Proceedings of the Second Annual LHCP
ATL-PHYS-PROC-2014-102
August 27, 2014

ATLAS results on top properties

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ABSTRACT

Recent measurements of top quark properties using $t\bar{t}$ events produced in proton-proton collisions at the Large Hadron Collider with centre of mass energies of 7 and 8 TeV and detected by the ATLAS experiment are presented. These results include top quark mass, the top and anti-top mass difference, the electric charge, the top quark polarization and spin correlation, the $t\bar{t}$ charge asymmetry and the search for flavour changing neutral currents.

PRESENTED AT

The Second Annual Conference
on Large Hadron Collider Physics
Columbia University, New York, U.S.A
June 2-7, 2014

[1] Work supported by the Polish France collaboration IN2P3-COPIN 10-140

1 Introduction

The datasets collected by the Large Hadron Collider (LHC [1]) in 2011 and 2012 open a precision era in the study of the properties of the top quark. This quark is the most massive elementary particle known to date, decays almost exclusively through a single decay mode ($t \to Wb$) and, due to its extremely short lifetime of $\sim 5 \times 10^{-24}$ s, decays before hadronization, allowing its spin information to be passed to the decay products. Such unique characteristics provide not only an excellent way of testing the Standard Model (SM), but also an important window to physics beyond it. A large variety of top quark properties can be studied for top quark pair production, either in production, decay, for the whole $t\bar{t}$ system or single top quarks. These proceedings focus on the measurement of its mass, the electric charge, the top quark polarization and spin correlation, the $t\bar{t}$ charge asymmetry and the search for flavour changing neutral currents.

All of the measurements discussed herein are the results of the analysis of 4.7 fb^{-1} of 7 TeV and 20.3 fb^{-1} of 8 TeV proton-proton collisions collected by the ATLAS detector [2].

2 Mass measurements

The most defining property of a particle is probably the value of its mass. In the case of the top quark, its mass plays an important role in particle physics, mainly because of its large coupling to the Higgs boson. the top quark mass (m_{top}) plays indeed an important role in electroweak radiative corrections which yield a quadratic dependence of the W boson mass (m_{W}) on m_{top}, while m_{W} depends only logarithmically on the Higgs boson mass (m_{H}). Therefore, the precise measurement of m_{top}, m_{W} and m_{H} provides an important consistency test of the Standard Model. Besides, calculations at next-to-next to leading order, assuming the SM to be valid up tho the highest energies, suggest that the Higgs potential might be unstable at high energies close to the GUT scale (10^{16} GeV), with this feature strongly dependent on the value of the top pole mass [3]. Setting aside the theoretical implications, from an experimental perspective this gives a strong motivation for a precise determination of this parameter. Usually, the top mass is measured as an invariant mass of its decay products, with corrections applied using Monte Carlo simulations. Unfortunately, beyond the leading order its value depends on the renormalization scheme, which is not well-defined in current Monte Carlo generators. This implies an ambiguous definition when the uncertainty is below 1 GeV and close to the QCD scale ($\Lambda_{QCD} \sim 0.5$ GeV).

ATLAS performed several measurements of the top mass. The most precise one is obtained with a three-dimensional fit to constrain the largest systematics [4]. The first step is the full reconstruction of the $t\bar{t}$ decay kinematics on an event-by-event basis. This is accomplished in the lepton+jets channel with a maximum likelihood approach, whose inputs are the four jets, the charged lepton and the missing transverse energy. The kinematic fit extracts the top mass using the jets permutation with the highest likelihood. This information is used to reconstruct the mass of the hadronically-decaying W boson, which depends on the jet energy scale, and a parameter called R_{lb} defined as the ratio between the transverse momenta of b-jets and light-jets in the hadronic decay of the top quark. This quantity, being a ratio, is independent of the jet energy scale by construction. A large number of templates are generated for different top mass hypotheses in the experimentally allowed range, and for different energy-scale factors of light jets (JSF) and b-jets (bJSF). An unbinned 3-dimensional fit extracts the most probable values of the top mass and the energy scale factors. These factors turn out to be close to unity. The total uncertainty on the final result is less than 1% :

$$m_{\text{top}} \quad = \quad 172.31 \pm 0.75(\text{stat} + \text{JSF} + \text{bJSF}) \pm 1.35(\text{syst})\,\text{GeV}\ . \tag{1}$$

The main uncertainties are the b-tagging efficiency, the jet energy scale and the statistical component of the b-jet energy scale, which will be reduced with more data.

