cascade decays, pairs of leptons can be produced in several ways, either independently in the same or in both decay chains, or via production and subsequent decay of $Z$-bosons, generating different kinematic signatures. In particular the shape of the invariant mass distribution can be used as a tool in the estimation, but also to search for edge features hinting at cascade decays.

In CMS, three separate analyses target the opposite-sign final state, specializing on different model phase-spaces and complementary methods[2, 3, 4]. We present here some of the key estimation methods and results.

Controlling the background from $t\bar{t} + \text{jets}$ events is straightforward when focusing on same-flavor final states, as it is flavor symmetric in $ee$, $\mu\mu$, and $e\mu$ channels. Hence the cross-flavor $e\mu$ channel can be used to estimate and subtract $t\bar{t}$ events from the same-flavor yields.

Selecting final states with leptonic $Z$ boson decays probes regions of the SUSY parameter space where the neutralinos have a large Higgsino or neutral Wino component, and where the decay $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z$ can enhance the production of $Z$ bosons[2]. After subtraction of the $t\bar{t}$ background, the remaining events are from $Z + \text{jets}$ processes, where the $E_T^{\text{miss}}$ is generated by jet mis-measurements.
The Jet-Z Balance (JZB) method exploits the fact that in a SUSY cascade decay, the $Z$ boson is correlated with $E_T^{\text{miss}}$, whereas in $Z + \text{jets}$ events they are independent. The JZB variable is defined as $\text{JZB} = |\sum_{\text{jets}} p_T| - |p_T^{Z}|$, and tends to be positive for signal, whereas it is expected to be symmetric for $Z + \text{jets}$ events. Using the negative arm of the distribution, one can then extrapolate to the positive tail defining the signal region (figure 1 (left)). No excess above predictions is observed, and the results are interpreted as constraints on the two parameters of a simplified model framework in which gluino pair production leads to two $Z$ bosons, two $\tilde{\chi}^{0}_1$’s (LSP), and several hadronic jets. The resulting exclusion curve in the gluino and LSP mass plane is shown in figure 1, right, for a scenario where the intermediate $\tilde{\chi}^{0}_2$ mass is fixed to be at 0.75 of the interval between $m_{\tilde{g}}$ and $m_{\tilde{\chi}^{0}_1}$. Furthermore, signal selection efficiencies in the model space are provided for validation and calibration of results from fast simulation software, to allow the application of these results to arbitrary BMS models.

Figure 1: Observed JZB distribution vs. prediction, with a possible MC signal overlaid, from [2] (left). 95 % C.L. upper limits on the cross-section of the inclusive $Z$ boson decay mode in a neutralino LSP scenario, using the JZB method (right).

2 Same-Sign Dilepton Channels

Signatures with two leptons of the same charge, $E_T^{\text{miss}}$, and hadronic jets have very low Standard-Model backgrounds to contend with. Three categories of backgrounds
remain: mis-reconstructed jets and leptons produced in heavy-flavor decays within jets can combine with prompt leptons from $W$ and $Z$ boson decays to form same-sign pairs; opposite-sign lepton pairs from $Z + \text{jets}$ or $t\bar{t} + \text{jets}$ with a mis-identified charge; and rare SM processes with genuine same-sign pairs. In CMS, two publications concern the same-sign channel: one with a general, inclusive approach[5], and one focussing on models with enhanced production of third-generation quarks[6]. Both employ similar background estimation techniques, employing purely data-driven methods for backgrounds involving mis-reconstructed leptons.

To estimate contributions from events with non-prompt leptons from heavy-flavor decays and mis-reconstructed jets, a loose-tight extrapolation method is employed. Two sets of lepton isolation and identification cuts are defined (loose and tight), and the ratio of tight to loose leptons is measured in a control region dominated by QCD multijet events. By relaxing the signal selection to include leptons passing loose cuts in sidebands, one can estimate the non-prompt contribution to the tight window by extrapolating with the measured tight-to-loose ratios. Backgrounds involving mis-identified charges are furthermore estimated by measuring the charge mis-identification probability in events with leptonic $Z$ decays, and extrapolating from opposite-sign control regions with cuts identical to the same-sign signal region.

Several search regions are defined using $E_T^{\text{miss}}$, and $H_T$ (defined as the scalar sum of jet $p_T$s), and the observed yields are compared with the result of background predictions. The non-observation of any excess over predictions is interpreted as excluding a region of parameter-space of the CMSSM, and information on signal selection efficiencies and detector response are provided to facilitate re-interpretation of the results in other models.

