

Spin measurements in top quark events at the LHC

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Measurements of polarisation and spin correlations are presented in events with top quarks produced in pp collisions at the LHC. The data correspond to integrated luminosities of 5 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$ and 20 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ collected with the ATLAS and CMS detectors. The top quark polarisation is measured in both single top quark production in the t -channel and $t\bar{t}$ pair-production, from the angular distributions of charged leptons in the rest frame of their parent top quarks. The spin correlations in $t\bar{t}$ events are measured using various angular distributions of the decay products. The measurements are made using both template fitting methods and by unfolding the distributions to the parton-level, where differential measurements with respect to the invariant mass, rapidity, and transverse momentum of the $t\bar{t}$ system are also made. The spin correlation measurements are used to search for new physics in the form of a light top squark or an anomalous top quark chromo-magnetic dipole moment. All measurements are found to be in agreement with predictions of the standard model.

8th International Workshop on Top Quark Physics, TOP2015

14-18 September, 2015

Ischia, Italy

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1. Introduction

The large mass of the top quark and its expected corresponding strong coupling to the Higgs boson suggest a connection between the top quark and the mechanism of electroweak symmetry breaking. New physics in this mechanism is likely to modify the spin properties of top quark events from the standard model (SM) expectations, either via underlying direct production modes or from interference effects from new physics at higher mass scales. Furthermore, the top quark is the only quark that decays before hadronising, meaning the information about its spin is transferred to its decay products undiluted by non-perturbative effects. Top quark spin measurements therefore provide an ideal laboratory to test perturbative QCD and probe for new physics.

2. Top quark polarisation

The top quark polarisation measures the average spin of produced quarks: $P_{\hat{n}} = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$, where $N(\uparrow)$ and $N(\downarrow)$ are the numbers of top quarks with spin up (+1) and spin down (-1), and \hat{n} is a unit vector defining the direction (basis) for spin measurement. The top quark polarisation is strongly dependent on the production process. In t -channel single top quark production, the top quark is produced at the electroweak Wtb vertex and is therefore constrained to have left-handed chirality, and the same is true of the ‘‘spectator’’ quark that recoils against the top. The top quarks are therefore expected to be strongly polarised, with approximately 95% of top quarks having spin up when measured in the direction of the spectator quark (spectator basis) [1]. In contrast, $t\bar{t}$ production proceeds largely via the strong interaction, which with unpolarised incoming partons is symmetric with respect to quark handedness. A very small top quark polarisation (0.3%), measured relative to the negative of the direction of the recoiling top quark (helicity basis), arises when including electroweak corrections to the NLO QCD calculations (NLO+EW) [2].

The top quark polarisation can be measured from the angular distributions of its daughter particles: $\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_{i,\hat{n}}^*} = \frac{1}{2}(1 + \kappa_i P_{\hat{n}} \cos\theta_{i,\hat{n}}^*)$, where $\theta_{i,\hat{n}}^*$ is the angle of daughter i measured in the chosen basis (defined by \hat{n}) in the rest frame of its parent top quark, and κ_i is its spin analysing power, where $\kappa_\ell = 1$, $\kappa_{\bar{d}} = 0.97$, $\kappa_u = -0.31$, and $\kappa_b = -0.39$ [3]. Then, $\kappa_i P_{\hat{n}} = 2A_{P_{\hat{n}}}$, where $A_{P_{\hat{n}}}$ is the asymmetry of the $\cos\theta_{i,\hat{n}}^*$ distribution about zero (in the absence of cuts).

