PROCEEDINGS OF SCIENCE

Measurement of the charge asymmetry in top quark pair production in pp collisions (CMS)

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We report on results of $\mathrm{t\bar{t}}$ charge asymmetry measurements in the electron+jets and muon+jets channels, based on a dataset corresponding to an integrated luminosity of 5 fb^{-1}. The data have been collected with the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC) at CERN at a centre-of-mass energy of 7 TeV. An inclusive measurement of the $\mathrm{t\bar{t}}$ charge asymmetry and three differential measurements as a function of the invariant mass, the transverse momentum, and the rapidity of the $\mathrm{t\bar{t}}$ system are presented. All measurements are in agreement with the predictions of the standard model.

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1. Introduction

One of the most interesting leftovers from the decommissioned Tevatron collider at Fermilab is the 2 sigma upwards-deviation of the $\mathrm{t\bar{t}}$ charge asymmetry from the standard model (SM) predictions, measured by the CDF and D0 collaborations [1, 2]. An overview of the different theories explaining this deviation with physics beyond the standard model (BSM) can be found in [3].

The SM predicts interference effects in the $\mathrm{q\bar{q}} \to \mathrm{t\bar{t}}$ process at higher order between the amplitudes of the Born diagram and the box diagram and between those of diagrams with initial-state radiation (ISR) and final-state radiation (FSR). As a result, the direction of motion of the produced top (anti)quark is correlated to the direction of motion of the incoming initial (anti)quark. At the LHC, the initial state is given by two colliding protons and is therefore charge symmetric. Quarks exist in protons as valence quarks while antiquarks exist only as sea quarks. With the valence quarks having on average larger fractions of the proton's momentum compared to the sea quarks, this connection of the momenta of initial (anti)quarks and top (anti)quarks leads to an observable effect in the $\mathrm{t\bar{t}}$ system: The top quarks tend to be produced more abundantly in forward and backward directions, while the top antiquarks are preferentially produced in the central region. A suitable observable to measure this effect is the difference of the absolute values of the rapidities of the top quark and antiquark, $\Delta|y|$. Using this observable, the $\mathrm{t\bar{t}}$ charge asymmetry can be defined as

$$A_C = \frac{N^+ - N^-}{N^+ + N^-} \quad , \tag{1.1}$$

where N^+ and N^- represent the number of events with positive and negative values of $\Delta|y|$.

As only $\mathrm{q\bar{q}}$ initial states contribute to the charge asymmetry, the prediction for A_C at the LHC is considerably smaller compared to the value at the Tevatron, where the fraction of $\mathrm{q\bar{q}}$ initial states in the top quark production is larger. The SM prediction for the LHC is $A_C^{theory} = 0.0115 \pm 0.0006$ [4].

It is of special interest to measure A_C also as a function of kinematic variables that are suited to enhance the charge asymmetry or that are sensitive to possible contributions from new physics. In the analysis described in this article, three kinematic variables have been chosen for this purpose. As the charge symmetric gluon-gluon fusion is dominant in the central region while $\mathrm{q\bar{q}} \to \mathrm{t\bar{t}}$ is enhanced in the forward directions, the rapidity of the $\mathrm{t\bar{t}}$ system is sensitive to the fraction of $\mathrm{q\bar{q}}$ initial states in the top quark pair production. And since only the $\mathrm{q\bar{q}}$ initial states contribute to the asymmetry, the measured asymmetry depends on $|y_{\mathrm{t\bar{t}}}|$. The interference between Born and box diagrams leads to a positive contribution to the charge asymmetry, while the interference terms between ISR and FSR processes contribute negatively. As the amount of ISR/FSR is closely related to the transverse momentum of the $\mathrm{t\bar{t}}$ system, $p_{\mathrm{T}}^{\mathrm{t\bar{t}}}$, this variable is sensitive to the ratio of negative and positive contributions. Similar as for the rapidity, also the invariant mass of the $\mathrm{t\bar{t}}$ system is sensitive to the fraction of $\mathrm{q\bar{q}}$ initial states and thus the charge asymmetry depends on this kinematic variable. Furthermore, new heavy particles could be exchanged between the initial quarks and these contributions could interfere with the SM contributions, leading to an enhanced asymmetry — with the enhancement depending on the mass of this potential new particle and thus depending on $m_{\mathrm{t\bar{t}}}$.

