Top Production Properties in ATLAS & CMS

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ABSTRACT

The large mass and short lifetime of the top quark mean that it decays before forming bound states. This allows the top quark to be studied as a bare quark and opens up the possibility to measure many properties that cannot be probed using other quarks. Precise study of these properties, including spin correlations, polarisations and asymmetries, may shed light on possible physics beyond the Standard Model.

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1 Introduction

The top quark is unique among the known quarks in that it decays before it has the opportunity to form hadronic bound states. This allows properties of the top quark to be studied as if it was a bare quark. These properties include the mass, charge and polarisation of the top quark amongst others. The large number of top quarks produced by the LHC means that these properties can be studied more accurately that ever before, allowing to precisely test the Standard Model (SM) and search for new physics beyond the SM.

In this article six measurements of top quark properties by the ATLAS \[1\] and CMS \[2\] collaborations are presented. For each experiment, the properties measured are the $t\bar{t}$ spin correlation and polarisation, the $t\bar{t}$ charge asymmetry and various CP asymmetries.

Top quarks decay to a $b$-quark and $W$ boson \(\approx 100\%\) of the time, and therefore top-antitop-quark pairs ($t\bar{t}$) are categorised based on how each of the two $W$ bosons decay. The measurements in this article are all performed in the dilepton channel, where both $W$ bosons decay to a charged lepton and neutrino pair, with the exception of the CP asymmetry measurements, which are performed in the single-lepton channel.

2 Spin correlation and polarisation

Top quarks pairs produced by the strong interaction have essentially unpolarised spins. However, the spins of the top quark and anti-top quark are expected to be correlated. As the top quark decays before it hadronises, information about the top quark spin is passed on to its decay products and the strength of the $t\bar{t}$ spin correlation can be measured using angular distributions. Charged leptons carry the most information about the top quark spin and can be well identified by the ATLAS and CMS detectors and so measurements of the $t\bar{t}$ spin correlation and the top quark polarisation can be performed more easily in the dilepton channel, although both ATLAS and CMS have also made measurements in the lepton-plus-jets channel \[3, 4\].

The normalised double-differential cross-section for $t\bar{t}$ production and decay is

\[
\frac{1}{\sigma} \frac{d^2 \sigma}{d (\cos \theta_a^+ d (\cos \theta_b^-)} = \frac{1}{4} (1 + B_a^+ \cos \theta_a^+ + B_b^- \cos \theta_b^- - C_{ab} \cos \theta_a^+ \cos \theta_b^-),
\]

where $B_a^+, b$ and $C_{ab}$ are the polarisation and spin correlation coefficients along spin quantisation axes $a$ and $b$ respectively and $\theta_a^+ (\theta_b^-)$ is the angle between the positive (negative) lepton and quantisation axis $a (b)$. Different spin-quantisation axes can be chosen, each with a different expected spin correlation or polarisation strength. The most commonly chosen axes used is the helicity axis, $\hat{k}$, in which the spin-quantisation axis is chosen as the direction of the top quark in the $t\bar{t}$ system rest frame. The angle $\theta$ is then formed using this axis and the direction of the charged lepton in the top quark rest frame.

The $\cos \theta^\pm$ distribution is shown in Figure 1 for both ATLAS and CMS. The top quark polarisation is expected to be very small in the SM and hence the expected distribution is flat. It can be seen that the data are in good agreement with the SM predictions.

The $\cos \theta_a^+ \cos \theta_b^-$ distribution has a non-zero asymmetry in the SM due to expected spin correlation and is shown in Figure 2 as measured by ATLAS and CMS. The data are in good agreement with the SM prediction. In Figure 2(b), the prediction in the case of zero spin correlation is also shown.