At CMS [4], using data corresponding to 20 fb^{-1} of integrated luminosity collected at $\sqrt{s} = 8 \text{ TeV}$, the polarisation in t -channel single top quark production in the spectator basis is measured [5]¹ in events with a single electron or muon (‘‘single lepton channel’’), after using a boosted decision tree to select a relatively pure event sample ($\sim 50\%$). The largest background contributions are from $W + \text{jets}$, $t\bar{t}$, and QCD multijet production, and are estimated using simulation validated in data control regions. The lepton $\cos\theta_\ell^*$ distribution is measured in the reconstructed top quark rest frame, using the direction of the jet with no b-tag to define \hat{n} (as a proxy for the spectator quark direction). After subtracting the contributions to the distribution from the background processes, simulated single top quark events are used to unfold the measured $\cos\theta_\ell^*$ distribution to the parton level in the spectator basis (Fig. 1, left). The polarisation is extracted from the asymmetry of the

¹In November 2015, the preliminary result [5] shown at the conference was replaced by a publication with significant modifications in analysis technique [6].

unfolded distribution: $P = 2A_P = [82 \pm 12 \text{ (stat)} \pm 32 \text{ (syst)}]\%$ – consistent with the SM expectation. The dominant sources of systematic uncertainty are the jet energy scale (JES), which affects the reconstruction of the top quark rest frame, and the background subtraction.

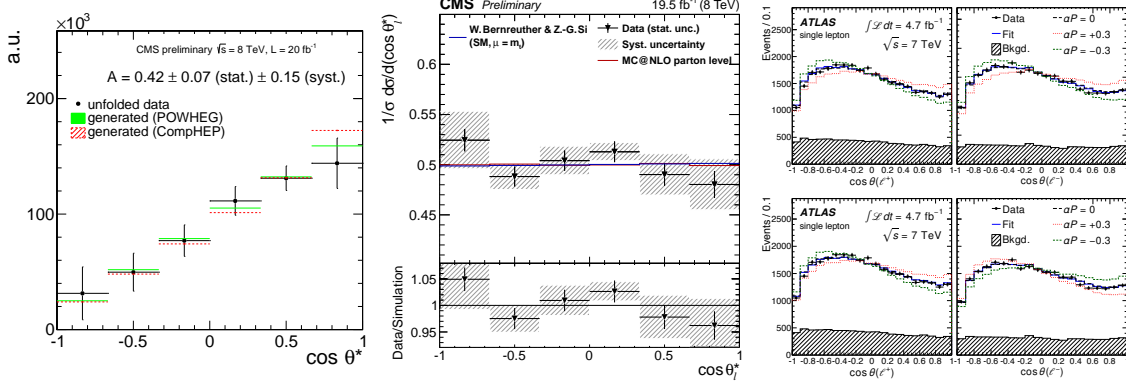


Figure 1: $\cos\theta_\ell^*$ distributions for t -channel single top quark production in the spectator basis (left: unfolded [5]) and for $t\bar{t}$ pair-production in the helicity basis (centre: unfolded in the dilepton channel [7], and right: at reconstruction level in the single lepton channel with CP conserving and violating template fits [11]).

At CMS, again with the 8 TeV data, a similar approach [7] is used to measure the top quark polarisation in $t\bar{t}$ events in the helicity basis, using events with exactly two charged leptons ($\ell = e/\mu$) of opposite charge (“dilepton channel”). A geometrical method is used to find the two top quark 4-vectors, which in the case of events with no exact real solutions finds the real solution with the vector sum of the neutrino p_T as close as possible to the measured missing transverse momentum [9]. After subtraction of the $\sim 9\%$ contribution from background events, with shape predicted from simulation and the dominant components validated and normalised using control regions in data, the $\cos\theta_\ell^*$ distribution is unfolded to the parton level. There are two measurements from each event, and under the assumption of CP conservation the two distributions can simply be combined (Fig. 1, centre), yielding $P = [2.2 \pm 1.5 \text{ (stat)} \pm 5.7 \text{ (syst)}]\%$. Alternatively, to probe for CP violating new physics, the CP-odd component of the polarisation can be measured by inverting the sign of $\cos\theta_\ell^*$ for negatively charged leptons before combining the distributions, yielding $P^{\text{CPV}} = [0.0 \pm 1.3 \text{ (stat)} \pm 1.1 \text{ (syst)}]\%$. In the CP conserving case the dominant systematic uncertainty comes from the JES, while in the CP violating case the systematic uncertainties largely cancel because their effects are opposite for positively and negatively charged leptons.

