

Top quark property measurements at the LHC

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Abstract. Measurements of top quark properties performed at the Large Hadron Collider are reviewed, with a particular emphasis on top-pair charge asymmetries, spin correlations and polarisation measurements performed by the ATLAS and CMS collaborations. The measurements are generally in good agreement with predictions from next-to-leading-order QCD calculations, and no deviations from Standard Model expectations have been seen.

1. Introduction

The top quark (t) is the heaviest known elementary particle, with a mass that is much higher than those of all the other quarks, and close to the masses of the W , Z and Higgs bosons. Its large mass means that it decays quickly without forming hadrons, offering the unique opportunity to study the properties of a ‘bare’ quark. With its $O(1)$ Yukawa coupling to the Higgs boson, it may also be closely connected to electroweak symmetry breaking, or offer a window to physics beyond the Standard Model (SM). Studies of the properties of the top quark are therefore central to both the LHC and Tevatron physics programs.

This review focuses on measurements of the top-pair ($t\bar{t}$) production charge asymmetry, and measurements of spin correlation and top polarisation in $t\bar{t}$ events, performed by ATLAS [1] and CMS [2] in $\sqrt{s} = 7\text{--}8$ TeV pp collisions at the CERN Large Hadron Collider. Other properties of the top quark are covered in other reviews presented to the Top2014 conference.

2. Top charge asymmetry

One of the most intriguing legacy results from the Tevatron is the $t\bar{t}$ forward-backward asymmetry. Analyses of the angular distributions of top quarks and anti-quarks by CDF and D0 indicate that the top quarks (antiquarks) are produced preferentially following the direction of the proton (antiproton) beam. The latest measurements from CDF suggest that the size of this asymmetry is slightly larger than expected in the SM, whilst the measurements from D0 are in agreement with the SM [3]. This asymmetry cannot be measured at the LHC, as it collides pp and not $p\bar{p}$, but an analogous $t\bar{t}$ charge asymmetry A_C can be defined by looking at the difference in absolute rapidity values of the produced top quark and antiquark. The rapidity difference $\Delta|y| = |y_t| - |y_{\bar{t}}|$ is positive when the top quark is produced at a smaller angle to the beam direction (large $|y|$) than the antiquark, and negative otherwise. The asymmetry is defined from event counts N as:

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

¹ On behalf of the ATLAS and CMS Collaborations

\sqrt{s}	Asymmetry (%)	ATLAS	CMS	LHC comb.	Theory
7 TeV	semilept. A_C	$0.6 \pm 1.0 \pm 0.5$	$0.4 \pm 1.0 \pm 1.1$	$0.5 \pm 0.7 \pm 0.6$	1.15 ± 0.06
	dilepton A_C	$2.1 \pm 2.5 \pm 1.7$	$-1.0 \pm 1.7 \pm 0.8$		1.15 ± 0.06
	dilepton A_{lep}	$2.4 \pm 1.5 \pm 0.9$	$0.9 \pm 1.0 \pm 0.6$		0.70 ± 0.03
8 TeV	semilept. A_C		$0.5 \pm 0.7 \pm 0.6$		1.11 ± 0.04

Table 1. Measurements of the inclusive $t\bar{t}$ asymmetry A_C and leptonic asymmetry A_{lep} from ATLAS [5, 11] and CMS [6, 8, 10] at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV with their statistical and systematic uncertainties, together with the LHC combination [7] and corresponding theoretical predictions [4].

In the SM, this asymmetry is slightly positive for $t\bar{t}$ pairs produced via $q\bar{q} \rightarrow t\bar{t}$, where interference effects generate a correlation between the direction of the incoming quark and the outgoing top quark, but zero for $gg \rightarrow t\bar{t}$. The total resulting asymmetry is an order of magnitude smaller than the Tevatron forward-backward asymmetry, *e.g.* an NLO QCD calculation including electroweak corrections gives $A_C = 0.0115 \pm 0.0006$ at $\sqrt{s} = 7$ TeV [4].

The most precise measurements of A_C come from the semileptonic $t\bar{t}$ final state, in which the W boson from one top quark decays to an electron or muon and a neutrino, and the other to a $q\bar{q}$ pair. By selecting events with an isolated electron or muon, missing transverse momentum (E_T^{miss}) and at least four jets, ATLAS and CMS both isolate samples of about 60 000 events with about 20% non- $t\bar{t}$ background, dominated by W +jets and single top production. Kinematic fits are used to fully reconstruct the $t\bar{t}$ system and determine $\Delta|y|$ on an event-by-event basis. The $\Delta|y|$ distribution is then unfolded to correct for background, efficiency and resolution effects, and the inclusive A_C corrected back to the parton level extracted. The measurements from ATLAS [5] and CMS [6] at $\sqrt{s} = 7$ TeV are shown in Table 1, and have been combined [7] to give a value of $A_C = 0.005 \pm 0.007 \pm 0.006$, consistent with both zero and the SM prediction. CMS has also measured A_C at $\sqrt{s} = 8$ TeV using a very similar analysis [8].