Another variable that can be used to probe $t\bar{t}$ spin correlation in the azimuthal angle between the two charged leptons in the lab frame, $\Delta \phi$. The major advantage of this variable is that one is not required to reconstruct the $t\bar{t}$ system to define a spin-quantisation axis. ATLAS and CMS have used this distribution to set limits on beyond the SM physics. Figure 3 shows an example of the expected impact on the $\Delta \phi$ distribution due to the presence of beyond the SM chromo-magnetic dipole moments. This difference is used to set limits on possible values of chromo-magnetic and chromo-electric dipole moments. Similarly, ATLAS has previously used the $\Delta \phi$ distribution to set limits on possible masses of a supersymmetric top partner \[7\].
Figure 1: The $\cos \theta$ distribution measured in the helicity basis by the ATLAS (a) and CMS (b) collaborations. Data are in good agreement with the SM predictions.

Figure 2: The $\cos \theta_+ \cos \theta_-$ distribution measured in the helicity basis by the ATLAS (a) and CMS (b) collaborations. Data are in good agreement with the SM predictions.
3 Charge asymmetry

$t\bar{t}$ production is predicted to be symmetric under charge conjugation at leading order in quantum chromodynamics (QCD) in the SM. However, at next-to-leading order a small ($\approx 1\%$) charge asymmetry is introduced resulting in the rapidity distribution being slightly broader for top quarks than for anti-top quarks. This asymmetry is passed on to the decay products of the top and anti-top quark and thus also exists between the charged leptons in dilepton $t\bar{t}$ events. Although the $t\bar{t}$ charge asymmetry is predicted to be small in the Standard Model, beyond the SM physics can cause it to be enhanced.

The ATLAS and CMS collaborations have measured both the $t\bar{t}$ charge asymmetry by reconstructing the $t\bar{t}$ system in dilepton $t\bar{t}$ events and also by directly using the charged leptons in such events [8, 9]. The $t\bar{t}$ charge asymmetry is defined as

$$A_{t\bar{t}}^{CP} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)},$$

where $\Delta|y| = |y_t| - |y_{\bar{t}}|$, while the lepton-based charge asymmetry is defined as

$$A_{t\bar{t}}^{\ell^+\ell^-} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)},$$

where $\Delta|\eta| = |\eta_t| - |\eta_{\bar{t}}|$. Figure 4 shows the measured $\Delta|y|$ distributions for ATLAS and CMS. In both cases good agreement is seen between the data and predictions. Figure 5 shows the measured $\Delta|\eta|$ distributions measured by ATLAS and CMS. As with the $\Delta|y|$ distribution the data are well modelled by the prediction.

In addition to the inclusive measurements of $\Delta|y|$ and $\Delta|\eta|$, ATLAS and CMS have both measured the $t\bar{t}$ charge asymmetry versus other variables, such as the invariant mass of the $t\bar{t}$ system, $m_{t\bar{t}}$. Beyond the SM physics may enhance the $t\bar{t}$ charge asymmetry at high $m_{t\bar{t}}$ for example due to the presence of a heavy resonance decaying to a $t\bar{t}$ pair. Figure 6 shows the measured $t\bar{t}$ charge asymmetry versus $m_{t\bar{t}}$ as measured by ATLAS and CMS. In both cases, the data are well modelled by the SM prediction and consistent with only a small charge asymmetry.

4 CP asymmetries

Despite a long history of study using other quarks, charge parity (CP) violation had been relatively unexplored in the top quark sector. ATLAS and CMS have recently used $t\bar{t}$ events to address this. While both collaborations are searching for CP violating effects, the approached taken by the two collaborations are somewhat different.
Figure 4: The $\Delta |y|$ distribution measured by the ATLAS (a) [8] and CMS (b) [9] collaborations. Data are in good agreement with the SM predictions.

Figure 5: The $\Delta |\eta|$ distribution measured by the ATLAS (a) [8] and CMS (b) [9] collaborations. Data are in good agreement with the SM predictions.
The ATLAS collaboration uses weakly decaying $b$-hadrons from top quark decays to probe CP violation [10]. This measurement is performed in the lepton-plus-jets channel, in which there is one high-$p_T$ charged lepton. The charge of this lepton is used to determine the charge of the $b$-quark at production, $\alpha$. Events are then required to contain an additional muon associated to a $b$-tagged jet, this is known as a “soft muon” and is used to determine the charge of the $b$-quark when it decays, $\beta$. Given the number of events with charges $\alpha$ and $\beta$, $N^{\alpha\beta}$, same-sign, $A^{SS}$, and opposite-sign, $A^{OS}$, charge asymmetries are constructed as

