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Top quark pair properties in the production and decays of $t\bar{t}$ events at ATLAS

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In proton-proton collisions at the LHC, pairs of top and anti-top quarks are expected to be mostly produced through gluon fusion. Making use of the large number of top quark pairs collected, we present measurements of the ATLAS experiment using 4.7 fb^{-1} of data. First, we present a measurement of the charge asymmetry and compare it to new physics models. Furthermore we show a measurement of the spin correlation between top and anti-top quarks using several variables and discuss their sensitivity to new physics. In addition, we present measurements of the top quark polarisation predicted in models with CP-conserving and CP-violating processes.

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1. Introduction

Since its discovery in 1995 by the D0 and CDF collaborations at the Tevatron [1, 2], at proton-antiproton collider at Fermilab, the top quark has been studied extensively at both Tevatron and at the LHC at CERN. With a mass of 173.34 ± 0.76 GeV [3], it is the heaviest fundamental particle known so far. Therefore it has a very large coupling to the Higgs boson, which could indicate a special role in the Electroweak Symmetry Breaking.

Due to its high mass and its small width, the top quark has a very short lifetime of $\approx 5 \times 10^{-24}$ s which is two orders of magnitude smaller than the hadronisation time scale. This leads to the fact that, in top quark pair production, the top quark spins to not become decorrelated and that the top quark spin information is carried to its decay particles. Thus, the top quark provides us with the unique opportunity to study a bare quark [4].

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 charge asymmetry, top quark spin correlation and polarisation measurements.

All of the measurements discussed herein are the results of the analysis of 4.7 fb^{-1} of 7 TeV collisions at the LHC, collected by the ATLAS detector [5]. The analyses are then performed in either the dilepton or lepton+jets final state, which are defined by whether the two W bosons coming from the top quarks decay both leptonically or one of them hadronically. The analyses are performed in the dilepton (ee/$\mu\mu$/eμ[1]) final state in which both W bosons decay leptonically, or lepton plus jets (e/μ + jets) final state in which one W boson decays leptonically and the other W decays hadronically. To enhance the signal, final-state dependent cuts are applied.

2. $t\bar{t}$ charge asymmetry

Measurements of the $t\bar{t}$ production asymmetry at the Tevatron performed by CDF and D0 showed some tension with respect to the SM prediction [6, 7]. Even though a recent measurement by D0 is in better agreement with the SM [8], many models describing an enhanced production asymmetry have been formulated [9]. At the LHC, an analogous effect, which is predicted by the SM to be of order 1 %, can be measured.

At leading order (LO), the production of $t\bar{t}$ pairs is completely symmetric. When including next-to-leading order processes, interferences between Born and loop diagrams can yield a positive asymmetry, while processes with initial and final state radiation lead to negative contributions to the asymmetry. A positive asymmetry means that the (anti)top quark is emitted preferentially in the direction of the interacting (anti)quark from the proton. An asymmetry only occurs from $q\bar{q}$ annihilation and qg processes and not from gg fusion. The latter is responsible for 80 % of $t\bar{t}$ production at the LHC for a center-of-mass energy of 7 TeV, that explains why the production asymmetry is smaller at the LHC than at the Tevatron. Furthermore, the same observable cannot be measured at both colliders because the LHC is a proton-proton and the Tevatron a proton-antiproton collider. The experiments at the Tevatron measured a forward-backward asymmetry A_{FB} since the quark direction could be inferred from the proton direction. At the LHC experiments, the rapidity distributions of both top and antitop quarks are symmetric. The difference in this case is the slightly

[1]Both charge possibilities are included, e.g. $e\mu$ is the short form for $e^+\mu^-$ & $e^-\mu^+$.

broader top quark rapidity distribution which comes from the more energetic valence quarks in the proton while the antiquarks are only come from the sea, thus usually carrying a smaller fraction of the proton's momentum. Therefore, at the LHC, the charge asymmetry, A_C, is measured as:

$$A_C = \frac{(\Delta|y| > 0) - (\Delta|y| < 0)}{(\Delta|y| > 0) + (\Delta|y| < 0)} \tag{2.1}$$

with $\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$, making use of the difference of absolute rapidities $|y_t|$ and $|y_{\bar{t}}|$ of top and antitop quark.

