Standard Model at LHC [*]

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Abstract

Even if the predictions of the Standard Model of particle physics are validated by the experiments at the energy currently probed, a deeper understanding and a better measurement of the Standard Model parameters at higher energy will allow to constrain the theory and search for deviations, highlighting in the same time signs of new physics. Here is a review of the Standard Model related analysis foreseen by ATLAS and CMS detectors in the context of the new generation proton-proton collider LHC.

1 Introduction

The Standard Model of particle physics (SM) has been successfully tested at the energy provided by the LEP and Tevatron colliders. However, many topics remain unclear, especially the electroweak symmetry breaking mechanism. The aim of the LHC (Large Hadron Collider) is to cover physics at the energy of this symmetry breaking mechanism, where evidences of new physics are expected. As we learned from the Tevatron, hadron colliders are able to perform precision measurements, as soon as the systematics uncertainties are understood and under control. Then, the LHC will allow to precisely measure SM parameters in view to :

- have a better understanding of SM, performing precision electroweak measurements and Top physics studies. Especially, a precise measurement of the W boson mass, the Top mass and the Weinberg angle can constrain the mass of the Higgs boson and then fix the limits of the SM;
- search for direct and indirect deviation from SM in experimental spectra.

To perform such a physics programme, the LHC proton-proton collider has been designed to reach an energy equal to $\sqrt{s} = 14$ TeV in the center of mass of the collision. A first luminosity phase at 10^{33} cm^{-2}s^{-1} providing 10 fb^{-1} per year is foreseen to perform the precision measurements. In a second phase, devoted mainly to new particles searches, the luminosity will reach 10^{34} cm^{-2}s^{-1} providing 100 fb^{-1} of data per year.

2 Experimental framework

Amongst the four detectors on the main ring of the LHC, ATLAS [1] and CMS [2] are two general purpose physics detectors allowing to study many physics channels related to the precise measurement

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of SM parameters thanks to there high granularity sub-detectors, covering the whole solid angle. Even if the technologies used by these two detectors are different, they will reach equivalent precision on measurements.

Thanks to the very high energy delivered by the proton-proton collider, the cross section of the main physical processes are one or two orders of magnitude larger than at the Tevatron. The LHC will be a W, Z and Top quark factory what will reduce the statistical error on measurements, which is the main source of uncertainty at the Tevatron. In addition, the large amount of collected data will also be used to understand the detector behaviour and control the systematics.

Nevertheless, protons beams are not ideal since protons are composite particles, leading to parton-parton collisions carrying only a part of the initial beam energy.

3 Precision electroweak measurement

3.1 W mass measurement

LHC expects to measure the W mass with a precision of 15 MeV/c^2. To perform this study, the useful decay channel is $W \rightarrow l\nu$, as at the Tevatron, but the main advantage of the LHC is its production rate : 60 million of reconstructed W per year at low luminosity.

The measurement of the W mass can be performed using several methods :

- the W mass can be assessed from the measurement of the M_W^T/M_Z^T ratio : in such a way, the systematics are small but the use of the Z boson reduces the statistics;

- CMS uses the transverse momentum of the lepton whose spectrum shape is sensitive to the W mass. This method, which relies on the well known Z boson spectrum shape, is weakly biased by the pile-up and suffers from the theoretical knowledge of the transverse momentum spectrum shape of the W boson;

- M_W^T can be used to assess the W mass at low luminosity. This method, which suffers from the pile-up, is traditionally used in ATLAS to cope with the unmeasured p_z^ν. The transverse momentum of the neutrino is estimated using the measured p_T^l and the recoil of the W.

In both ATLAS and CMS methods discussed here, the W mass is extracted by a fit of the experimental shape to Monte-Carlo samples simulated with different values of M_W.

Table 1 summarizes the different sources of uncertainties on the W mass measurement. The statistical error is negligible and the systematics come from physics and detector effects reported on the table. At the LHC, these systematics will be estimated using other physics channels. For example, the PDF are sensitive to $W \rightarrow e\nu$ rapidity distributions (electron and positron rapidity in figure 1). Despite the effect of the detector, the cross section in function of the rapidity will allow to distinguish between various PDF sets.

With only one channel of the W decay, the LHC expects to reach a precision on the W mass measurement better than 25 MeV/c^2 after one year at low luminosity. Combining the channels and both experiments, the LHC should reach an uncertainty of 15 MeV/c^2. A precise measurement of W mass is one of the challenge of LHC, pushed by the last results from Tevatron which are already very precise (~ 26 MeV$/c^2$).