Both collaborations have also measured A_C differentially, as a function of the rapidity, transverse momentum and invariant mass of the $t\bar{t}$ system. The latter in particular increases the sensitivity to new physics scenarios, which are expected to be more prominent at high $m_{t\bar{t}}$ as shown in Figure 1. ATLAS has also measured the asymmetry for $\beta_{t\bar{t}} > 0.6$, this cut on the longitudinal velocity of the $t\bar{t}$ system increasing the fraction of $q\bar{q} \rightarrow t\bar{t}$ events and the potential new physics contributions, but no significant deviations from the SM have been seen.

The $t\bar{t}$ charge asymmetry has also been measured in the dilepton channel at $\sqrt{s} = 7$ TeV [10, 11]. In dileptonic $t\bar{t}$ events, the W bosons from both top quarks decay to leptons and neutrinos, giving an under-constrained system since the E_T^{miss} measurement cannot resolve the separate contributions of each neutrino. Extra assumptions, such as the expected distribution of neutrino rapidities, are used to find the most probable kinematic configuration for each event, allowing $\Delta|y|$ to be extracted and A_C to be measured. In dileptonic events, a complementary asymmetry observable A_{lep} can be defined, based on the difference in $|\eta|$ between the positive and negatively charged leptons: $\Delta|\eta| = |\eta^{\ell^+}| - |\eta^{\ell^-}|$. The distributions of both variables for the updated ATLAS dilepton analysis [11] (new for this conference) are shown in Figure 2, and the A_C and A_{lep} values from both ATLAS and CMS are shown in Table 1.

The inclusive charge asymmetry measurements are summarised in Table 1. The semileptonic measurements have a precision of around 1%, not yet precise enough to distinguish between zero and the small non-zero asymmetry expected in the SM. The dilepton measurements have lower precision, due to the smaller event samples and ambiguities inherent in the dileptonic final state.

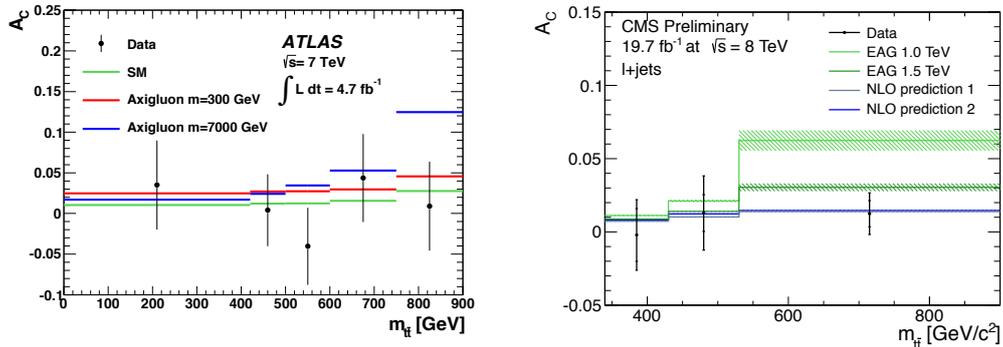


Figure 1. Measurements of the $t\bar{t}$ charge asymmetry A_C as a function of the invariant mass of the $t\bar{t}$ system in semileptonic $t\bar{t}$ events from ATLAS at $\sqrt{s} = 7$ TeV [5] and CMS at $\sqrt{s} = 8$ TeV [8]. The measurements are compared to SM NLO QCD predictions with electroweak corrections from Ref. [4] (CMS NLO1) and Ref. [9] (CMS NLO2 and ATLAS), and to various beyond-Standard Model scenarios (see [5, 8] for details).