The ATLAS and CMS measurements of the top quark mass in different topologies were combined with the results obtained by the CDF and D0 experiments at the Tevatron, as summarized in Fig. 1. This combination was done with the Best Linear Unbiased Estimate (BLUE) method and the individual measurements were found to be in good agreement, leading to a χ^2/ndf of 4.3/10. The current efforts by the different collaborations to harmonise the treatment of the systematic uncertainties should be noted. The world combination result has a total relative uncertainty of 0.4%, dominated by the systematic uncertainties [5].

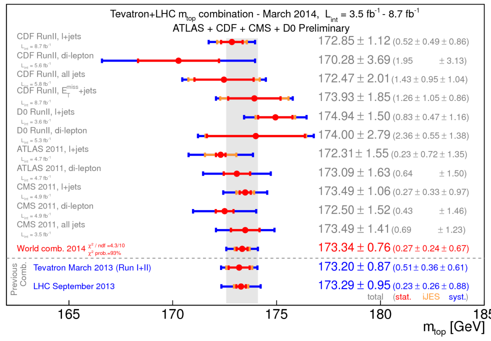

Figure 1: Input $m_{\rm top}$ measurements and result of their combination from the Tevatron and LHC. For each measurement, the total uncertainty, the statistical and the iJES (Jet Energy Scale) contributions (when applicable), as well as the sum of the remaining uncertainties are reported separately. The iJES contribution is statistical in nature and applies only to analyses performing in situ (top quark pair based) jet energy calibration procedures. The grey vertical band reflects the total uncertainty on the combined $m_{\rm top}$ value.

ATLAS is also measuring an eventual difference between the top and anti-top masses using 4.7 $\rm fb^{-1}$ of data at 7 TeV [6]. The measurement is $m_t - m_{\bar{t}} = 0.67 \pm 0.61(\rm stat) \pm 0.41(\rm syst)$ GeV, with the dominant sources of systematic uncertainties being the choice of the b quark fragmentation model (0.34 GeV) and the different calorimeter response to b and $\bar{b}$ initiated jets (0.08 GeV).

3 Electric charge

In the SM, the top quark is an up-type quark so its charge is $+2/3$ of the electron charge. Shortly after the discovery of the top quark, an exotic alternative to the SM was proposed in which a top-like particle appears with charge $-4/3$. The analysis strategy adopted by ATLAS [7] relies on the fact that in the SM the product of the charges of the lepton and that of the b-quark is always negative, while in the exotic model it is always positive. The sign of the top quark charge is transferred to the W boson and then to the charged lepton, and it is quite easy to measure this quantity experimentally. This is not true for the b-quark, because the charge of a jet is not a well-defined quantity. Experimentally the weighted sum of the track charges is used as proxy for this quantity.

A harsh set of cuts is applied to the collected events to isolate a very pure sample. The observable is then compared against the two models. The resulting top charge is $0.64 \pm 0.02(\rm stat) \pm 0.08(\rm syst)$, compatible with $+2/3$, as predicted by the SM. The exotic model is now excluded by more than 8 standard deviations.

4 Top spin related measurements

In the SM, $t\bar{t}$ pairs are produced essentially unpolarized at the LHC but the correlation of the spin orientation of the top and the anti-top quark is predicted to be non-zero. New physics models beyond the SM can change the spin correlation of the top and the anti-top quark by either changing the spin of the daughter particles of the top and anti-top quarks, or by changing the production mechanism of the $t\bar{t}$ pair.

The spin correlation of $t\bar{t}$ pairs can be extracted by analysing the angular distributions of the top quark decay products.The differential distribution of the decay width, $d\Gamma/d|cos(\theta_{\pm})|$, is proportional to the cosine of the angle, $\theta_{\pm}$, between the positively (negatively) charged lepton from the top (anti-top) quark decay and the top (anti-top) quark spin quantization axis in the top (anti-top) quark rest frame. The spin correlation is expressed by the double differential cross-section :

$$\frac{1}{\sigma}\frac{d^2\sigma}{d[\cos(\theta_+)][\cos(\theta_-)]} = \frac{1}{4}\left(1 + \alpha_+ P_+ \cos(\theta_+) + \alpha_- P_- \cos(\theta_-) + A\alpha_+\alpha_- \cos(\theta_+)\cos(\theta_-)\right) \ , \tag{2}$$

where A is the asymmetry built from the ratio between the number of events where the top quark and anti-top quark spins are parallel and the number of events where they are anti-parallel, α represents the spin analysing power and $P_{\mp}$ is the polarisation of the top/anti-top quark.

Since $\alpha \approx 1$ at leading order for charged leptons, leptons are taken as the final state particles for the following measurements. As spin quantization axis, the helicity basis of the top quark is used since it is well defined and provides predictions from theory.