3.2 Weinberg angle

The Weinberg angle will be measured using the Forward-Backward asymmetry (A_{FB}) which occurs in the angular distribution of the lepton from the Z boson decay due to the parity violation in neutral current.

source of uncertainty	CDF, RunII, Combined channel 200 pb^{-1} [3]	LHC [1] 60 M event, 10 pb^{-1}
Statistics	0 MeV/c^2	$<$ 2 MeV/c^2
Lepton scale	17 MeV/c^2	15 MeV/c^2
Energy resolution	3 MeV/c^2	5 MeV/c^2
Recoil model	12 MeV/c^2	5 MeV/c^2
Lepton id.	———	5 MeV/c^2
p_W^T	3 MeV/c^2	5 MeV/c^2
PDF	11 MeV/c^2	10 MeV/c^2
W width	———	7 MeV/c^2
Radiative decays	11 MeV/c^2	$<$ 10 MeV/c^2
Background	0 MeV/c^2	5 MeV/c^2
TOTAL	26 MeV/c^2	25 MeV/c^2

Table 1: *Source of uncertainties related to the W mass measurement in $W \to l\nu$ channel for LHC (one lepton species, at low luminosity, per experiment after one year) compared to last results from CDF (electron and muon combined channels).*

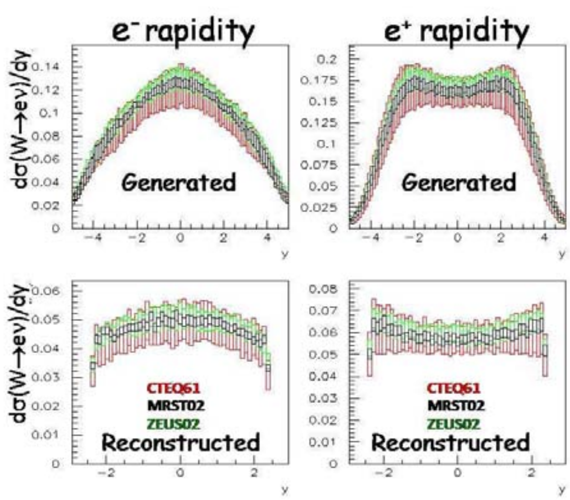

Figure 1: *Differential cross section for various PDF sets in function of the $e^{\pm}$ rapidity.*

Coupling	Current value	LHC sensibility (95% C.L., 30 fb^{-1}, 1 experiment)
Δg_1^Z	$-0.016^{+0.022}_{-0.019}$	0.005-0.011
$\Delta\kappa_\gamma$	$-0.027^{+0.044}_{-0.045}$	0.03-0.076
$\Delta\kappa_Z$	$-0.076^{+0.061}_{-0.064}$	0.06-0.12
λ_γ	$-0.028^{+0.020}_{-0.021}$	0.0023-0.0035
λ_Z	$-0.088^{+0.063}_{-0.061}$	0.0055-0.0073

Table 2: *Current value and uncertainty on 5 Triple Gauge Couplings parameters, and expected uncertainty at LHC for one experiment after three years of data taking at low luminosity.*

More specifically, at the Z pole, A_{FB} comes from interferences between vector and axial components of the coupling, leading to :

$$A_{FB} = b(a - sin^2\theta_W)$$

where a and b are calculated to NLO in QED and QCD.

The Z boson is produced by $q\bar{q}$ fusion. The $\bar{q}$, coming from the sea, has in average a lower momentum. At LHC, the assumption is made that the quark direction is the same as the boost of the Z. This assumption is valid for large di-lepton rapidities, this is why $Z \to e^+e^-$ channel is used thanks to the larger η coverage of the electromagnetic calorimeter.

The sensitivity on A_{FB} increasing with forward electrons, cuts are applied on the rapidity of each lepton and di-leptons, leading to a statistical uncertainty on A_{FB} of the order of 2.3×10^{-4}. The statistical uncertainty on the Weinberg angle is then 1.4×10^{-4} [4], of the order of the world average error. To reach a global uncertainty of the order of the current one, the systematics have to be small enough. So, errors due to the parton density function (PDF), the lepton acceptance and efficiency, and the effects of higher order QCD have to be well estimated, and under control. This will be only reached after few years of data taking.

3.3 Triple gauge boson couplings

LHC planned also to probe the non abelian structure of the SM from the measurement of Triple Gauge Couplings leading to WW, ZW, γW production in the final state. Thus, the measurement of the Triple Gauge Couplings will be assessed from the diboson cross sections, the shape of high p_T bosons spectrum or the production angle between the two final state bosons.