3 Single and Multilepton Channels

Several analysis efforts within CMS target the single lepton signature, where the main backgrounds arising are from $W + \text{jets}$ and $t\bar{t} + \text{jets}$ events, using complementary background estimation methods[7, 8], and focussing on models with enhanced production of third generation superpartners[9].

Final states with three and more leptons can be used to probe parameter spaces of many BSM models, such as the slepton co-NLSP scenario in gauge mediated SUSY breaking frameworks, or direct electro-weak production of SUSY particles. In CMS, one analysis is dedicated to multilepton channels [10], and one combined effort of leptonic channels investigates electroweak production [11].
References


Searches for New Physics with Jets in the Final State at CMS

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1 Introduction

We present the results of searches for physics Beyond the Standard Model (BSM) with the CMS detector [1] at the LHC using final states containing jets. Unless otherwise noted, we used the entire √s = 7 TeV proton-proton collision dataset collected in 2011, which corresponds to about 5 fb⁻¹ of integrated luminosity.

2 Summary of the Searches and Results

Highly-Boosted t¯t Decaying Hadronically: Various BSM scenarios predict an enhancement of the t¯t production at high invariant mass in the form of resonances, such as Topcolor Z′ and Randall-Sundrum (RS) Kaluza-Klein (KK) gluon, or as a continuum, such as in models proposed to resolve the anomalous forward-backward asymmetry measured at the Tevatron. In 46% of the cases, both top quarks decay to 3 jets, which often merge due to the boost of the mother quark. The last steps of the jet reconstruction algorithm are reversed in order to perform a W-jet and a top-jet tagging based on the jet substructure and mass. Fig. 1-left shows the jet mass of the highest mass jet in a boosted muon-plus-jets data sample. The dominant standard model (SM) background is non-top multi-jet production, which is estimated by computing the probability for non-top jets to satisfy the top-jet selection criteria in data control regions. After the final event selection, the t¯t mass spectrum is consistent with SM expectations and 95% C.L. limits on the cross section times the branching ratio (BR) are set. The Topcolor Z′ is excluded in the mass ranges 1.3-1.5, 1.0-1.6 and 1.0-2.0 TeV for a resonance width of 1%, 3% and 10%, respectively. The RS KK gluon is excluded between masses of 1.4-1.5 TeV and in a small region near 1 TeV. A 2.6 upper limit at 95% CL is set on a possible continuum enhancement of the cross section with respect to SM expectation for t¯t masses above 1 TeV [2].

Search For Microscopic Black Holes: A prediction of the Arkani-Hamed, Dimopoulos, and Dvali (ADD) model, which introduces a number of large and flat extra-dimensions of space to solve the hierarchy problem, is the formation of microscopic Black-Holes (BH). Evaporated semiclassical and quantum BH leave a signature
with a large number (N) of particles, most of them jets. The event selection requires large values of \( S_T \) (Fig. 1-right), defined as the scalar sum of the \( p_T \) of all reconstructed objects (including \( E_T \)) above a 50 GeV threshold. The dominant background at high \( S_T \) is QCD multi-jet production, and is determined from data by exploiting the empirically observed \( S_T \) invariance with respect to N. Model-independent limits are set on new physics processes producing high-multiplicity, energetic final states. Also, limits are set on specific subsets of the several probed models using optimized \( S_T \) and N selections [3].

**Searches For Randall-Sundrum Gravitons and \( W' \) Decaying to Di-Bosons:**

We report on the RS graviton searches in 3 channels: a) \( G^* \rightarrow ZZ \rightarrow q\bar{q}νν, \) where \( q \) and \( \bar{q} \) are merged into a single jet; b) \( G^*(W') \rightarrow VZ \rightarrow q\bar{q}ll, \) where V is either a Z or a W boson that decays to a \( qq \) merged into a single jet (when the V is a W, this analysis is sensitive to the possible existence of a \( W' \)); and c) \( G^* \rightarrow ZZ \rightarrow q\bar{q}ll. \)

In analysis a), events are selected by requiring a jet with \( p_T > 300 \text{ GeV} \) and invariant mass \( m_{\text{jet}} > 70 \text{ GeV} \) (the \( m_{\text{jet}} \) distribution is shown in Fig. 2-left), a missing transverse energy \( \not{E}_T > 300 \text{ GeV}, \) a jet-\( \not{E}_T \) transverse mass \( m_T(\text{jet},\not{E}_T) > 900 \text{ GeV}, \) no more than 2 jets with \( p_T > 30 \text{ GeV}, \) and no isolated leptons. The main surviving background is \( Z(\rightarrow \nu\bar{\nu})+\text{jets}. \) As no departure from SM expectation is observed, upper limits on the cross section times BR are set, and the RS graviton is excluded in a mass range between 1.0 and 1.5 GeV for values of the coupling constant of the model, \( k/M_{\text{Pl}}, \) varying from 0.11 to 0.29 [4].