\begin{align}
A^{SS} &= \frac{(N^{++}/N^+)-(N^{-+}/N^-)}{(N^{++}/N^+)+(N^{-+}/N^-)}, \\
A^{OS} &= \frac{(N^{+-}/N^+)-(N^{-+}/N^-)}{(N^{+-}/N^+)+(N^{-+}/N^-)},
\end{align}

where $N^{+(-)}$ is the number of events in which the charged lepton has positive (negative) charge. The number of events falling into each category is shown in Figure 7, for events in which a prompt muon and a soft muon have been identified as being associated to the same top quark (via a $W$ boson and $b$-quark decay respectively). The values of $A^{SS}$ and $A^{OS}$ measured by the ATLAS collaboration are

\begin{align}
A^{SS} &= -0.007 \pm 0.006 \text{ (stat.)} \pm 0.002 \text{ (expt.)} \pm 0.005 \text{ (model)} \\
A^{OS} &= 0.0041 \pm 0.0035 \text{ (stat.)} \pm 0.0003 \text{ (model)} \pm 0.0027 \text{ (model)}
\end{align}

consistent with zero.

CMS has measured CP asymmetries using four observables constructed using the momenta of the top quark decay products [11]. They are

\begin{align}
O_2 &\propto (\vec{p}_b + \vec{p}_\ell) \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \\
O_3 &\propto Q_\ell \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \\
O_4 &\propto Q_\ell \vec{p}_b - \vec{p}_\ell \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \\
O_7 &\propto (\vec{p}_b - \vec{p}_\ell) \cdot (\vec{p}_b \times \vec{p}_{j1})
\end{align}

where $\vec{p}_b$, $\vec{p}_\ell$, $\vec{p}_\ell$, and $\vec{p}_{j1}$ are the momenta of the $b$-jet associated to the top quark, the $b$-jet associated to the anti-top quark, charged lepton and highest $p_T$ jet from the $W$ boson decay. All observables are defined in the
Figure 7: The number of events in which the charges of a prompt muon from a top quark to $W$ boson decay ($t \rightarrow W \rightarrow \mu$) and a soft muon from a top quark to $b$ quark decay ($t \rightarrow b \rightarrow \mu$) are either the same or different. Taken from Ref. [10].

Figure 8: The four observables that are sensitive to CP violating effects measured by CMS. In all observables the data are well modelled by the prediction. Taken from Ref. [11].
Figure 9: The measured asymmetries for the four observables sensitive to CP violating effects measured by CMS. In all cases the measured asymmetries are consistent with zero. Taken from Ref. [11].

lab-frame, with the exception of Equation 8b, which is defined in the $b\bar{b}$ centre-of-mass frame. Figure 8 shows the four measured observables. The data are well described by the SM prediction.

All four of these observables are predicted to be symmetric around zero in the SM and thus the asymmetry of each observable is measured. However, in the case of $O_3$ and $O_4$ asymmetries as large as 8% can be introduced in models beyond the SM. Results are presented as raw asymmetries, $A'_{\text{CP}}$, as measured in the detector, and also corrected by MC, $A_{\text{CP}}$. Both the corrected and raw asymmetries are presented as the corrected asymmetry includes Standard Model assumptions. Figure 9 shows a summary of the measured asymmetries.

5 Summary and outlook

The large number of $t\bar{t}$ pairs produced at the LHC allow ATLAS and CMS to make precise measurements of top quark properties. To date, all measurements have been in agreement with SM predictions and several models beyond the SM physics have been excluded. However, the measurements presented here use only data taken by the LHC in 2012 at $\sqrt{s} = 8$ TeV. Since 2015 ATLAS and CMS have been recording data at $\sqrt{s} = 13$ TeV. This new dataset will allow top quark properties to be measured more precisely than ever before.

References


11. CMS Collaboration. Search for CP violation in $t\bar{t}$ production and decay in proton-proton collisions at $\sqrt{s} = 8$ TeV. JHEP 03, 101 (2017).