This article summarizes the analysis and results as presented in a dedicated talk at the ICHEP conference in Melbourne. A more detailed description of the analysis itself can be found in [5].

2. Event selection and background estimation

The data used for this analysis have been collected with the CMS detector at the LHC at a centre-of-mass energy of 7 TeV. A detailed description of the CMS detector can be found in [6]. The collected data correspond to an integrated luminosity of 5.0 fb^{-1}.

Collision data as well as simulated events are subjected to requirements tuned to select a sample of events with a lepton+jets signature, where "lepton" refers to either an electron or a muon. In $\mathrm{t\bar{t}}$ events this corresponds to the decay channel where one of the produced W bosons decays leptonically into an electron or muon and the corresponding neutrino while the other W boson decays hadronically into a pair of jets. Electron (muon) candidates must have $p_\mathrm{T} > 30(20)\,\mathrm{GeV}/c^2$ and be within $|\eta| < 2.5(2.1)$. Jets are required to have $p_\mathrm{T} > 30\,\mathrm{GeV}/c^2$ and $|\eta| < 2.4$. At least four jets are required, at least one of which must be identified as originating from a b quark.

After applying these selection criteria, 57697 events remain in both channels combined. For the determination of the contributions from background processes, a binned likelihood fit to the distributions of two discriminating variables is performed: The missing transverse energy $E_\mathrm{T}^\mathrm{miss}$ and the M3 mass, defined as the invariant mass of the combination of three jets that yields the largest p_T value. The results of the background estimation can be found in table 1; Figure 1 shows the observed distributions of the two variables used for the background estimation and of the sensitive variable $\Delta|y|$ along with the simulated templates normalized to the results obtained by the fit.

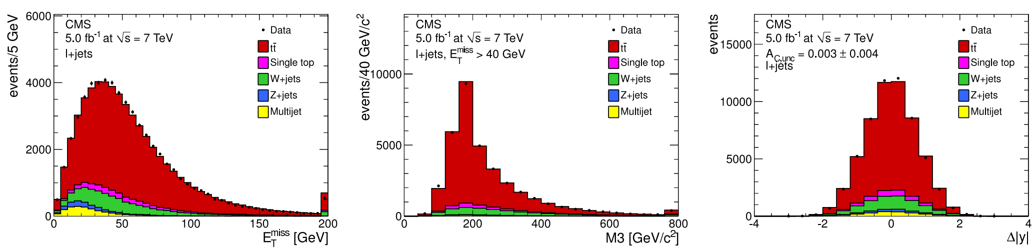

Figure 1: Comparison of the combined lepton+jets data with simulated contributions for the distributions in $E_\mathrm{T}^\mathrm{miss}$(left), M3 (middle), and the sensitive variable $\Delta|y|$ (right). The simulated signal and background contributions are normalized to the results of the fits given in table 1.

Process	Electron+jets	Muon+jets	Total
Single top (t + tW)	1113 ± 338	1418 ± 505	2532 ± 608
W^++jets	1818 ± 227	1807 ± 290	3625 ± 369
W^-+jets	1454 ± 224	1320 ± 275	2773 ± 355
Z+jets	535 ± 153	600 ± 170	1135 ± 229
Multijet	1142 ± 227	863 ± 209	2005 ± 308
Total BG	6062 ± 540	6008 ± 698	12070 ± 882
$\mathrm{t\bar{t}}$	18634 ± 390	26976 ± 468	45610 ± 609
Observed data	24705	32992	57697

Table 1: Results for the different contributions from fits to data, along with their uncertainties.