The measurement was performed in the lepton+jets channel using a dataset of 4.7 fb^{-1} collected at the ATLAS experiment [10]. For the reconstruction of the $t\bar{t}$ system, a kinematic likelihood method (KLFitter) [11] was used. Figure 1 shows the comparison of data with the estimated signal and background contribution for the $\Delta|y|$ variable after reconstruction. To compare the calculated result with the theoretical prediction of $A_C^{theo.} = 1.23 \pm 0.05\%$ [12], the distribution has to be unfolded back to parton level. For this procedure, the Fully Bayesian Unfolding method [13] was used. The unfolded distribution gives a result of the charge asymmetry of $A_C = 0.6 \pm 1.0\%(\mathrm{stat}+\mathrm{syst})$, which agrees well with the SM prediction A_C^{theo} and is still dominated by the statistical uncertainty. Differential measurements in bins of the invariant mass $m_{t\bar{t}}$, transverse momentum $p_{T,t\bar{t}}$ and absolute rapidity $|y_{t\bar{t}}|$ of the $t\bar{t}$ system also show agreement with the SM as can be seen in Fig. 2. They are further compared to two axigluon models [14] consistent with the measurements of A_{FB} at the Tevatron. To increase the contribution of $t\bar{t}$ events coming from $q\bar{q}$ annihilation in the selected data sample, cuts on $m_{t\bar{t}}$ and the boost $\beta_{z,t\bar{t}}$ of the $t\bar{t}$ system with respect to the beam axis are applied.

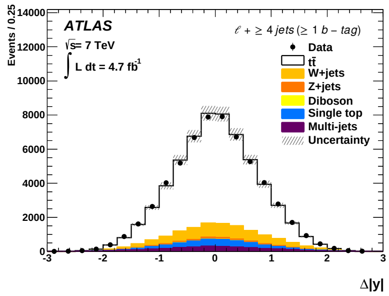


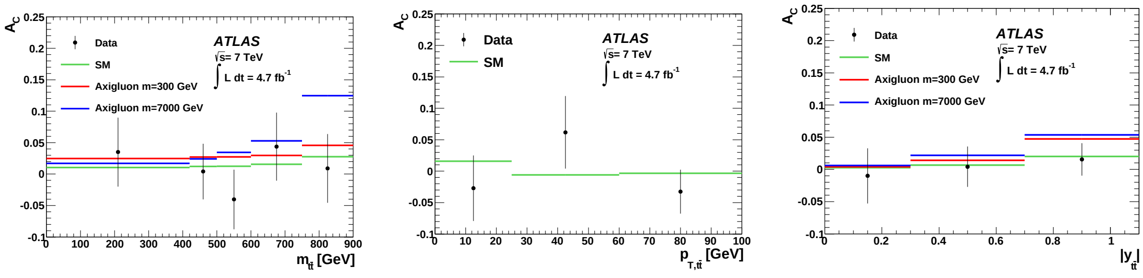
Figure 1: $|\Delta y|$ distribution comparison of data (black dots) and signal+background estimation before unfolding back to parton level [10].

The corresponding results can be found in Table 1 and are also in agreement with the SM. To compare the charge asymmetry results obtained at the LHC with the measurements of the forward-backward asymmetry at the Tevatron, the parameter space of different new physics models [9] is expressed in terms of those observables (see Fig. 3). The LHC results, indicated by horizontal lines with their corresponding 1σ uncertainty bands, cut heavily in this parameter space, but more data is needed to decrease the statistical uncertainty and exclude certain models.

A_C	Data	Theory
Unfolded	0.006 ± 0.010	0.0123 ± 0.0005
$m_{t\bar{t}} > 600$ GeV	0.018 ± 0.022	$0.0175^{+0.0005}_{-0.0004}$
$\beta_{z,t\bar{t}} > 0.6$	0.011 ± 0.018	$0.020^{+0.006}_{-0.007}$

Table 1: Comparison of measurements and predictions of charge asymmetry A_C with and without applying kinematics cuts [10].