The search b) targets heavy resonances with boosted decay products. The mass of the single jet is required to satisfy \( 65 < m_{\text{jet}} < 120 \text{ GeV}, \) while special isolation requirements are applied to the leptons to allow for small \( ll \) opening angles. The shape and overall normalization of the \( M_{VZ} \) distributions of the main SM backgrounds (\( Z/\gamma^*+\text{jets dominates} \)) are determined from data, and no deviation from SM expec-
tation is observed (Fig. 2-center shows the ee case, similar results are found for \( \mu\mu \)). The RS graviton is excluded for masses between 700 and 924 GeV for \( k/M_{Pl}=0.05 \) while the Sequential Standard Model \( W' \) is excluded between 700 and 929 GeV [5].

Analysis c) explores the \( M_{ZZ} \) region between 400 and 1000 GeV, and all decay products are separately reconstructed. An angular likelihood discriminant between the spin-2 signal and the background hypotheses is constructed using 5 measured angles, see Fig. 2-right. Events are categorized according to having 0, 1 or 2 b-tagged jets, and the di-jet and di-lepton masses are required to be consistent with the \( Z \) mass. The kinematics of the jets is corrected using a fit that imposes the \( M_{dijet}=M_Z \) constraint. The \( M_{ZZ} \) distribution is consistent with SM background, \( Z/\gamma^*+\text{jets} \) being the dominant source, and graviton masses in the range 400-945 GeV (400-720 and 760-850 GeV) are excluded for \( k/M_{Pl}=0.1 \) \((0.05) \) [6].

**Searches For Dark Matter and Large Extra Dimension in Monojet Events:** A signature with an energetic jet with \( p_T \) imbalance arises in the ADD model of large extra-dimensions, as well as in dark matter (DM) interactions with SM particles. The event selection requires a jet with \( p_T>110 \text{ GeV}, E_T>350 \text{ GeV}, \) no additional jets with \( p_T>30 \text{ GeV} \) (but 2-jet events are kept if \( \Delta\phi(\text{jet1, jet2})<2.5 \)) and no isolated leptons. The main SM background are \( Z(\rightarrow \nu\bar{\nu})+\text{jets} \) and \( W+\text{jets} \), both determined from data using \( Z(\rightarrow \mu\mu)+\text{jets} \) and \( W(\rightarrow \mu\nu)+\text{jets} \), and no deviation from SM expectations is observed. 90\% CL upper limits on the DM-nucleon cross section are set for spin-independent and spin-dependent models (Fig. 3-left and -center), while 95\% CL lower limits on the fundamental mass scale \( M_D \) of the ADD model are set versus the number of extra-dimension [7].

**Searches for Di- and Three-Jet Resonances:** A search for pair-produced di-jet resonances in events with at least 4 separated jets [8], and a search for di-jet resonances using the \( \Delta\eta\) ratio distribution [9] are performed using the first 2.2 fb\(^{-1}\)
of the 2011 dataset. No deviations from SM background expectations are observed in either cases. 95% CL upper limits on the pair-production of di-jet resonances are set. These are compared with a model of pair-produced colorons, each decaying to $qq$, to exclude coloron masses between 320 and 580 GeV. The angular ratio analysis is used to set 95% CL upper limits on the cross sections of new spin-1/2 quark-gluon resonances, and excited quarks of mass less than 3.2 GeV are excluded.

Various extensions of the SM predict resonances that decay to multi-jet states, such as heavy colored fermions and SUSY gluinos with an R-parity violating decay. The pair production of gluinos, each decaying to 3 jets, is used as a benchmark model. Events with high jet multiplicity and large scalar sum of jet $p_T$ are selected from the 5.0 fb$^{-1}$ of analyzed data. A jet ensemble technique is used to select jet-triplet combinations out of 6 high-$p_T$ jets. The large combinatoric and SM background is fit to a functional form plus a gaussian and, since no excess is observed, gluino masses below 460 GeV are excluded at 95% CL assuming a BR of 100% to 3 jets [10].