In the SM framework, only the $WW\gamma$ and WWZ interactions are allowed, leading to 14 possible couplings. Among them, only 5 independent, CP conserving, gauge invariant preserving are used. At the SM tree level, each of these parameters is equal to zero. Their behaviour in function of the energy in the center of mass is however different : Δg_1^Z, $\Delta\kappa_\gamma$ and $\Delta\kappa_Z$ are growing with $\sqrt{s}$ whereas λ_γ and λ_Z are growing with s what is a big advantage for the LHC.

Table 2 reports the current values and LHC expected sensitivity for each parameter : the LHC expectation are similar to the current world average uncertainty [5].

4 Top quark physics

Discovered in 1995, the Top quark, whose high mass is still a mystery, completes the three family structure of the SM. The large amount of Top events produced at LHC will allow to measure most of the Top properties.

$t\bar{t}$ Channel	Luminosity (fb^{-1})	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$
semi-leptonic	10	$9.7\%(syst) \pm 0.4\%(stat) \pm 3\%(lumi)$
di-lepton	10	$16\%(syst) \pm 1.3\%(stat) \pm 3\%(lumi)$
full hadronic	1	$20\%(syst) \pm 3\%(stat) \pm 5\%(lumi)$

Table 3: *Precision on the $t\bar{t}$ cross section measurement expected by CMS.*

The Top quark can be produced by strong interaction leading to a $t\bar{t}$ pair in the final state, with a cross section of about 833 ± 100 pb at the LHC [6], leading to 8 million of Top pairs per year at low luminosity. The Top quark can also be produced in a single way from weak interaction with a cross section of 330 pb.

The signature of $t\bar{t}$ events is dominated by the W decay leading to two quarks or a lepton/ν pair. So, the three possible final states are :

- the fully hadronic channel where both W decay into quarks. Even if this channel is the dominant one, it suffers from a huge background mainly from QCD.
- the di-lepton channel where both W decay into lepton/ν pair. This channel benefits from a very small background but the two neutrinos make difficult the complete reconstruction of the Top quarks.
- the golden channel is the semi-leptonic one where, in the leptonic side, the lepton is used to trigger the event, and where the hadronic Top is completely reconstructed on the other side. This channel benefits from a large event yield and a small background.

In the golden channel, the events are selected requiring at least 4 jets with $p_T > 40$ GeV$/c$, one electron (or muon) with $p_T > 20(25)$ GeV$/c$ according to the trigger menu and a missing transverse energy above 20 GeV.

4.1 Top quark mass measurement

For the Top quark mass measurement, ATLAS foresee to reconstruct $t\bar{t}$ events with early data without applying b-tag algorithms which will not be optimized at the LHC start. Top quarks are reconstructed using the 3 jets whose the sum of the p_T is the highest [7], with a reconstruction efficiency of about 5 %.

When using the b-tagging, requiring the presence of 2 b-jets among the jets, 100 pb^{-1} of data lead to a significance of $S/B = 100$ and an efficiency of roughly 1 %. The precision on the Top mass is then of the order of 1.3 GeV/c^2 [8]. An other method, using both leptonic and hadronic sides and a kinematical fit can reach a precision of the order of 1 GeV/c^2 [8] on the Top mass measurement.

4.2 $t\bar{t}$ cross-section measurement

The $t\bar{t}$ events reconstruction will also be used to measure the production cross section. These studies have been performed for each of the 3 channels of $t\bar{t}$ decay. The semi-leptonic channel gives the best precision on the cross section measurement, with the best reconstruction efficiency. Other channels lead to a precision between 17 % and 21 % on this measurement [9], as shown on table 3.

4.3 Top polarization

The Top polarization will be measured through the polarization of the W boson coming from the $t \rightarrow Wb$ vertex. So, the three polarizations $\mathrm{F_0}$, $\mathrm{F_L}$ and $\mathrm{F_R}$ will be measured using the angular distribution of the

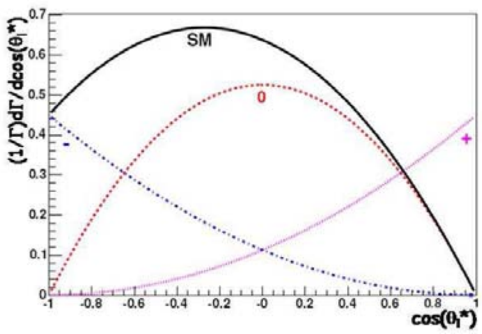

Figure 2: *Differential cross section in function of* $\cos\theta_l^*$ *in the Standard Model framework.*

