Measurement of the charge asymmetry in top quark pair production at CMS

Frank Roscher for the CMS Collaboration

Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe, Germany

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The $t\bar{t}$ charge asymmetry is measured in the lepton+jets decay channel using a dataset of 19.7fb^{-1} collected with the CMS detector at the LHC. We present an inclusive measurement as well as three differential measurements as functions of rapidity, transverse momentum, and invariant mass of the $t\bar{t}$ system. The measured inclusive $t\bar{t}$ charge asymmetry is 0.005 ± 0.007 (stat.) ± 0.006 (syst.); both this result and the differential measurements are consistent with the predictions of the Standard Model.

1 Introduction

One interesting feature of pairwise top quark production is the difference in the angular distributions of top quarks and top antiquarks. In the pp collisions of the LHC this effect is called $t\bar{t}$ charge asymmetry, and calculations within the Standard Model (SM) predict an effect on the order of one percent.

Measurements of the related forward-backward asymmetry in $p\bar{p}$ collisions presented by the CDF and D0 collaborations [1, 2] show deviations of up to 3σ compared to SM calculations, motivating further investigation by other experiments.

The charge asymmetry occurs only in quark-antiquark initial states. Since at the LHC the quarks in the initial state are mainly valence quarks while the antiquarks are sea quarks, the antiquarks have a lower average momentum fraction; in the case of a positive charge asymmetry this leads to an excess of top quarks produced in the forward directions. The sensitive variable $\Delta|y| = |y_t| - |y_{\bar{t}}|$ is used to measure this effect by defining the charge asymmetry A_C as

$$A_C = \frac{N^+ - N^-}{N^+ + N^-} \ , \tag{1}$$

where N^+ and N^- represent the numbers of events with positive and negative values in the sensitive variable, respectively.

In this analysis we measure the charge asymmetry as a function of the rapidity, the transverse momentum and the invariant mass of the $t\bar{t}$ system. Each of these differentiating variables v_d is motivated differently: The rapidity $|y_{t\bar{t}}|$ allows a suppression of the symmetric production processes, while the transverse momentum $p_T^{t\bar{t}}$ allows to discriminate between the positive and negative SM contributions to the asymmetry. The invariant mass $m_{t\bar{t}}$, finally, yields the highest sensitivity to possible new physics contributions.

2 Event selection and background estimation

We analyse data collected with the CMS detector in proton-proton collisions at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of $19.7\,\mathrm{fb}^{-1}$. The analysis focuses on $\mathrm{t\bar{t}}$ events where one of the W bosons from the decay of a top quark pair subsequently decays into a muon or electron and the corresponding neutrino, while the other W boson decays into a pair of jets. We therefore select events containing exactly one electron or muon and four or more jets, at least one of which is identified as originating from the hadronization of a b quark. The particle-flow (PF) algorithm [3] is used for the reconstruction of the events.

Electron candidates are required to be isolated, to have a transverse energy larger than 30 GeV and to be within $|\eta| < 2.5$. Muon candidates also must be isolated, and they are required to have a transverse momentum larger than $26\,\mathrm{GeV}/c$ and a pseudorapidity of $|\eta| < 2.1$. Jets, finally, have to lie within $|\eta| < 2.5$ and are required to have $p_\mathrm{T} > 30\,\mathrm{GeV}/c$.

For the estimation of the background contributions we make use of the discriminating power of the transverse mass of the W boson m_W^T, and of M3, the invariant mass of that combination of three jets that corresponds to the largest vectorially summed transverse momentum.

Background contributions are estimated in both channels separately by means of binned maximum-likelihood fits to the two discriminating distributions. The m_W^T distribution discriminates between events with and without real W bosons. We separate the data sample into events with $m_\mathrm{W}^\mathrm{T} < 50\,\mathrm{GeV}/c^2$ and $m_\mathrm{W}^\mathrm{T} > 50\,\mathrm{GeV}/c^2$, and simultaneously fit the m_W^T distribution for the low-m_W^T sample and the M3 distribution for the high-m_W^T sample. Single-top-quark and Z+jets production are well understood theoretically and their expected contributions are modest, so their normalizations are constrained to the simulation predictions.

With the exception of QCD multijet production all processes are modelled using simulated events. QCD multijet events instead are modelled using a sideband region in data defined by an inversion of the isolation criterion of the charged lepton.

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

The measurement of the $\mathrm{t\bar{t}}$ charge asymmetry is based on the fully reconstructed four-momenta of t and $\mathrm{\bar{t}}$ in each event. We reconstruct the leptonically decaying W boson from the measured charged lepton and the missing transverse energy $E_\mathrm{T}^\mathrm{miss}$, and associate the measured jets in the event with quarks in the $\mathrm{t\bar{t}}$ decay chain using a likelihood-based approach to find the right association. For a detailed description of the reconstruction procedure see Ref. [4].