References

1 Introduction

Due to the outstanding performance of the Large Hadron Collider [1] (LHC) that in 2011 delivered more than 5 fb$^{-1}$ of proton-proton collision data at center-of-mass energy of 7 TeV, the ATLAS experiment [2] has been able to explore a wide range of exotic models in order to address the questions unanswered by the Standard Model (SM) of particle physics. ATLAS searches for new particles decaying to jets, photons and jets, monojet, $t\bar{t}$ resonances and 4th generation particles decaying hadronically are presented in this paper. No evidence for physics beyond the SM is found and model-independent limits and limits on the parameters of particular models are set.

2 New Physics searches with jets in the final state

Searches in Dijet Mass and Angular Distribution

The production of events with two energetic jets of particles (dijet events) is well understood within the Standard Model. An enhanced production of dijet final states is expected in several scenarios of new physics. A variety of models of new physics, including models with excited quarks and axigluons, predict the resonant production of states decaying predominantly to two jets. Other models, such as quark contact interactions, predict an excess of events with two jet of central rapidity and forming a high invariant mass. By studying the dijet invariant mass ($m_{jj}$) and the dijet angular distributions, sensitive searches for both resonant and non-resonant deviations from the Standard Model are performed. In the dijet resonance search, the $m_{jj}$ of the two leading jets is studied using 4.8 fb$^{-1}$ of data collected in 2011. In the analysis the BumpHunter [4] algorithm is used to evaluate the presence of an excess of events in the $m_{jj}$ spectrum on top of a smooth background estimate by fitting the data with the formula $f(x) = p_1(1 - x)^{p_2} + p_3 + p_4 \ln x$ (where the $p_i$ are the fit parameters and $x \equiv m_{jj}/\sqrt{s}$). No resonant structure is found and masses of excited quark less then 3.35 TeV are excluded at 95% confidence level (C.L.). In the angular analysis convenient variables that emphasizes the dijet central scattering region are employed. The $\chi$ variable is defined as the exponential of the rapidity difference of the two jets with the highest transverse momenta ($p_T$). In Figure 1 (left) the $\chi$ distribution for different $m_{jj}$ interval is shown in data along with background predictions from NLO QCD. The $F_\chi(m_{jj})$
variable is defined as the ratio \( F_\chi(m_{jj}) = N_{\text{central}}/N_{\text{total}} \) where \( N_{\text{central}} \) is the number of dijet events in a defined central region, and \( N_{\text{total}} \) is the number of dijet events in the full distribution extending to \( \chi < 30 \). This variable has excellent sensitivity to resonant as well as non-resonant excesses of central jets. The resulting distribution for different \( m_{jj} \) values is shown in Figure 1 (right) for the data and the NLO QCD background. Data and QCD prediction agrees in each \( m_{jj} \) bin. Limits at 95% C.L. are set on models of contact interactions and quantum black holes. The full analysis details, including limits on additional models, are given in Reference [3].

**Searches in Photon-Jet Mass Distribution**

The photon-jet invariant mass distribution \( (m_{\gamma j}) \) is shown to be a useful tool for searching for resonances indicative of new physics. The most recent ATLAS results [5] are obtained from the analysis of 2.11 fb\(^{-1}\) of 2011 proton-proton collision data. Data events with \( m_{\gamma j} \) masses up to 2 TeV are compared with a smooth background estimate, and no evidence of resonant production is found. Limits are set on generic Gaussian-shape signals (excluded below 2 TeV) and on a benchmark excited-quark model excluding masses below 2.46 TeV.

**Searches in Monojet plus Missing Transverse Momentum Final States**

The search for new physics in events with a jet of high transverse energy and large missing transverse energy constitute one the simplest and most striking signatures that can be observed at a hadron collider. Different theoretical models for physics Beyond the Standard Model predict the presence of monojet signatures in the final state like, for example, Large Extra Dimension scenarios. In the analysis presented in Reference [6] 1 fb\(^{-1}\) of data are used to select events with one high \( p_T \) jet and a large amount of missing transverse energy. A lepton veto is applied to reduce the electroweak background. The shape of the dominant
electroweak background is taken from Monte Carlo normalized using data in control regions, while the multi-jet contribution and the non-collision background are estimated with a data-driven technique. Good agreement is observed between the data and the Standard Model predictions. Model-independent upper limits at 95% C.L. are set on the fiducial cross section for the non-Standard Model production of different signal $p_T$-region varying between 2.02 pb and 0.045 pb. Additionally, an interpretation is made in terms of the Large Extra Dimensions model. Values of the fundamental Planck scale between 3.2 and 2.0 TeV are excluded for a number of extra dimensions corresponding to 2 and 6, respectively.