	Standard Model (m_t = 175 GeV/c^2)	Error $\pm$stat $\pm$syst
F_0	0.703	$\pm 0.004 \pm 0.015$
F_L	0.297	$\pm 0.003 \pm 0.024$
F_R	0.000 ($m_b = 0$ GeV/c^2)	$\pm 0.003 \pm 0.012$

Table 4: *Expected statistical and systematics uncertainties on Top polarization parameters at LHC (ATLAS).*

leptons :

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l^*} = \frac{3}{8}(1+\cos\theta_l^*)^2 F_R + \frac{3}{8}(1-\cos\theta_l^*)^2 F_L + \frac{3}{4}\sin^2\theta_l^* F_0$$

θ_l^* being the angle between the lepton in the W rest frame and the W in the Top rest frame.

Figure 2 shows the expected differential cross section in function of $\cos\theta_l^*$ in the Standard Model framework, leading to the measurement of F_0, F_L and F_R reported in table 4, with the statistical and systematics uncertainties foreseen by ATLAS experiment [10].

4.4 Single Top cross-section measurement

The three single Top production processes will be measured at LHC. Table 5 gives the expected uncertainty on the cross section measurement for both ATLAS and CMS experiments, for each single Top channel.

5 Conclusion

The precise measurement of electroweak parameters, as well as the Top physics studies allowed by the LHC will lead us to a better understanding of the Nature, providing constraints on the SM. With few years of data taking at low luminosity, both ATLAS and CMS experiments can reach a precision on these measurements of the order of the current world average precision, what will improve the sensitivity to new physics phenomena.

Channel	$\Delta\sigma/\sigma$ ATLAS (30 fb^{-1}) [11]	$\Delta\sigma/\sigma$ CMS (10 fb^{-1}) [9]
t-channel	$12\%(syst) \pm 1\%(stat) \pm 5\%(lumi)$	$8\%(syst) \pm 2.7\%(stat) \pm 5\%(lumi)$
Wt-channel	$14\%(syst) \pm 1.5\%(stat) \pm 5\%(lumi)$	$23.9\%(syst) \pm 8.8\%(stat) \pm 9.9\%(MC)$
s-channel	$16\%(syst) \pm 12\%(stat) \pm 5\%(lumi)$	$31\%(syst) \pm 18\%(stat) \pm 5\%(lumi)$

Table 5: *Precision on the single Top cross section measurement expected by ATLAS and CMS.*

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References

[1] The ATLAS Collaboration, ATLAS Technical Proposal, 1994, CERN/LHCC/94-43.

[2] The CMS Collaboration, CMS Technical Proposal, 1994, CERN/LHCC/94-38.

[3] T. Aaltonen *et al.*, First Measurement of the W Boson Mass in Run II of the Tevatron, 2007, hep-ex/0707.0085.

[4] K. Sliwa, S. Riley, U. Baur, Effects of possible extensions to rapidity coverage of the ATLAS detector on the determination of $sin^2\Theta_{eff}(M_Z^2)$., 2000, ATL-PHYS-2000-018.

[5] Tom LeCompte, Precision Electroweak Measurements at the LHC, 2007 Aspen Winter Conference on Particle Physics Program, `{http://conferences.fnal.gov/aspen07/monday/LeCompte_PrecisionEWK.ppt}`.

[6] Bonciani R. *et al.*, Nucl. Phys. **B529** (1998).

[7] S. Bentvelsen, M. Cobal, Top studies for the ATLAS Detector Commissioning, 2005, ATL-PHYS-PUB-2005-024.

[8] I. Borjanovic *et al.*, Investigation of top mass measurements with the ATLAS detector at LHC, 2005, [hep-ex/0403021].

[9] The CMS Collaboration, CMS Physics TDR: Volume II (PTDR2), Physics Performance, 2006, CERN-LHCC-2006-021.

[10] F. Hubaut, E. Monnier, P. Pralavorio, V. Simk, K. Smolek, ATLAS Collaboration, ATLAS sensitivity to top quark and W boson polarization in $t\bar{t}$ events, 2005, SN-ATLAS-2005-052.

[11] A. Lucotte, A. Llres, F. Chevallier, Prospects for single top cross-section measurements in ATLAS, 2007, ATL-PHYS-PUB-2007-005.