4.1 Top quark polarization

The measurement of the top quark polarization in $t\bar{t}$ events is performed in the lepton+jets and dilepton channels [11]. To extract the polarization from the $\cos\theta$ distribution, templates with assumed polarizations of $\alpha P = \pm 0.3$ were created. Two different mechanisms were considered to account for CP conservation (CPC) as in the SM and CP violating (CPV) $t\bar{t}$ production. For the CP conserving case, the top quarks are polarized in the same way whereas for the CP violating case, the top quarks have opposite polarizations. This implies that for one of the $\cos\theta$ distributions (either top or antitop indicated by the lepton charge), the templates for CPC and CPV are swapped. With the templates, a binned likelihood fit is performed to extract the fraction of positive polarization f from the $\cos\theta$ distributions. Together with the polarization, the $t\bar{t}$ cross section is fitted to reduce uncertainties coming from the normalization of the processes. The background normalization is not fitted during the procedure, but estimated from Monte Carlo (MC) and data driven techniques The combination was done by multiplying the likelihoods of each channel. All the results are in good agreement with the SM within the uncertainties. The combined result of lepton+jets and dilepton channels for the two production mechanisms is then :

$$\begin{aligned} \alpha_l C_{\mathrm{CPC}} &= -0.035 \pm 0.014(\mathrm{stat}) \pm 0.037(\mathrm{syst}) \\ \alpha_l C_{\mathrm{CPV}} &= -0.020 \pm 0.016(\mathrm{stat})^{+0.013}_{-0.017}(\mathrm{syst})\ . \end{aligned} \tag{3}$$

Dominant systematic uncertainties come from modelling of the signal MC and jet energy related quantities.

4.2 Top quark spin correlation

Top quark spin correlation has already been observed at ATLAS at a significance of 5.1σ using 2.1 fb^{-1} of data [8]. The full dataset has been analysed to check the compatibility with the SM spin correlation strength prediction [9]. The spin correlation strength A gives the difference between like-helicity and unlike-helicity top quarks and is defined as :

$$A = \frac{N_{\Uparrow\Uparrow} + N_{\Downarrow\Downarrow} - N_{\Uparrow\Downarrow} - N_{\Downarrow\Uparrow}}{N_{\Uparrow\Uparrow} + N_{\Downarrow\Downarrow} + N_{\Uparrow\Downarrow} + N_{\Downarrow\Uparrow}}\ . \tag{4}$$

In order to extract the spin correlation strength from the selected data, four different observables are investigated, which are different linear combinations of components in the spin density matrix of $t\bar{t}$ production: the azimuthal difference $\Delta\phi$ of the charged lepton momentum directions in the laboratory frame, the ratio of the squares of matrix elements for top quark pair production and decay from the fusion of like-helicity gluons with and without spin correlation at leading order (S-Ratio), and the product of $\cos(\theta_+)$ and $\cos(\theta_-)$* in both the helicity basis and the so called maximal basis, which maximizes the value of the spin correlation strength. No prediction from the SM exists for the maximal basis, so the value from MC simulation $A_{\mathrm{max}} = 0.44$ with MC@NLO+Herwig [10] was taken. The SM prediction for the helicity basis is $A_{\mathrm{hel}} = 0.31$ at 7 TeV. A template fit is then performed for all four observables using templates with SM spin correlation and without it, both generated with MC@NLO. The result is expressed in the parameter f_{SM} with $f_{\mathrm{SM}} = 1$ being the SM spin correlation case and $f_{\mathrm{SM}} = 0$ being the uncorrelated case and is shown in Fig. 2 (left part) for the four different observables. To get the measured spin correlation strength, the f_{SM} obtained from the fit has to be multiplied with the SM prediction. The dominant systematic uncertainties come from $t\bar{t}$ modelling.

*The subscripts "+" and "-" refer to the leptons charge.

5 $t\bar{t}$ charge asymmetry

The $t\bar{t}$ production is predicted by the SM to be symmetric at leading order (LO) under charge conjugation. At NLO, however, for the $q\bar{q}$ and qg production modes, there is a small preference to produce the $t\bar{t}$ in the direction of the incoming quark (anti-quark). It is therefore useful to define the following charge asymmetry, $A_c = \frac{(\Delta|y|>0)-(\Delta|y|<0)}{(\Delta|y|>0)+(\Delta|y|<0)}$, with $\Delta|y| = |y_t| - |y_{\bar{t}}|$, making use of the difference of absolute rapidities $|y_t|$ and $|y_{\bar{t}}|$ of top and antitop quarks. At NLO in the SM it is expected to be 0.0115 ± 0.0006 for pp collisions at 7 TeV. In the lepton+jets channels, ATLAS measured the charge asymmetry in $t\bar{t}$ events using 4.7 fb^{-1} of data. The collaboration unfolded the reconstructed $\Delta|y|$ distribution to parton level and measured $0.006 \pm 0.010(\mathrm{stat}) \pm 0.005(\mathrm{syst})$[13]. Furthermore, a combination [14] with the results of the CMS experiment has been done and is presented in Fig. 2 (right part).