3. Measurement of the $t\bar{t}$ charge asymmetry

For each selected event the four-momenta of the top quark and antiquark are reconstructed from the observed objects: The leptonically decaying W boson is reconstructed from the observed charged lepton and the missing transverse energy, and the measured jets are associated with the quarks in the $t\bar{t}$ decay chain. The reconstructed top quark and antiquark four-momenta are used to obtain the inclusive and differential distributions of $\Delta|y|$. Before calculating the asymmetry according to equation 1.1, the reconstructed distributions of the sensitive variable $\Delta|y|$ and of the three kinematic variables $y_{t\bar{t}}$, $p_{\mathrm{T}}^{t\bar{t}}$, and $m_{t\bar{t}}$ have to be corrected for background contributions, reconstruction effects, and selection efficiencies. Only then the obtained results can be compared to predictions from theory. After subtracting the background contributions, we apply a regularized unfolding procedure to the data [7] through a generalized matrix-inversion method. In this method, the distorting effects are described by a smearing matrix S that translates the true spectrum $\vec{x}$ into the measured spectrum $\vec{w} = S\vec{x}$. As reconstruction and selection effects factorize, the smearing matrix S can be constructed as the product of a migration matrix and a diagonal matrix with the efficiencies for each of the bins on the diagonal, and all other elements set to zero. Figure 2 shows the migration matrices for the inclusive measurement and for the differential measurement in $m_{t\bar{t}}$, as an example for the three migration matrices for the differential measurements. The migration matrices as well as the selection efficiencies are obtained using samples of simulated $t\bar{t}$ events.

While for the inclusive measurement the migration matrix describes the migration of selected

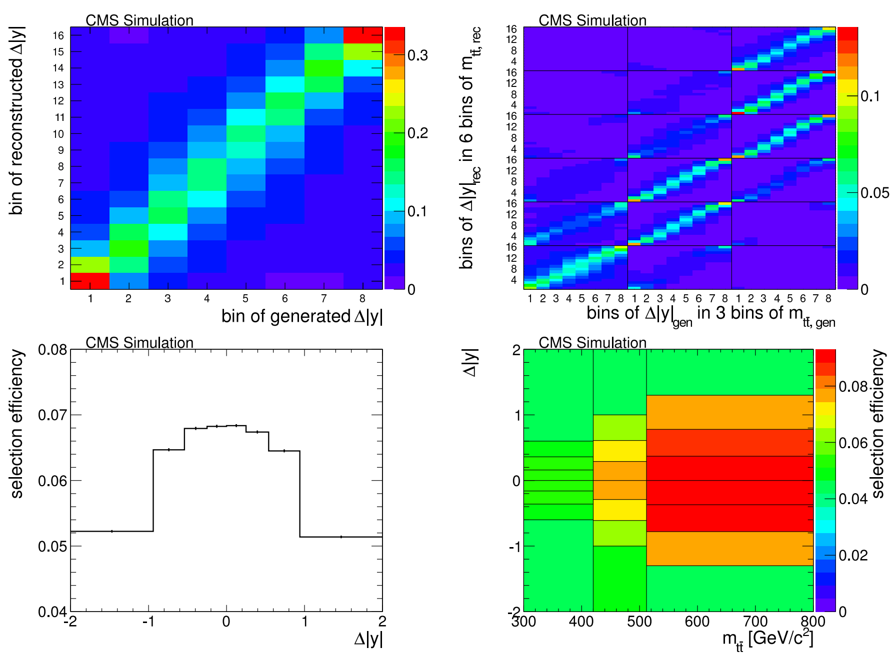

Figure 2: Migration matrix (upper row) between the generated and the reconstructed values after the event selection for $\Delta|y|$ (left) and for the measurement differential in $m_{t\bar{t}}$ (right). Selection efficiency (lower row) as a function of generated $\Delta|y|$, defined with respect to inclusive $t\bar{t}$ production (left) and for the measurement differential in $m_{t\bar{t}}$ (right).

events from true values of $\Delta|y|$ to different reconstructed values, for the migration matrices of the differential measurements not only the migration between bins of $\Delta|y|$ has to be taken into account, but also the migration between bins of the kinematic variable. The selection efficiencies as a function of $\Delta|y|$ for the inclusive measurement and as a function of $\Delta|y|$ and $m_{t\bar{t}}$ for the differential measurement in $m_{t\bar{t}}$ are depicted in Fig. 2.