At ATLAS [10], using the 7 TeV data, the measurement [11] is made in both the single lepton and dilepton channels using a template method. At reconstruction level, the $\cos\theta_\ell^*$ distributions are fit (Fig. 1, right) to templates constructed from simulated $t\bar{t}$ events reweighted to give a top quark polarisation of $\pm 30\%$, combined with a simulated background template with shape predicted from simulation and the dominant components validated and normalised using control regions in data. After combining the channels, the CP-even and odd components of the polarisation are measured to be $P = [-3.5 \pm 1.4 \text{ (stat)} \pm 3.7 \text{ (syst)}]\%$ and $P^{\text{CPV}} = [-3.5 \pm 1.6 \text{ (stat)}^{+1.3}_{-1.7} \text{ (syst)}]\%$, respectively, assuming $\kappa_\ell = 1$. Again, the dominant uncertainty in the CP conserving case comes from jet reconstruction, while in the CP violating case the systematic uncertainties largely cancel.

3. $t\bar{t}$ spin correlations

The SM predicts a rich structure of spin correlations in $t\bar{t}$ events, with opposite sign in the same-helicity and opposite-helicity gluon initial states [12]. For the same-helicity gluon initial state, the SM spin correlations result in a strong correlation in the azimuthal separation ($\Delta\phi$) of the top quark decay products in the laboratory frame. In the dilepton channel, the azimuthal separation between the charged leptons $|\Delta\phi_{\ell^+\ell^-}|$ can be very precisely reconstructed, and is the most precise probe of spin correlations at the LHC.

The ATLAS experiment analyses the $|\Delta\phi_{\ell^+\ell^-}|$ distribution with a template fit [13], using simulated $t\bar{t}$ events with the expected SM spin correlations and with the spin correlations removed, along with a background template based on simulated events with data-driven corrections (Fig. 2, left). The result of the fit gives the degree of spin correlations relative to the SM prediction: $f_{\text{SM}} = 1.20 \pm 0.05$ (stat) ± 0.13 (syst). The dominant sources of systematic uncertainty are in $t\bar{t}$ modelling. A similar technique is used to set limits on supersymmetry (SUSY). When the SUSY spectrum is such that top squarks decay to produce top quarks with little momentum in the top squark rest frame, top squark pair events look kinematically very similar to $t\bar{t}$ events and for this reason are not excluded by direct searches (Fig. 2, right) [14]. However, top squarks have spin zero and thus can transmit no spin information from the initial state to their daughter top quarks, and such events look similar to $t\bar{t}$ events with the spin correlations removed (as used in the fit for f_{SM}). Making similar fits with the uncorrelated $t\bar{t}$ events replaced with simulated SUSY events sets limits on the fractions of such SUSY events in the sample. Top squarks with mass between the top quark mass and 191 GeV are excluded at the 95% confidence level (Fig. 2, centre). The information from the $|\Delta\phi_{\ell^+\ell^-}|$ shape and total event yield contribute to the exclusion in roughly equal measure.

