Top Quark Asymmetry Results at the LHC

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Abstract. In 2011, an integrated luminosity of more than 5 fb$^{-1}$ at 7 TeV has been delivered by the Large Hadron Collider (LHC). The measurements of the top-antitop quark charge asymmetry in top quark pair production have been performed at the ATLAS and CMS experiments. The measured charge asymmetry values from both experiments are within the uncertainties in agreement with the SM theory predictions. An overview of the latest results of these measurements by the time of TOP2012 conference will be presented.

1. Introduction

Top-antitop quark pair production is symmetric under charge conjugation at leading order in the standard model (SM). However, the top-antitop charge asymmetry can appear in $t\bar{t}$ pair production through quark and anti-quark annihilation at next-to-leading order (NLO) in perturbative QCD through the interference between Initial State Radiation (ISR) and Final State Radiation (FSR), which can contribute to negative asymmetry, and the interference between the Born and box diagrams that enhances the asymmetry [1]. Tevatron has observed significant deviations in forward-backward measurements at CDF and D0 [2]–[3]. In particular, CDF has observed 3.4$\sigma$ deviation with respect to SM above 450 GeV for $t\bar{t}$-based forward-backward asymmetry ($A_{FB}$) and D0 for $A_{FB}$ using final state leptons from top decays. These latest results have had large attention and triggered many theoretical explanations. For example, the deviation could be explained by possible exchange of new particles in $t$-channel and the charge asymmetry variable is sensitive to this additional production mode.

Unlike Tevatron, it is hard to measure at the LHC due to the symmetric initial state of pp collisions since the rapidity distributions of top and anti-top quarks are symmetrically distributed around zero. However, it is feasible when we consider the fact that the top quark (valence quark) width in rapidity distribution is broader than anti-top quark (see quark) width. At ATLAS [4] and CMS [5], the analyses were previously performed with around 1 fb$^{-1}$ showing no deviations [6]–[7].

In 2011, an integrated luminosity of more than 5 fb$^{-1}$ at 7 TeV has been delivered by the LHC. The measurements of the top-antitop quark asymmetry in top-antitop quark pair production have been performed with this data at the ATLAS and CMS experiments. In addition to $t\bar{t}$-based top-antitop quark asymmetry measurement, since the charge asymmetry from $t\bar{t}$ production can be transmitted to leptons from top decays in the dilepton decay mode, the purely lepton-based asymmetry measurement was performed in ATLAS, taking advantage of the high resolution for leptons. The lepton-based asymmetry measurement is also sensitive to top polarization. The variables sensitive to the $t\bar{t}$ and lepton-based asymmetries used at the LHC are following:
\[ A_C^{ll} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}, \quad A_C^{\mu\mu} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)} \]

where \( \Delta|y| = |y_t| - |y_{\bar{t}}| \) (\( \Delta|\eta| = |\eta_t^+| - |\eta_{\bar{t}}^-| \)) represents the difference of absolute values of top and anti-top rapidities (positively and negatively charged lepton pseudorapidities) and \( N \) is the number of events with \( \Delta|y| \) (\( \Delta|\eta| \)) being positive or negative. The rapidity \( y \) is defined as \( y = \frac{1}{2} \ln \frac{E + P_T}{E - P_T} \), where \( E \) is the particle energy and \( P_T \) its momentum component along the beam direction. In order to confirm the Tevatron results, it is also important to measure the asymmetry as a function of variables that can enhance the charge asymmetry in certain regions. Therefore, the differential top-antitop quark asymmetry measurements are performed in CMS. In this proceedings, an overview of the latest results of these measurements by the time of TOP 2012 conference will be presented.

2. Charge asymmetry measurement at ATLAS

At ATLAS, with around 5 fb\(^{-1}\) data, the inclusive top charge asymmetry using the sensitive variable \( y_t \) and the lepton-based charge asymmetry using the sensitive variable \( \eta_t \), are measured in the dilepton decay mode [8].

The event selection is following. Muons (Electrons) are required to have \( p_T \) larger than 20 (25) GeV and \( |\eta| \) smaller than 2.5 (2.5). The events which have the dilepton invariant mass from opposite-sign isolated leptons within 10 GeV respect to \( m_Z \) are rejected and the missing transverse momentum \( E_T^{miss} \) should be larger than 60 GeV in the \( ee \) and \( \mu\mu \) decay modes. The scalar sum of energy of two leptons and jet should be larger than 130 GeV in the \( ee \) decay mode. The events also should have at least 2 jets with \( p_T > 25 \) GeV and \( |\eta| < 2.5 \). The contribution from fake leptons such as semi-leptonic \( b \) decays is estimated using the so called Matrix method [8]. Other backgrounds from single top production, \( Z \rightarrow ll+\)jets and diboson processes are evaluated using Monte Carlo simulated samples. Top quark four-momentum is reconstructed using kinematic reconstruction method constraining top quark mass and \( W \) boson mass together with missing transverse energy and transverse momentum of \( t\bar{t} \) system, which yields the true combination matches in 47% of the cases where the solution is found.

In order to compare with theory predictions or with other experiments, the results at reconstruction level need to be corrected for bin migration and efficiency. These corrections are estimated using \( tt \) samples simulated with MC@NLO. The \( tt \) samples are reweighted to vary the size of the asymmetry at the generated level. Dependency of the reconstructed \( A_C \) on the generated \( A_C \) is described by a straight line. The background-subtracted data raw \( A_C \) is corrected using both the slope and the offset of the fitted straight line. The slope of the correction for the lepton-based asymmetry is very close to unity while around 0.5 for the \( ll \)-based asymmetry since top quark kinematic quantities are more affected by the detector effect.