3 Searches of High-Scale physics scenarios with Boosted Objects in the Final State

Hadronic decays of heavy particles such as W bosons, top quarks and potential hitherto unobserved particles may be collimated into a single heavy jet characterized by a distinct substructure and large mass. In this section exotic analyses using boosted or mostly resolved reconstruction topology are presented.

Figure 2: Left: Reconstructed invariant mass distribution of the $t\bar{t}$ candidates after the lepton plus jets signal selection. The shaded band indicates the uncertainty in the normalization of the Standard Model prediction [7]. Right: Distribution of the numbers of events observed in the data and expected from SM processes for $N_{jets} = 6, 7, \geq 8$ with $N_W = 0, 1, \geq 2$. The expected $b'$ signals for two masses are also shown, stacked on top of the backgrounds [9].

Search for $t\bar{t}$ resonances in lepton plus jets events with highly boosted top quarks

A search for resonant production of high-mass top-quark pairs is performed on 2.05 fb$^{-1}$ of ATLAS 7 TeV data [7]. The signal is assumed to originate from the resonance of a leptophobic Z\' or a Kaluza-Klein gluon. The analysis focuses on the lepton plus jets final state obtained when one W boson decays to a charged lepton and a neutrino, and the other
decays to a quark and an anti-quark pair. The selection and reconstruction are specifically designed for the collimated topology that arises from the decay of boosted top quarks. The hadronically decaying top quark candidate is identified as a single fat jet with radius parameter $R = 1$. In Figure 2 (left) the reconstructed $t\bar{t}$ mass spectrum is compared with a template for the Standard Model prediction constructed using a combination of Monte Carlo simulations and data-driven measurements using control samples. The data are found to be compatible with the SM within uncertainties. Upper limits at 95% CL on the production cross section times the branching ratio of narrow $Z'$ resonances and broad colored resonances are derived. Leptophobic $Z'$ with masses between 600 GeV and 1.2 TeV is excluded and Kaluza-Klein gluon with a mass smaller than 1.5 TeV is also excluded. The sensitivity of this search obtained with highly boosted top quarks is significantly enhanced in the 1-2 TeV region with respect to a previously published search using the same data set [8].

Search for exotic heavy quarks

A search for pair production of a fourth generation down-type quark $b'$ in events with one lepton is performed with 1.04 fb$^{-1}$ of 7 TeV data [9]. In the model where $b'$ is a chiral quark with mass larger than $m_t + M_W$, the predominant decay mode is $b' \rightarrow Wt \rightarrow WWb$, which leads to four W bosons and two $b$ quarks in the $b\bar{b}$ production events. Due to the high expected $b'$ mass, the W bosons coming from the $b' \rightarrow Wt$ decay are expected to have a high momentum and the decay products of such W bosons should be closer together than jets for background processes, but still resolvable as separate jets (mostly resolved topology). Considering this, the quantity suitable for distinguishing $b'$ signal from background is the number of jet pairs with small opening angle and an invariant mass close to the W boson mass. The final discriminant consists of nine exclusive bins as a function of the multiplicity of hadronic W decays ($N_W = 0, 1, \geq 2$) and jet multiplicity ($N_{jet} = 6, 7, \geq 8$), as shown in Figure 2 (right). A binned maximum likelihood fit is performed to derive the most likely cross-section of $b\bar{b}$ pairs. No evidence of $b'$ production is observed with 1.04 fb$^{-1}$ data. The $b'$ masses below 480 GeV are excluded at 95% confidence level.

References

Concluding remarks (on the Higgs boson)

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I want to focus here on the lessons that we have learned from preliminary LHC results on Higgs searches. I will concentrate mostly on the Higgs boson, rather than on new physics, not only because the mechanism of electroweak (EW) symmetry breaking is one of the priorities in the LHC program, but also because we have new data on the Higgs and it is exciting to think about where they lead us to.