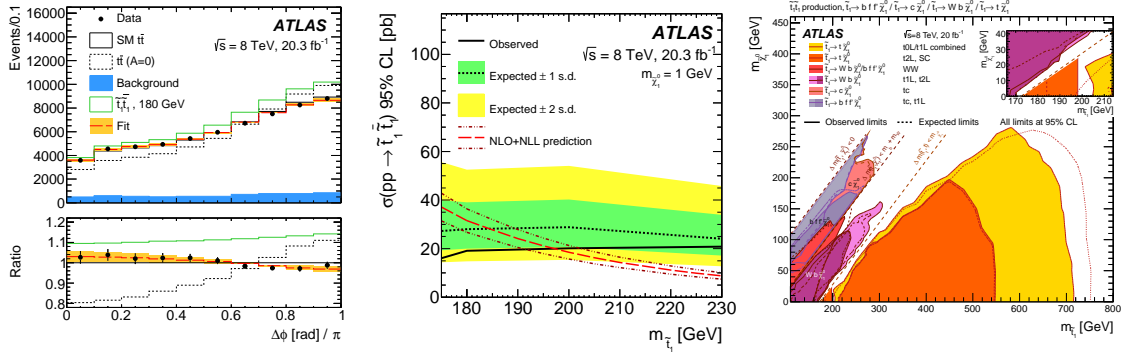


Figure 2: $|\Delta\phi_{\ell^+\ell^-}|$ distribution at reconstruction level with fit using MC@NLO templates with and without spin correlations (left) [13]. Limits on top squark mass from similar fit using top squark pair templates (centre) [13]. Exclusion in the context of the limits set by direct searches (right) [14].

The CMS experiment analyses the $|\Delta\phi_{\ell^+\ell^-}|$ distribution using the same unfolding method as for the dilepton channel polarisation measurement described in Section 2 [7]. With the $t\bar{t}$ system reconstructed, the lepton directions in their parent top rest frames can be used as proxies for the top spins to construct two further variables sensitive to spin correlations: the opening angle φ between the two lepton directions, and the product $\cos\theta_{\ell^+}^* \cos\theta_{\ell^-}^* \equiv c_1 c_2$ of the cosines of the helicity angles of the two leptons. The measured normalised differential cross section as a function of $|\Delta\phi_{\ell^+\ell^-}|$, $c_1 c_2$, and $\cos\varphi$ is shown in Fig. 3. The asymmetries about zero of the $\cos\varphi$ ($A_{\cos\varphi}$) and $c_1 c_2$

($A_{c_1c_2}$) distributions are directly sensitive to the D and C_{hel} spin correlation coefficients [2], yielding $D = -2A_{\cos\phi} = 0.205 \pm 0.021$ (stat) ± 0.028 (syst) and $C_{\text{hel}} = -4A_{c_1c_2} = 0.278 \pm 0.053$ (stat) ± 0.065 (syst), and as for the polarisation measurement the dominant systematic uncertainties are in the JES. The asymmetry $A_{\Delta\phi}$ of the $|\Delta\phi_{\ell^+\ell^-}|$ distribution is quantified about $\pi/2$, yielding $A_{\Delta\phi} = 0.094 \pm 0.005$ (stat) ± 0.012 (syst), where by far the dominant source of uncertainty is the top quark p_T modelling.

In Table 1 the measured asymmetries are converted into estimates of f_{SM} using theoretical predictions for their values and their uncertainties (which are large for $A_{\Delta\phi}$), calculated at NLO+EW with and without spin correlations. The $|\Delta\phi_{\ell^+\ell^-}|$ distribution is also fit to a theoretical parameterisation of the distribution with an anomalous top quark chromo-magnetic dipole moment $\text{Re}(\hat{\mu}_t)$ as the free parameter [2], yielding $\text{Re}(\hat{\mu}_t) = -0.013 \pm 0.032$. A value of $\text{Re}(\hat{\mu}_t)$ outside the range $-0.076 \leq \text{Re}(\hat{\mu}_t) \leq 0.050$ is excluded at the 95% confidence level [7].