After applying unfolding procedure, the combined value for the lepton charge asymmetry is \( A_C^{ll} = 0.023 \pm 0.012 \) (stat.) \( \pm 0.008 \) (syst.) and for the top quark charge asymmetry, \( A_C^{t\bar{t}} = 0.057 \pm 0.024 \) (stat.) \( \pm 0.015 \) (syst.). Figures 1–2 show the measured \( \Delta|\eta| \) distributions for lepton pairs and top quark pairs, respectively after the final selection for the \( ee, \mu\mu \) and \( \mu\mu \) decay modes. The \( ll \)-based asymmetry in this dilepton analysis is further combined with the previous lepton+jets analysis [6]. The combined value for the top quark charge asymmetry is \( A_C^{t\bar{t}} = 0.029 \pm 0.018 \) (stat.) \( \pm 0.014 \) (syst.). These results are compatible with the SM predictions (from the MC@NLO Monte Carlo generator) of \( A_C^{ll} = 0.004 \pm 0.001 \) and \( A_C^{t\bar{t}} = 0.006 \pm 0.002 \), respectively for the lepton-based and the \( ll \)-based asymmetries.
3. Charge asymmetry measurement at CMS

At CMS, the previous analysis [7] in the lepton+jets decay mode is updated with an integrated luminosity of 5.0 fb$^{-1}$ [9]. Event selection follows the lepton+jets typical analysis requiring 4 jets and one $b$-tagging with one exclusive isolated muon (electron) with $p_T$ larger than 20 (30) GeV and $|\eta|$ smaller than 2.1 (2.5). The contribution from multi-jet process is obtained from data events with loosened lepton isolation requirement. The four-momenta of top and anti-top quark are reconstructed by reconstructing the missing $z$ component of neutrino four-vector considering the $W$ boson to be on shell and then associating the measured jets in $t\bar{t}$ decays with a likelihood ratio function of masses of the reconstructed top quarks and the hadronically decay $W$ boson and using $b$-tagging information. The sensitive variables related to the top quark are reconstructed with correct sign in 72% of all events.

In the SM, it is possible to increase or decrease the asymmetry by changing the kinematic boundary conditions. Therefore, it is crucial to measure the asymmetry differentially in kinematic variables that are sensitive to the asymmetry. Three different variables are used in CMS, namely the rapidity, the transverse momentum and the invariant mass of $t\bar{t}$ system, the vectorially summed four-vector of top quark and anti-quark in the laboratory frame. The reasons why these three variables are chosen are the following. For $y_{t\bar{t}}$, the charge asymmetry occurs only in the $q\bar{q}$ initial state and $t\bar{t}$ production through $q\bar{q}$ annihilation is more prominent.
Table 1. The measured inclusive asymmetry at the different stages of the analysis and the corresponding theory prediction from the SM.

| Stage                | Asymmetry             |
|----------------------|-----------------------|
| Uncorrected          | 0.003 ± 0.004 (stat.) |
| BG-subtracted        | 0.002 ± 0.005 (stat.) ± 0.003 (syst.) |
| Final corrected      | 0.004 ± 0.010 (stat.) ± 0.011 (syst.) |
| Theory prediction (SM)| 0.0115 ± 0.0006       |

at larger values of rapidity $y_{t\bar{t}}$. For $p_T^{t\bar{t}}$, the presence of ISR or FSR implies on average higher $p_T^{t\bar{t}}$ so the negative contribution from the ISR or FSR interference is enhanced with large values of $p_T^{t\bar{t}}$. For $m_{t\bar{t}}$, if heavy particles with different couplings to top quarks and anti-quarks exist, one can expect an effect on the charge asymmetry with rising invariant mass of the $t\bar{t}$ system.

The results at reconstruction level are corrected for bin migration and efficiency. For bin migration correction, the regularized unfolding method is applied. For the response matrix, POWHEG which preserves the asymmetry in NLO is used. For the differential measurement, in order to take into account the bin migration not only between the sensitive variable $\Delta|y|$ but also between differential sensitive variables, 2D regularized unfolding method is applied. The bin width is determined in a way that the statistical uncertainty in each bin becomes approximately the same. The 2D response matrix and efficiency for the measurement differential in $m_{t\bar{t}}$ are shown in Fig. 3.

Table 1 shows the values of the measured inclusive asymmetry at the different stages of the analysis. Figure 4 shows the distributions of the inclusive and three differential measurements comparing with predictions from the SM calculations and also from an effective field theory [10]. The results from the inclusive measurement and differential cross section measurement show a good agreement with the SM predictions.

![Figure 3. The 2D response matrix (left) and efficiency (right) for the measurement differential in $m_{t\bar{t}}$ variable at CMS [9].](image)

4. Conclusions

The top-antitop quark charge asymmetry performed by ATLAS and CMS with 2011 data have been presented. The lepton-based $A_C$ in the dilepton decay mode as well as differential asymmetry in the lepton+jet decay mode have been also measured. All measured charge asymmetry values are within the uncertainties in agreement with the SM theory predictions.
Figure 4. Unfolded inclusive $\Delta|y|$ spectrum (upper-left) and corrected asymmetry as a function of $|y_{t\bar{t}}|$ (upper right), $p_T^{h}$ (lower left) and $m_{t\bar{t}}$ (lower right). The NLO SM calculation and the prediction featuring an effective axial-vector coupling of the gluon (EAG) [10] are also shown [9].

The LHC results do not confirm the Tevatron observation of charge asymmetry deviation: more statistics is needed to validate or exclude the deviation.

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