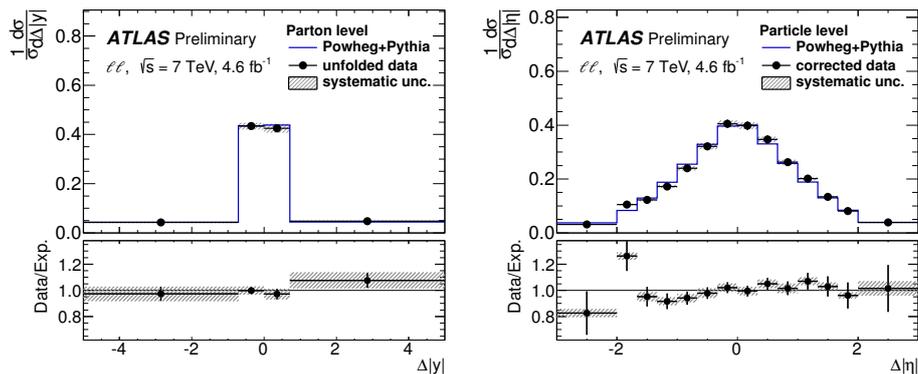


Figure 2. Unfolded normalised $t\bar{t} |\Delta|y|$ distribution (left) and dilepton $\Delta|\eta|$ distribution (right) from the ATLAS dilepton charge asymmetry analysis at $\sqrt{s} = 7$ TeV [11]. The data is compared to the simulation predictions based on POWHEG+PYTHIA.

3. Spin correlations and polarisation

The top quark lifetime of about 3×10^{-25} s is much shorter than the time required to form hadrons, so the top quark decays as a ‘bare’ quark, transferring information on its spin to the decay products. In $t\bar{t}$ pair production, the polarisation is expected to be negligible, but the spins of the t and \bar{t} are correlated, such that the asymmetry in the numbers of events where the t and \bar{t} have like and unlike spins, $A = (N_{\text{like}} - N_{\text{unlike}})/(N_{\text{like}} + N_{\text{unlike}})$, is non-zero. The double-differential cross-section in the decay angles of the two top quarks, $\cos \theta_+$ and $\cos \theta_-$, is given by:

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos \theta_+ d\cos \theta_-} = \frac{1}{4} (1 + A\alpha_+ \alpha_- \cos \theta_+ \cos \theta_-)$$

where the asymmetry parameter A is scaled by the spin-analysing power of the chosen top quark decay products, and $\cos \theta_+$ and $\cos \theta_-$ are the cosines of the angles between the top quark decay product and the chosen polarisation axis. Normally the helicity basis is used, in which the polarisation is measured using the direction of the top quark momentum in the $t\bar{t}$ rest frame. The spin-analysing power α is 0.998 for positively-charged leptons, -0.966 for down quarks from

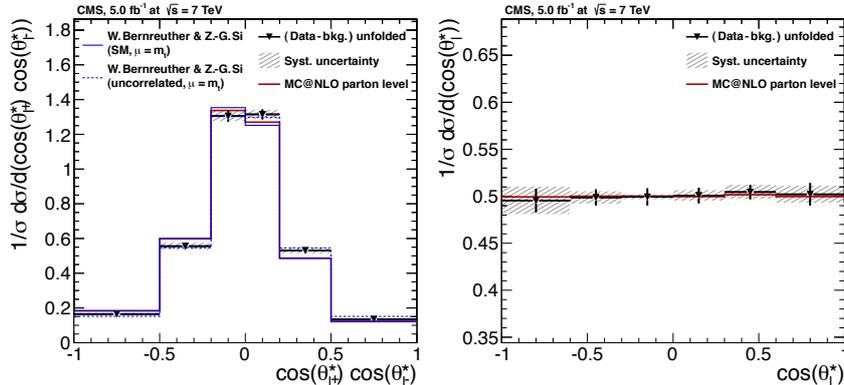


Figure 3. Unfolded distributions of $\cos\theta_+\cos\theta_-$ (left) and top quark decay angle $\cos\theta$ (right) measured by CMS in dilepton $t\bar{t}$ events at $\sqrt{s} = 7$ TeV [12], and compared to predictions with and without $t\bar{t}$ spin correlations and from the MC@NLO $t\bar{t}$ event generator.

the W decay, and -0.393 for b quarks from the top decay.

Measurement of the $t\bar{t}$ spin correlations using the above formalism requires the full reconstruction of the $t\bar{t}$ system, using techniques similar to those used in the charge asymmetry measurement. They have been measured at $\sqrt{s} = 7$ TeV by CMS in dilepton events [12] (see Figure 3 (left)), and by ATLAS in both dileptonic and semileptonic events [13], using both the helicity basis and the so-called maximal basis which is particularly sensitive to correlations in the $gg \rightarrow t\bar{t}$ subprocess. All measurements are consistent with the spin correlations predicted by the Standard Model.