3. Top spin related measurements



(a) $m_{t\bar{t}}$ (b) $p_{T,t\bar{t}}$ (c) $|y_{t\bar{t}}|$

Figure 2: Differential measurements of the charge asymmetry with comparison of data (black) to the SM prediction (green) and an axigluon model [14] of two different masses (blue and red [10]).

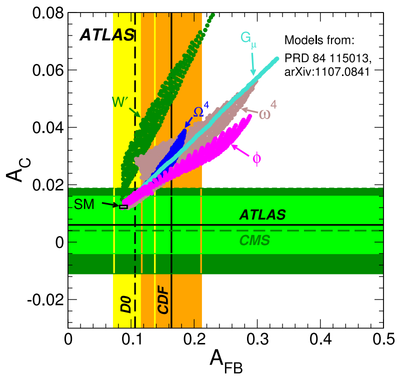


Figure 3: Comparison of measured forward-backward asymmetry A_{FB} and charge asymmetry A_C with predictions from the SM and new physics models. The SM is favored by the measurements.

Top quark pairs are produced via the strong interaction which conserves parity. Since the initial state of the reaction is unpolarized, the same is true for the produced top quarks, but the spins between the top and antitop quark are still correlated. Both top polarization and $t\bar{t}$ spin correlation are sensitive to various physics models beyond the SM and are measurable precisely at the LHC.

The double differential cross section for $t\bar{t}$ production is:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1+\alpha_1 P_1\cos\theta_1 + \alpha_2 P_2 \cos\theta_2 - \alpha_1\alpha_2 A\cos\theta_1\cos\theta_2) \qquad (3.1)$$

It shows the relation to $\cos\theta$, which is the cosine of the angle between a final state particle and a spin quantization axis that has to be chosen. P is the polarization for top and antitop quark and A is the spin correlation strength. The indices 1 and 2 indicate the top and antitop quarks, respectively, while the spin analyzing power α_i gives the correlation of the final state particle's direction of flight and its parent top quark spin. 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. It should be noted, that full reconstruction of the event is needed to compute $\cos\theta$.

3.1 Top quark polarization

The measurement of the top quark polarization in $t\bar{t}$ events is performed in the lepton+jets and dilepton channels [15]. As for the charge asymmetry measurement, the KLFitter package is used for the reconstruction of the $t\bar{t}$ system in the lepton+jets channel, and the neutrino weighting method [16] is used in the dilepton channel. 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 come 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. Figure 4 shows the fit results of the CPC case broken down into the analysed channels.

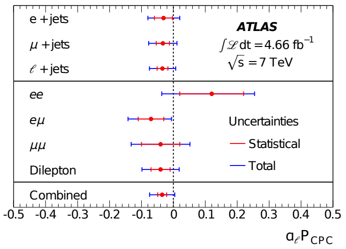


Figure 4: Polarization results for the template fit of all different channels and the combination in the CP conserving case. Statistical uncertainties are indicated by the red lines, the systematic uncertainties (blue lines) are added quadratically. All results are in agreement with the SM of almost zero polarization [15].

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+jet and dilepton channels for the two production mechanisms is then

$$\alpha_l P_{CPC} = -0.035 \pm 0.014(\text{stat}) \pm 0.037(\text{syst})$$
$$\alpha_l P_{CPV} = 0.020 \pm 0.016(\text{stat})^{+0.013}_{-0.017}(\text{syst}).$$

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

3.2 Top quark spin correlation

Top quark spin correlation has already been observed at ATLAS at a significance of 5.1 σ [17] using 2.1 fb^{-1} of data. The full dataset has been analysed to check the compatibility with the SM spin correlation strength prediction [18].

The spin correlation strength A (see eqn. 3.1) gives the difference between like-helicity and unlike-helicity top quarks and is defined as

$$A = \frac{N_{\Uparrow\Uparrow} + N_{\Downarrow\Downarrow} - N_{\Uparrow\Downarrow} - N_{\Downarrow\Uparrow}}{N_{\Uparrow\Uparrow} + N_{\Downarrow\Downarrow} + N_{\Uparrow\Downarrow} + N_{\Downarrow\Uparrow}}. \quad (3.2)$$

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 $\cos\theta_-$ [2] in both the helicity basis and the so called maximal basis, which maximizes the value of the spin correlation strength [18]. No prediction from the SM exists for the maximal basis, so the value from MC simulation with MC@NLO+Herwig [19] was taken, which is $A_{max} = 0.44$. The SM prediction for the helicity basis is $A_{hel} = 0.31$ 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

[2] The subscripts "+" and "-" refer to the lepton's charge.