The phenomenon of EW symmetry breaking had already been established before the LHC. After LEP we had ample evidence for gauge structure in interactions (including triple gauge bosons couplings $\gamma WW$ and $ZWW$) and for the existence of longitudinal components of $W$ and $Z$. Combining this information with knowledge of gauge boson masses, we conclude that propagating particles do not share the full symmetry of interactions, and thus that the EW symmetry is spontaneously broken. This means that every known phenomenon in particle physics (at least before December 13, 2011) can be described by the Lagrangian

$$L = -\frac{1}{4} \text{Tr} F_{\mu\nu} F^{\mu\nu} + i \mathcal{J} \gamma^\mu D_\mu f + \frac{v^2}{4} \text{Tr} D_\mu \Sigma^\dagger D^\mu \Sigma - \frac{v}{\sqrt{2}} f L \Sigma \lambda f R + \text{h.c.}$$

where $\Sigma \equiv \exp \left( \frac{i T^a \pi^a}{v} \right)$,

The first two terms in eq. (1) describe the kinetic terms and gauge interactions of the SM particles. The last two term contain the effect of the longitudinal polarizations and the mass terms that arise when gauge symmetry is realized non-linearly.

Although the Lagrangian in eq. (1) was fully satisfying from the experimental point of view, even before Dec 13 every theorist knew that it could not be the full story. Scattering amplitudes of longitudinal gauge bosons grow like $(E/4\pi v)^2$, signaling loss of perturbative unitarity, and thus the onset of new phenomena, at $E \approx 4\pi v = 3$ TeV.

The goal of the LHC is to discover what is the new phenomenon. It is well known that the simplest option is given by a single real scalar field $h$, which forms a complete $SU_2$ doublet together with $\pi^a$. So $3/4$ of the Higgs have already been found and the LHC must find the missing $1/4$. However, there is no strong motivation, other than simplicity, for choosing a single $h$ and nature may have good reasons to make different choices. In this respect, hunting for the Higgs is not just looking for the last missing
piece of the SM, but it means exploring an unknown territory and identifying the nature of the new force responsible for EW breaking, which I will call the fifth force.

When we examine the SM, we note that almost all of its open problems originate from Higgs interactions. The flavor problem comes from Yukawa couplings, the hierarchy problem from the Higgs bilinear, the stability problem from the Higgs quartic coupling (and one can add the cosmological constant problem from a constant term in the scalar potential). The crux of these puzzles is that the fifth force is not a gauge force. Therefore, it lacks the properties of uniqueness, robustness against deformations, and predictivity, which are characteristic of gauge theory.

In order to discuss what we have learned from Higgs searches, I will identify two fundamental questions. The first question is: What is the fifth force? We want to know if it is weak or strong; if it is a gauge force or associated with a fundamental scalar. The answer to this question will come from measurements of Higgs couplings. These measurements will play the role that precision EW data played at the time of LEP. An important difference is that, in the case of Higgs couplings, deviations from the SM expectation could be large (not necessarily of one-loop size) and thus show up even at an early stage. Actually, the more natural the Higgs boson is, the more its properties must deviate from the SM. This is because a natural theory must give large corrections to the Higgs two-point function (to cure the hierarchy problem). These large corrections must also modify the Higgs production rate at the LHC and some of its decay channels, as can be easily seen by inserting two gluons (or two photons) in the Feynman diagram of the Higgs two-point function. This expectation is fully confirmed in all the examples of natural theories known to us. So measuring the Higgs couplings is the way to probe the fifth force and may be the first way for new physics to show up.

The second question is: Is the Higgs natural? This is not an idle question. Its importance goes beyond EW symmetry breaking and its answer will influence the strategy for future directions in particle physics. Naturalness is a concept fully linked to the use of effective field theories (EFT). EFT is the tool that we use to implement an intuitive notion: separation of scales. In simple words, separation of scales means that we don’t need to know the motion of every atom inside the moon to compute its orbit. Or we don’t need to know about quarks to describe physics at the atomic scale. We build a stack of EFT, one on top of the other, just like a matryoshka doll with one layer inside the other. Each EFT is appropriate to describe a certain energy regime, but it is connected to the next in the sense that free parameters in one layer can be computed in the next layer. One of the most remarkable results of modern physics has been the discovery that at each layer we find simpler physical laws, larger symmetry, unification of concepts that seemed unrelated in the previous layer. It is amazing that nature works this way, but it is just an empirical fact. We can use the criterion of naturalness in EFT to infer the energy at which the validity of one layer ends and a new layer must set in. Whenever a next layer exists, this procedure gives
a reasonable answer, as shown by various examples (electron self-energy, pion mass difference, neutral kaon mass difference). When applied to the Higgs boson mass, this criterion gives a maximum scale for new physics at about 500 GeV.