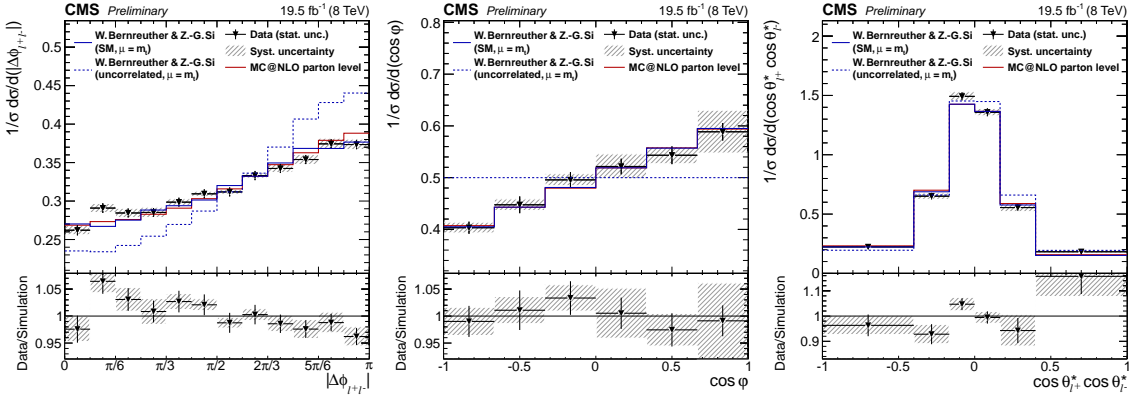


Figure 3: Normalised differential $t\bar{t}$ production cross section as a function of $|\Delta\phi_{\ell^+\ell^-}|$, $\cos\phi$, and $\cos\theta_{\ell^+}^* \cos\theta_{\ell^-}^*$ (points) [7]; parton-level predictions from MC@NLO (red histograms); and theoretical predictions at NLO+EW with and without spin correlations (solid and dashed blue histograms).

The asymmetry variables are also measured differentially with respect to the $t\bar{t}$ system variables $M_{t\bar{t}}$, $|y_{t\bar{t}}|$, and $p_T^{t\bar{t}}$, and one example is shown in Fig. 4 (left). The measurement of $A_{\Delta\phi}$ in bins of $M_{t\bar{t}}$ minimises systematic uncertainties affecting the modelling of the $M_{t\bar{t}}$ shape – in particular, the top quark p_T modelling – and thus yields a more precise measurement of $A_{\Delta\phi} = 0.095 \pm 0.006$ (stat) ± 0.008 (syst) and $f_{\text{SM}} = 1.16 \pm 0.15$.

The ATLAS experiment uses a similar unfolding method with the 7 TeV data to measure the $\cos\theta_{\ell^+}^* \cos\theta_{\ell^-}^*$ distribution [15], and the results are shown in Fig. 4 (centre), resulting in a measurement of $C_{\text{hel}} = 0.315 \pm 0.061$ (stat) ± 0.049 (syst).

Spin correlation measurements are more difficult in the single lepton channel due to the reduced spin analysing power on the hadronic side (the light jet flavours cannot be reliably identified, and the b quark has low spin analysing power $\kappa_b = -0.39$). To extract more information than is possible using a single variable, CMS calculates a likelihood ratio λ_{event} for each event from the ratio of event probabilities evaluated using leading order matrix elements with and without spin correlations [16]. Templates in λ_{event} are constructed using MC@NLO events with and without spin correlations, and from simulated background events using control regions in data for normalisation