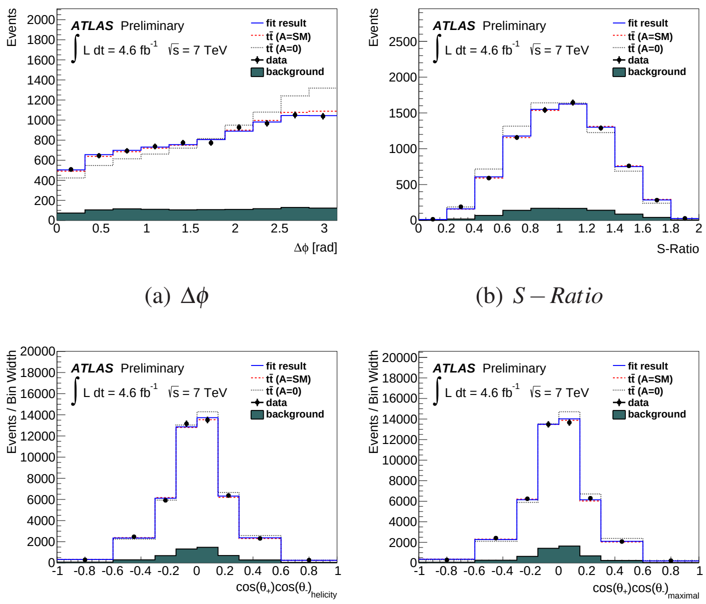
Basis	$\Delta\phi$	S-Ratio	$(\cos\theta_+ \cos\theta_-)_{hel.}$	$(\cos\theta_+ \cos\theta_-)_{max.}$
$A^{measured}_{hel.}$	$0.37 \pm 0.03 \pm 0.05$	$0.27 \pm 0.03 \pm 0.04$	$0.23 \pm 0.06 \pm 0.10$	-
$A^{measured}_{max.}$	$0.52 \pm 0.04 \pm 0.07$	$0.38 \pm 0.05 \pm 0.06$	-	$0.36 \pm 0.06 \pm 0.09$

Table 2: Comparison of spin correlation strengths in helicity and maximal basis computed from the fit parameter f_{SM} after the template fit.

$f_{SM} = 1$ being the SM spin correlation case and $f_{SM} = 0$ being the uncorrelated case and is shown in Fig. 5 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. Table 2 shows the results from the multiplication which are all in agreement with the SM within the uncertainties. There are no entries for the spin correlation strength in the maximal basis via the $(\cos\theta_+ \cos\theta_-)$ measurement in the helicity basis and vice versa since those are direct measurements for the specific basis. The dominant systematic uncertainties come from $t\bar{t}$ modelling.

3.3 Conclusion

With the 2011 dataset from the LHC, it is possible to measure a big variety of top quark properties in top quark pair production and decay. The measurements for the charge asymmetry, top quark polarization and $t\bar{t}$ spin correlation performed using a dataset corresponding to an integrated luminosity of 4.7 fb^{-1} taken with the ATLAS detector at the LHC, have been presented. All results are in good agreement with the SM and no sign of new physics has been found so far. The charge asymmetry measurement is still statistically limited while the spin related measurements are dominated by systematic uncertainties. Extended analyses using the full 8 TeV dataset of 20 fb^{-1} taken at the LHC in 2012 are already in preparation and will give even more precise results.



(a) $\Delta\phi$ (b) $S-Ratio$

(c) $(\cos\theta_+ \cos\theta_-)_{hel}$ (d) $(\cos\theta_+ \cos\theta_-)_{max}$

Figure 5: Distributions of the four different spin correlation observables. The results of the fit to data (blue) are compared to the templates for background plus $t\bar{t}$ signal with SM spin correlation (red dashed) and without spin correlation (black dotted).

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PoS(DIS2014)145