Since we have not yet found any new physics at the LHC, one may wonder what is the fate of naturalness. The issue is not yet settled. It is quite possible that new physics is just around the corner. After all, the LHC has entered the territory of naturalness, but the exploration is far from complete. The alternative is that the idea of naturalness does not apply to the Higgs because there is a failure of the EFT approach. After all, dark energy could already be taken as evidence for failure of EFT, since the naturalness of the cosmological constant suggests new physics around $10^{-3}$ eV. Holography, gauge-gravity duality, and the AdS-CFT correspondence show that some theories are much richer than what a single Lagrangian can capture. The best we can do to describe the physical content is to resort to two different Lagrangians, two dual versions. Maybe this is an indication that our theoretical tools are failing, that an EFT Lagrangian is not able to catch all the underlying physics. There could be connections between small and large scales. A numerological curiosity is that, if we combine the largest possible scale (the Hubble length $H^{-1} = 10^{26}$ m) with the smallest (the Planck length $M_P^{-1} = 10^{-35}$ m), we can reproduce the scale of the cosmological constant ($\Lambda_{CC} = \sqrt{H M_P} = 5 \times 10^{-3}$ eV) and the weak scale ($\Lambda_{EW} = \sqrt{\Lambda_{CC} M_P} = 5$ TeV). If behind this numerical curiosity there is some theoretical IR/UV connection, we will never be able to catch it with an EFT.

Another approach which would invalidate naturalness is the idea of the multiverse. Out of the process of eternal inflation, a multitude of universes are created, each with its own values of the fundamental constants and its own physical laws. Anthropic arguments then select the kind of universe in which we live in or, in other words, the physical laws that govern nature. It may sound like a crazy idea to some (bordering on science fiction), but at present the multiverse yields the most convincing explanation of the cosmological constant. A lesson from the multiverse is that some of the questions that we thought to be fundamental may actually be just the result of environmental conditions, and carry no more significance than the shape of continents or the emergence of a particular animal species in Darwinian evolution.

So physics has reached a branching path and the LHC will tell us which way we have to follow. One path follows the road that guided us towards the extraordinary successes of particle physics in the last 100 years or so: a new layer, new symmetry, more unification that bring us closer to a single governing principle of nature. The other path is marked by the failure of naturalness, the collapse of the picture of a multi-layered matryoshka doll hiding a single final truth. We have only vague ideas of where this path leads to, and maybe the multiverse is the most concrete construction along this path. It is clear that establishing the fate of Higgs naturalness has far-reaching consequences for particle physics, well beyond the problem of EW breaking.

The LHC will teach us which path we have to follow. The first path is very
Figure 1: Regions of absolute stability, meta-stability and instability of the SM vacuum in the $M_t-M_h$ plane. The frame on the right zooms in the region of the preferred experimental range of $M_h$ and $M_t$ (the gray areas denote the allowed region at 1, 2, and 3σ). The three boundaries lines correspond to $\alpha_s(M_Z) = 0.1184 \pm 0.0007$, and the grading of the colors indicates the size of the theoretical error. The dotted contour-lines show the instability scale $\Lambda$ in GeV assuming $\alpha_s(M_Z) = 0.1184$.

familiar to particle physicists and promises new discoveries on the road towards final unification. The other path may mean finding the Higgs and nothing else at the LHC. It will force us to abandon naturalness and EFT, and look for new paradigms in a holistic vision, where nature should be seen as a whole and cannot always be reduced to its smaller components. But physics is a natural science and we want to find answers with the experimental method. While along the first path there are new phenomena to be studied and the goals are clear, how will we be able to make progress if the second path turns out to be true? This is a difficult question and I don’t have an answer. However, I want to show that measuring the Higgs mass may give us some indirect hints.