With the resulting measured distribution of the sensitive variable the asymmetry can be calculated using Eq. 1. To be able to compare the asymmetry with predictions from theory at generator level, the reconstructed distributions have to be corrected for several effects. These have their origin in background contributions, reconstruction imperfections and selection efficiencies. After a background subtraction has been performed the distributions are translated from the reconstruction level to the particle level after event selection, and from there to the particle level before event selection. These corrections are achieved by applying a regularized unfolding procedure to data [5] through a generalized matrix-inversion method. In this method, the disturbing effects are described by a smearing matrix S that translates the true spectrum $\vec{x}$ into the measured spectrum $\vec{w} = S\vec{x}$. Technical details of this unfolding procedure can be found in Ref. [4].

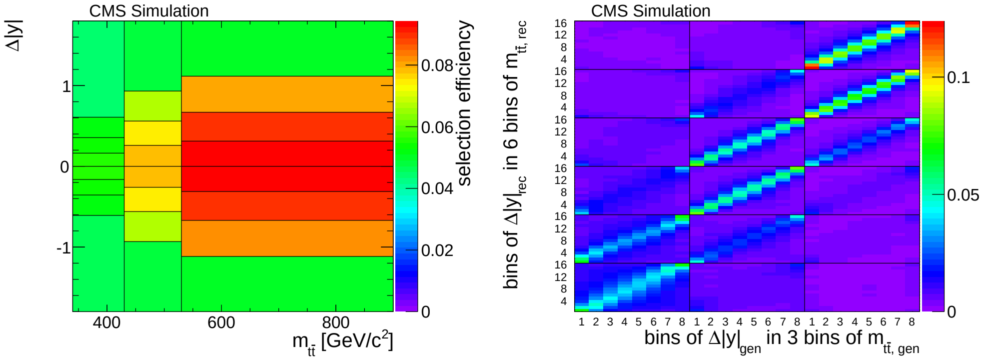

Figure 1: Selection efficiency (left) and migration matrix (right) for the measurement differential in $m_{\mathrm{t\bar{t}}}$.

The number of bins and especially the bin ranges used for $\Delta|y|$ and the differentiating variables v_d have to be chosen with care. To stabilize the unfolding procedure it is desirable that the number of entries in each bin of the reconstructed distributions is approximately equal. Similarly, the spectra of generator values after the selection are flattened to give comparable statistics and thus uncertainties to all bins involved in the migration.

We use separate smearing matrices for the inclusive measurement and the three differential measurements, obtained from simulated $\mathrm{t\bar{t}}$ events. As an example Figure 1 shows the selection efficiency and migration matrix making up the smearing matrix for the differential measurement in $m_{\mathrm{t\bar{t}}}$. In the inclusive measurement the migration matrix simply describes the migration from true values to reconstructed values of $\Delta|y|$; for the migration matrices of the differential measurements migration between bins of the differentiating variable has to be taken into account as well.

The consistency and performance of the unfolding procedure have been verified in a suite of pseudo experiments, each of which tests the unfolding on a sample distribution generated randomly from the templates used in the background estimation.

4 Estimation of systematic uncertainties

Each source of systematic uncertainty is evaluated by repeating the measurement on data using modified simulated samples; the systematic uncertainty for each source is taken to be the maximal observed shift in the values of the unfolded asymmetry. An explanation of the specific methods used to determine the more important uncertainties follows below.

To estimate the uncertainty resulting from possible mismodelling of the $\mathrm{t\bar{t}}$ signal we compare samples of simulated $\mathrm{t\bar{t}}$ events produced with MC@NLO to samples produced with POWHEG, where both are interfaced to HERWIG for the modelling of the parton shower. In a similar way the impact of a possible mismodelling of the parton shower is studied by comparing samples using two different hadronization models, namely the one implemented in PYTHIA and the one implemented in HERWIG. Finally, the impact of variations in the renormalization and factorization scale (Q^2) in the simulated $\mathrm{t\bar{t}}$ events is determined using dedicated samples generated at scales shifted systematically by factors of 2.

Systematic uncertainty	shift in inclusive A_C	range of shifts in differential A_C
JES	0.001	$0.001 - 0.005$
JER	0.001	$0.001 - 0.005$
Pileup	0.001	$0.000 - 0.003$
b tagging	0.000	$0.001 - 0.003$
Lepton ID/sel. efficiency	0.002	$0.001 - 0.003$
Generator	0.003	$0.001 - 0.015$
Hadronization	0.000	$0.000 - 0.016$
p_{T} weighting	0.001	$0.000 - 0.003$
Q^2 scale	0.003	$0.000 - 0.009$
W+jets	0.002	$0.001 - 0.007$
Multijet	0.001	$0.002 - 0.009$
PDF	0.001	$0.001 - 0.003$
Unfolding	0.002	$0.001 - 0.004$
Total	0.006	$0.007 - 0.022$

Table 1: Systematic uncertainties for the inclusive measurement of A_C and ranges of systematic uncertainties for the individual bins of the differential measurements.