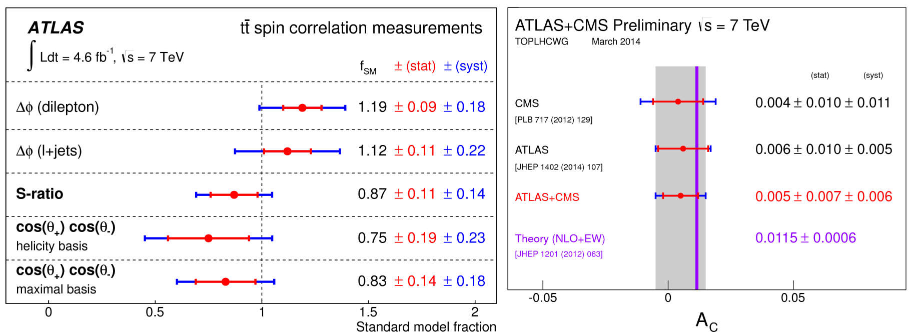

Figure 2: Left : summary of the measurements of the fraction of t anti-t events corresponding to the SM spin correlation hypothesis, f_{SM}, in the dilepton final state, using four spin correlation observables sensitive to different properties of the production mechanism, and in the single-lepton final state. Dashed vertical line at $f_{\mathrm{SM}} = 1$ indicates the SM prediction. The inner, red error bars indicate statistical uncertainties, the outer, blue error bars indicate the contribution of the systematic uncertainties to the total uncertainties. Right : summary of the single measurements and the LHC combination of the $t\bar{t}$ charge asymmetry compared to the theory prediction (calculated at NLO including electroweak corrections). The inner red error bars indicate the statistical uncertainty, the blue outer error bars indicate the total uncertainty. The grey band illustrates the total uncertainty of the combined result.

6 Flavour Changing Neutral Currents

In the SM, the top quark decays to a W boson and a b-quark with a branching ratio very close to unity. Non-standard couplings can affect the way a top quark can be produced or decays. In the SM, these couplings do not exist at tree level, and are GIM-suppressed at higher orders

The $qg \to t$ analysis [15], is performed on data collected in 2012, corresponding to an integrated luminosity of 14.2 fb^{-1} at 8 TeV. FCNC $t \to qg/qg \to t$ is searched for in the production of single top-quark events. No evidence of FCNC single top-quark production is found and the upper limit at 95% CL on the production cross section is 2.5 pb. Using the NLO predictions for the FCNC single top-quark production cross-section and assuming BR($t \to Wb$)= 1, the measured upper limit on the production cross-section is converted into limits on the coupling constants which in turn can be converted into limits on the branching fractions: BR($t \to ug$)$< 3.1 \times 10^{-5}$ and BR($t \to cg$)$< 1.6 \times 10^{-4}$.

A search is performed for FCNC in the decay of a top quark to an up-type (c,u) quark and a Higgs boson, where the Higgs boson decays to two photons [16]. The proton-proton collision data set used corresponds to 20.3 fb^{-1} at 8 TeV. Top quark pair events are searched for in which one top quark decays to qH and the other decays to bW. Both the hadronic and the leptonic decay modes of the W boson are used. No significant signal is observed (cf. Fig. 3) and an upper limit is set on the $t \to qH$ branching ratio of 0.79% at the 95% confidence level.

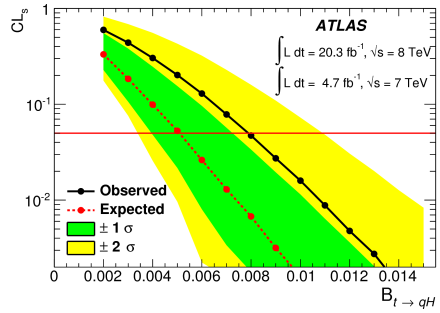

Figure 3: Evolution of CLs as a function of the branching fraction B of the t to qH decay for the observation of a signal at 125.5 GeV (solid line) and the expectation in the absence of signal (dashed line). The 1 and 2σ uncertainty bands around the expected curve are also shown.

7 Conclusions

Thanks to the outstanding performance of the LHC, the experimental physics of the top quark entered the precision era, with most measurements already dominated by systematic uncertainties. The mass of the top quark is now known with a precision below 1 GeV. A big variety of top quark properties in top quark pair production and decay have been measured and presented. All results are in good agreement with the SM and no sign of new physics has been found so far.

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