For the sake of argument, let me assume that the SM with a single Higgs fully describes physics up to a very large energy scale. I will also take seriously the LHC indication for a Higgs mass around 125–126 GeV. In this case, as shown in fig. 1, we learn that our universe lives in a very critical condition, at the verge of a cosmic catastrophe. It is a remarkable coincidence that we happen to live just at the boundary between two phases: the ordinary Higgs phase and a region where the Higgs field slides to very large values. The condition for absolute stability is

$$M_h [\text{GeV}] > 129.4 + 1.4 \left( \frac{M_t [\text{GeV}] - 173.1}{0.7} \right) - 0.5 \left( \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0_{\text{th}}.$$
Precise experimental information on the Higgs and top mass is needed to ascertain the ultimate fate of the universe and whether we live a stable vacuum or not. The Higgs mass can be measured very precisely at the LHC. Then the top mass will become the largest source of uncertainty and every GeV in $M_t$ counts as a shift of 2 GeV in the Higgs mass. A reduction in the error on the top mass may become the best telescope to peek into the future of our universe.

Also the hierarchy problem can be interpreted as a sign of near criticality between two phases. The coefficient $m^2$ of the Higgs bilinear in the scalar potential is the order parameter that describes the transition between the symmetric phase ($m^2 > 0$) and the broken phase ($m^2 < 0$). In principle, $m^2$ could take any value between $-M_P^2$ and $+M_P^2$, but quantum corrections push $m^2$ away from zero towards one of the two end points of the allowed range. The hierarchy problem is the observation that in our universe the value of $m^2$ is approximately zero or, in other words, sits near the boundary between the symmetric and broken phases. Therefore, if the LHC result is confirmed, we must conclude that both $m^2$ and $\lambda$, the two parameters of the Higgs potential, happen to be near critical lines that separate the EW phase from a different (and inhospitable) phase of the SM. Is criticality just a capricious numerical coincidence or is it telling us something deep?

The occurrence of criticality could be the consequence of symmetry. For instance, supersymmetry implies $m^2 = 0$. If supersymmetry is marginally broken, $m^2$ would remain near zero, solving the hierarchy problem. But if no new physics is discovered at the LHC, we should turn away from symmetry and look elsewhere for an explanation of the near-criticality. It is known that statistical systems often approach critical behaviors as a consequence of some internal dynamics or are attracted to the critical point by the phenomenon of self-organized criticality. As long as no new physics is discovered, the lack of evidence for a symmetry explanation of the hierarchy problem will stimulate the search for alternative solutions. The observation that both parameters in the Higgs potential are quasi-critical may be viewed as evidence for an underlying statistical system that approaches criticality. The multiverse is the most natural candidate to play the role of the underlying statistical system for SM parameters. If this vision is correct, it will lead to a new interpretation of our status in the multiverse: our universe is not a special element of the multiverse where the parameters have the peculiarity of allowing for life, but rather our universe is one of the most common products of the multiverse because it lies near an attractor critical point. In other words, the parameter distribution in the multiverse, instead of being flat or described by simple power laws (as usually assumed) could be highly peaked around critical lines because of some internal dynamics. Rather than being selected by anthropic reasons, our universe is simply a very generic specimen in the multitude of the multiverse. If you complained that string theory was making no predictions about our universe, do not rejoice in this. Now the situation may become even worse: the multiverse is making predictions, but about other universes.
What does a Higgs mass of 125-126 GeV tell us about natural theories? A Higgs mass smaller than 120 GeV would have been perfect for natural supersymmetry, while a mass larger than 130 GeV would have excluded the simplest scenarios. If the Higgs mass is really 125 GeV, right in the middle, then it looks like nature wants to tease theoretical physicists. In supersymmetry, a Higgs mass of 125 GeV can be reached, but only for extreme values of the parameters, especially those of the stop. Therefore certain natural setups, where parameters are correlated, are in bad shape (for instance gauge mediation), but the idea of low-energy supersymmetry is not killed. As shown in fig. 2, a Higgs mass of 125 GeV rules out the idea of Split Supersymmetry with a high scale, say larger than $10^8$ GeV. However, it fits very well with Split Supersymmetry with a low scale. Actually the simplest model of Split Supersymmetry, based on anomaly mediation, predicts a hierarchy between scalars and fermions of a one-loop factor and thus looks like a very satisfactory solution.

The indication for a Higgs mass in the range 125–126 GeV is the most exciting result from the LHC so far. It has important consequences for supersymmetry and other theories beyond the SM, but the most puzzling (and surprising) message that we obtained from preliminary LHC data on the Higgs is the apparent near-criticality of the parameters entering the SM Higgs potential.
Physics in LHC 2012
Vancouver BC Canada
June 4 – 9, 2012

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PHYSICS IN LHC 2012
JUNE 4 – 10, 2012

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