The $t\bar{t}$ spin correlation also affects the distribution of $\Delta\phi_{\ell\ell}$, the difference in azimuthal angles (transverse to the beamline) of the two leptons in dileptonic $t\bar{t}$ events. Both collaborations exploited this variable to demonstrate the existence of spin correlations in $\sqrt{s} = 7$ TeV data. The CMS analysis [12] unfolded the $\Delta\phi_{\ell\ell}$ distribution to parton level, correcting for background, acceptance and resolution effects, and compared the result to simulation predictions with and without spin correlations as predicted by the SM (see Figure 4 (left)). The level of spin correlation was quantified from the asymmetry of the parton-level $\Delta\phi_{\ell\ell}$ distribution about $\Delta\phi_{\ell\ell} = \pi/2$ as $A_{\Delta\phi} = 0.113 \pm 0.010 \pm 0.013$, in agreement with the NLO prediction of 0.115 . ATLAS [13] instead compared the detector-level $\Delta\phi_{\ell\ell}$ distribution to fully-simulated events with and without spin correlation, quantifying the spin correlation strength with a fit to SM-like correlated and uncorrelated simulation-derived templates. The fitted fraction of correlated template f_{SM} was measured to be $1.19 \pm 0.09 \pm 0.18$, compatible with unity. At the conference, ATLAS presented a new analysis using the $\Delta\phi_{\ell\ell}$ distribution at $\sqrt{s} = 8$ TeV [14] with an optimised dilepton event selection having higher efficiency; as shown in Figure 4 (right), this is also compatible with the SM expectation, with a fitted $f_{\text{SM}} = 1.20 \pm 0.05 \pm 0.15$, corresponding to a spin correlation strength in the helicity basis of $A = 0.38 \pm 0.04$. The $\Delta\phi_{\ell\ell}$ distribution can also be used to set limits on new physics contributions within the selected $t\bar{t}$ event sample, for example top squark pair production as shown by ATLAS [15], or an anomalous $t\bar{t}$ -gluon interaction parameterised as a chromomagnetic dipole moment as explored by CMS [16].

The CMS collaboration also used the same $\sqrt{s} = 7$ TeV dilepton sample to measure the top quark polarisation in $t\bar{t}$ events, via the unfolded distribution of the decay angle $\cos\theta$ [12]. The results are shown in Figure 3 (right), and are consistent with zero polarisation. ATLAS also measured the top polarisation in both dilepton and semileptonic events, looking for polarisation effects which polarise the t and \bar{t} quarks with the same (CP-conserving) or opposite (CP-violating) signs, and again found results compatible with zero [17].

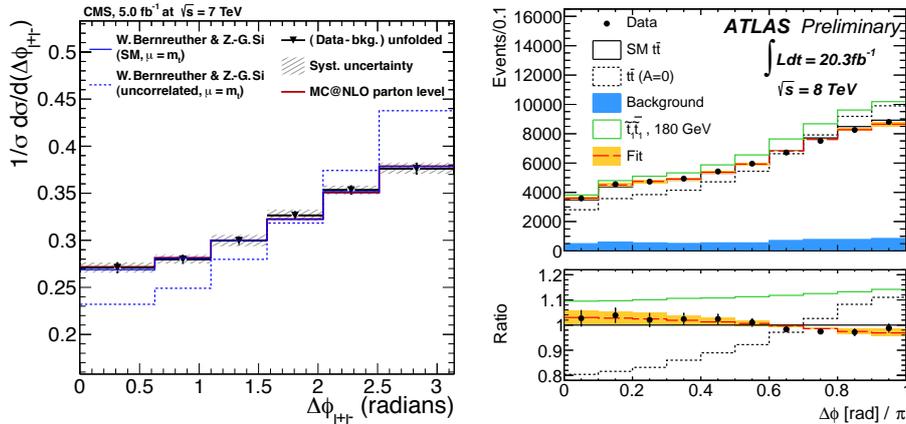


Figure 4. Measurements of spin correlation using the $\Delta\phi_{\ell\ell}$ distribution in dilepton $t\bar{t}$ events from CMS at $\sqrt{s} = 7$ TeV [12] and ATLAS at $\sqrt{s} = 8$ TeV [14], compared to simulation predictions with and without spin correlation at parton level (CMS) or detector level (ATLAS).

4. Outlook

The LHC data have already produced a wealth of top quark property measurements, so far mainly at $\sqrt{s} = 7$ TeV. Top-pair charge asymmetry measurements are reaching 1% precision, and the inclusion of the full $\sqrt{s} = 8$ TeV dataset may allow the small non-zero expected asymmetry to be observed. No hints of deviations in either the inclusive or differential asymmetries have been seen, strongly constraining various new physics scenarios. The expected $t\bar{t}$ spin correlations have been clearly observed at both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, and the top quark polarisation in $t\bar{t}$ events has been seen to be consistent with the expectation of zero within about 2%. Many of these measurements are limited by systematics, and advances in $t\bar{t}$ modelling or new analysis techniques will be needed to fully exploit the $\sqrt{s} = 8$ TeV dataset. This will be even more important in the upcoming $\sqrt{s} = 13$ –14 TeV run, which in particular will allow top charge asymmetry measurements to be pushed to sub-percent precision and extended to higher $t\bar{t}$ invariant masses.

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