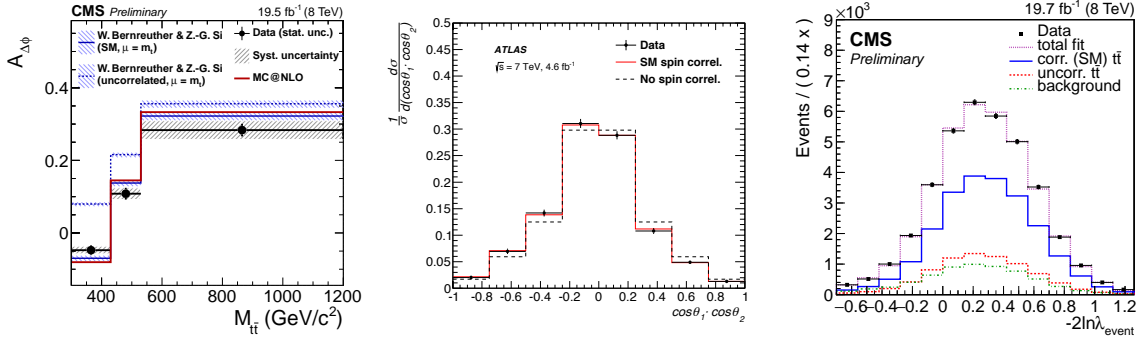


Figure 4: Dependence of $A_{\Delta\phi}$ on $M_{t\bar{t}}$ (left) [7]. Normalised differential $t\bar{t}$ production cross section as a function of $\cos\theta_{\ell^+}^* \cos\theta_{\ell^-}^*$, compared to the MC@NLO prediction with (red solid) and without (black dashed) spin correlations (centre) [15]. Single lepton channel likelihood ratio λ_{event} template fit results (right) [16].

and validation, and fit to the data to extract $f_{\text{SM}} = 0.72 \pm 0.09$ (stat) $^{+0.15}_{-0.13}$ (syst) (Fig. 4, right). The dominant sources of systematic uncertainty are the JES and the Q^2 scale.

With the 7 TeV data, ATLAS used a template method similar to the one described for the $|\Delta\phi_{\ell^+\ell^-}|$ measurement at the beginning of this section to measure a suite of variables sensitive to spin correlations using both the single lepton and dilepton channels [18]. CMS also made a similar unfolding analysis with the 7 TeV data [19]. These results were presented at the Top 2014 conference [20] and are not discussed in detail here.

Table 1: Summary of recent LHC spin correlation results, all converted into f_{SM} values for comparison. The preliminary results [7, 16] shown at the conference have since been replaced by publications [8, 17].

Variable	Collaboration	Channel	Method	f_{SM}
$ \Delta\phi_{\ell^+\ell^-} $	ATLAS (7 TeV)	Dilepton	Template [18]	1.19 ± 0.20
$ \Delta\phi_{\ell^+\ell^-} $	ATLAS (8 TeV)	Dilepton	Template [13]	1.20 ± 0.14
$ \Delta\phi_{\ell^+\ell^-} $	CMS (8 TeV)	Dilepton	Unfolding [7]	1.18 ± 0.18
$ \Delta\phi_{\ell^+\ell^-} $ (vs. $M_{t\bar{t}}$)	CMS (8 TeV)	Dilepton	2D Unfolding [7]	1.16 ± 0.15
$\cos\theta_{\ell^+}^* \cos\theta_{\ell^-}^*$	ATLAS (7 TeV)	Dilepton	Unfolding [15]	1.02 ± 0.26
$\cos\theta_{\ell^+}^* \cos\theta_{\ell^-}^*$	CMS (8 TeV)	Dilepton	Unfolding [7]	0.87 ± 0.27
$\cos\varphi$	CMS (8 TeV)	Dilepton	Unfolding [7]	0.90 ± 0.16
Matrix element	ATLAS (7 TeV)	Dilepton	Template [18]	0.87 ± 0.18
$ \Delta\phi_{\ell,d} , \Delta\phi_{\ell,b} $	ATLAS (7 TeV)	Lepton+jets	Template [18]	1.12 ± 0.25
Matrix element	CMS (8 TeV)	Lepton+jets	Template [16]	0.72 ± 0.17

4. Summary

Spin measurements in top quark events are an excellent test of the SM, and are being made with increasing precision at the LHC. A summary of recent LHC spin correlation results, all converted into values of f_{SM} , the strength of the spin correlations relative to the SM prediction, is given in Table 1. The measurements give important sensitivity to new physics, but so far have been found to be in good agreement with the SM predictions. Many of the measurements are no longer statistically limited, and improvements in systematic and theoretical uncertainties are essential to keep pace with the order of magnitude increase in production rates at the LHC in Run 2.

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