Systematic uncertainties with an impact on the selection efficiency, on the reconstructed top-quark momenta, or on the background rates can bias the results. To evaluate each source of systematic uncertainty, we repeat the background estimation and the measurement of A_C using modified simulated samples. The expected systematic uncertainty for each source is taken to be the shift in the values of the corrected asymmetry between the default measurement and the one using the modified templates. The systematic uncertainties can be divided into three different categories: experimental sources, uncertainties in the modeling of the signal and background processes, and uncertainties due to the applied unfolding procedure. The total systematic uncertainty for the inclusive measurement amounts to ± 0.011, while for the differential measurements the systematic uncertainties range between ± 0.010 and ± 0.023, depending on the actual bin.

4. Results

The unfolded $\Delta|y|$ distribution (Fig. 3) is used to calculate the corrected inclusive asymmetry:

$$A_C = 0.004 \pm 0.010\ (\text{stat.}) \pm 0.011\ (\text{syst.})\ . \tag{4.1}$$

The results of the three differential measurements can also be found in Fig. 3. The measured values are compared to the SM predictions — based on the calculation of Ref. [4] — and as an illustrative example to the predictions from a BSM model that introduces an anomalous effective axial-vector coupling to the gluon at the one-loop level [8, 9]. Within the uncertainties the data do not show any significant asymmetry and all measured values are consistent with a null asymmetry as well as with the SM predicted values.

5. Conclusion

Although the measured values constitute the most precise determination of the $t\bar{t}$ charge asymmetry at the LHC to date, the current precision does not yet allow distinguishing a zero asymmetry from the values predicted in the standard model or in BSM theories. The reported results nonetheless indicate that LHC data disfavor large deviations from the SM predictions.

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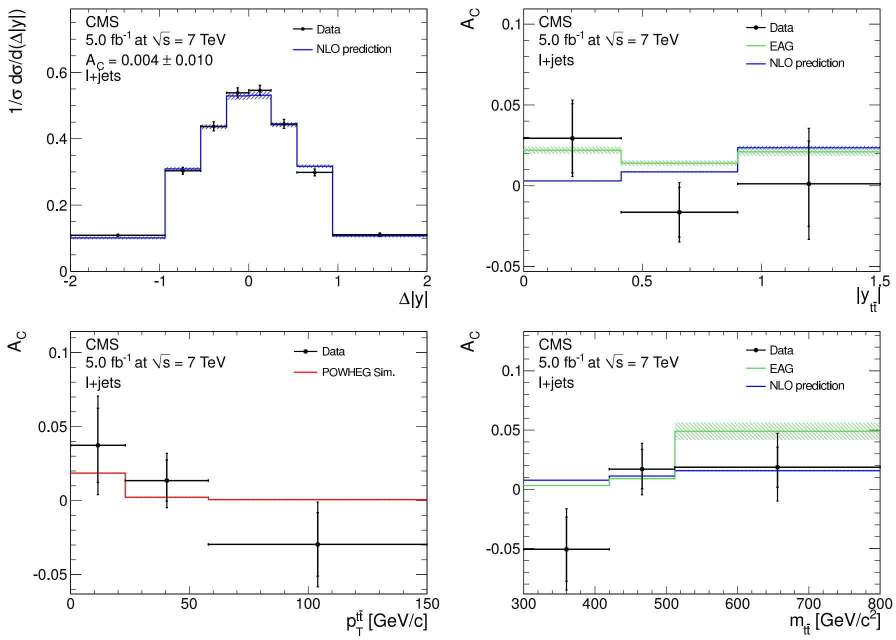

Figure 3: Unfolded inclusive $\Delta|y|$ distribution (upper left), corrected asymmetry as a function of $|y_{t\bar{t}}|$ (upper right), $p_T^{t\bar{t}}$ (lower left), and $m_{t\bar{t}}$ (lower right). The measured values are compared to NLO calculations for the SM — based on the calculations of Ref. [4] — and to the predictions of a model featuring an effective axial-vector coupling of the gluon (EAG) [9]. The error bars on the differential asymmetry values indicate the statistical and total uncertainties, determined by adding statistical and systematic uncertainties in quadrature. The shaded areas indicate the theoretical uncertainties on the NLO calculations.

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