In order to estimate the influence of possible mismodelling of the W+jets background the measurement is repeated using a W+jets template from a sideband region in data, defined by an inversion of the b-tag requirement.

We perform a conservative estimation of the uncertainty of the data-driven QCD multijet background by taking the maximum deviation out of three scenarios: Replacing the multijet template with the $\mathrm{t\bar{t}}$ signal template, replacing it with the simulated W+jets template, or inverting the asymmetry of the multijet template itself.

In contrast to the other systematic effects, the uncertainty due to the unfolding method is estimated by performing pseudo experiments. The simulated $\mathrm{t\bar{t}}$ events are reweighted to reproduce the asymmetries observed in the differential measurements on data. The uncertainty of each measurement is estimated as the maximum deviation produced by the unfolding in the three reweighting scenarios corresponding to the three differentiating variables v_d.

5 Results

The result of the inclusive asymmetry measurement is

$$0.005 \pm 0.007\ (\text{stat.})\ \pm 0.006\ (\text{syst.})\,,$$

which can be compared to SM theory predictions of 0.0102 ± 0.0005 [6, 7] and 0.0111 ± 0.0004 [8, 9]. The results of the three differential measurements can be found in Fig. 2, where the measured values are compared to predictions from SM calculations [6, 7, 8, 9] and to predictions from an effective field theory [10, 11, 12]. The latter theory is capable of explaining the CDF results for the forward-backward asymmetry at a new physics scale of about $\Lambda = 1.3\,\mathrm{TeV}$ by introducing an anomalous effective axial-vector coupling to the gluon at the one-loop level.

All measured values are consistent with the predictions of the Standard Model and no hints for deviations due to new physics contributions have been observed. Furthermore, the charge

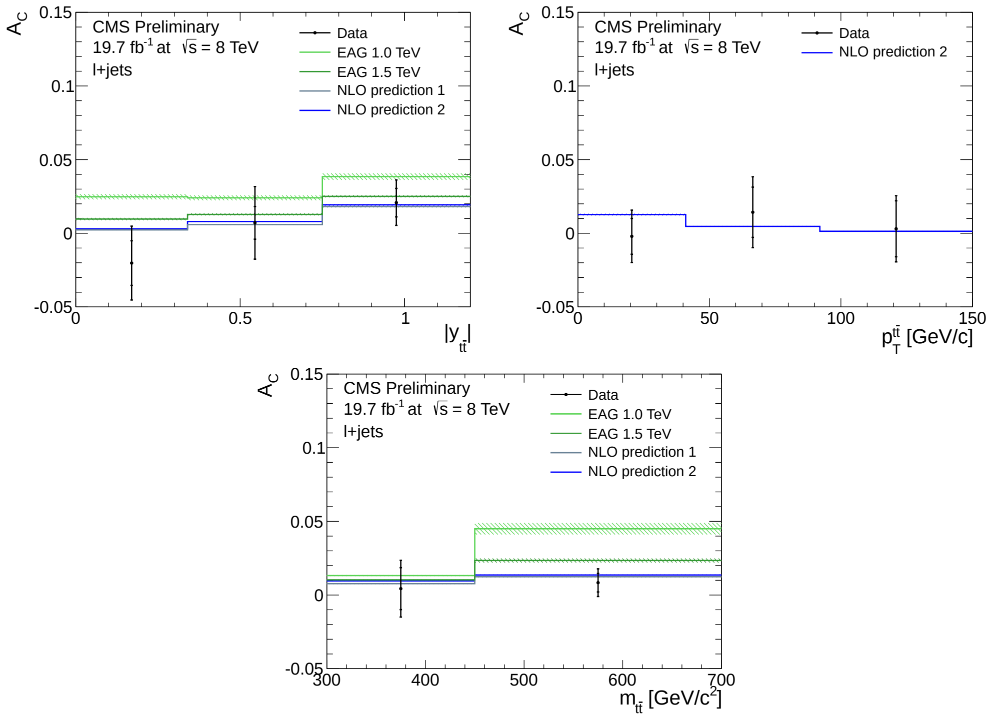

Figure 2: Corrected asymmetry as a function of $|y_{t\bar{t}}|$, $p_{T,t\bar{t}}$, and $m_{t\bar{t}}$. The measured values are compared to NLO calculations for the SM (1: [6, 7], 2: [8, 9]) and to the predictions of a model featuring an effective axial-vector coupling of the gluon (EAG) [10, 11, 12].

asymmetry in the high-mass region is about 1.5 standard deviations below the predictions from the previously mentioned effective field theory with a new physics scale of $\Lambda = 1.5\,\mathrm{TeV}$ and about 3.5 standard deviations below the predictions for $\Lambda = 1.0\,\mathrm{TeV}$.

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