EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

FERMILAB-PUB-16-099-CMS

CERN-EP/2016-059
2016/03/22

CMS-TOP-15-009

Measurements of $\mathrm{t\bar{t}}$ charge asymmetry using dilepton final states in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

The charge asymmetry in $\mathrm{t\bar{t}}$ events is measured using dilepton final states produced in pp collisions at the LHC at $\sqrt{s} = 8\,\mathrm{TeV}$. The data sample, collected with the CMS detector, corresponds to an integrated luminosity of $19.5\,\mathrm{fb}^{-1}$. The measurements are performed using events with two oppositely charged leptons (electrons or muons) and two or more jets, where at least one of the jets is identified as originating from a bottom quark. The charge asymmetry is measured from differences in kinematic distributions, unfolded to the parton level, of positively and negatively charged top quarks and leptons. The $\mathrm{t\bar{t}}$ and leptonic charge asymmetries are found to be $0.011 \pm 0.011\,\text{(stat)} \pm 0.007\,\text{(syst)}$ and $0.003 \pm 0.006\,\text{(stat)} \pm 0.003\,\text{(syst)}$, respectively. These results, as well as charge asymmetry measurements made as a function of $\mathrm{t\bar{t}}$ system kinematic properties, are in agreement with predictions of the standard model.

Submitted to Physics Letters B

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*See Appendix A for the list of collaboration members

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

1 Introduction

The top quark is the heaviest known elementary particle, with mass $m_{\mathrm{t}} = 172.44 \pm 0.48\,\mathrm{GeV}$ as measured by this experiment [1]. Precision measurements of top quark properties have the potential to identify the first hints of new particles, particularly those with stronger couplings to top quarks than to other fundamental particles. The standard model (SM) predicts a charge asymmetry in $\mathrm{t\bar{t}}$ production at hadron colliders through quark-antiquark annihilation. This asymmetry is caused by the interference between the Born and the box diagrams, as well as between the initial- and final-state radiation diagrams, and is predicted by quantum chromodynamics (QCD) calculations at next-to-leading order (NLO) [2, 3]. Early measurements of this asymmetry by the CDF [4] and D0 [5] collaborations exceeded the NLO predictions [2, 3] by about two standard deviations, and the discrepancy was more pronounced in the CDF events with large $\mathrm{t\bar{t}}$ invariant mass ($M_{\mathrm{t\bar{t}}} > 450\,\mathrm{GeV}$). These results have led to considerations that the large asymmetry might be generated by additional axial-vector couplings of the gluon or the presence of heavy particles with unequal vector and axial-vector couplings to top quarks and antiquarks. Recent developments in experimental techniques [6, 7] and theoretical predictions such as the inclusion of electroweak (EW) [8–11] and next-to-next-to-leading-order (NNLO) QCD [12] corrections have largely resolved the disagreement between theory and the Tevatron measurements. Nonetheless, charge asymmetry remains an important probe of new physics.

At the Tevatron, colliding valence quarks from the proton and antiproton beams result in asymmetric rapidity (y) distributions of top quarks and antiquarks. The proton-proton (pp) initial state at the LHC is expected to produce top quark and antiquark rapidity distributions that are symmetric about $y = 0$. However, since the quarks in the initial state can be valence quarks, while the antiquarks are sea quarks, the larger average momentum-fraction of quarks leads to an excess of top quarks produced in the forward directions. The rapidity distribution of top quarks in the SM is therefore broader than that of the more centrally produced top antiquarks, and $\Delta|y| = |y_{\mathrm{t}}| - |y_{\mathrm{\bar{t}}}|$ is a suitable observable to measure the $\mathrm{t\bar{t}}$ charge asymmetry [13], defined in terms of event yields N as

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

While the measurement of A_{C} relies on the reconstruction of the top quark and antiquark directions from complex final states, an advantage of the dilepton final state is that one can alternatively measure the leptonic charge asymmetry defined using only the lepton pseudorapidities [14] $\eta_{\ell^\pm}$ as

$$A_{\mathrm{C}}^{\mathrm{lep}} = \frac{N(\Delta|\eta_\ell| > 0) - N(\Delta|\eta_\ell| < 0)}{N(\Delta|\eta_\ell| > 0) + N(\Delta|\eta_\ell| < 0)},$$

where $\Delta|\eta_\ell| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$. This observable is useful because it is free of any ambiguities associated with the top quark reconstruction, and the correlation between the direction of a top quark and its decay products means an asymmetry in the parent top quark direction induces an asymmetry in the lepton direction. Furthermore, its dependence on the top quark polarization implies that it is not fully correlated with A_{C} and provides complementary information [13]. Previous ATLAS and CMS measurements of A_{C} using data from pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ [15, 16] and $8\,\mathrm{TeV}$ [17–20], and of $A_{\mathrm{C}}^{\mathrm{lep}}$ using the $7\,\mathrm{TeV}$ data samples [21, 22], are consistent with the SM predictions.

In this Letter, measurements are presented of A_{C} and $A_{\mathrm{C}}^{\mathrm{lep}}$ from $\mathrm{t\bar{t}}$ events in the dilepton final states, using CMS data from pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ corresponding to an integrated luminosity of $19.5\,\mathrm{fb}^{-1}$.

The analysis strategy is similar to that presented in Ref. [21] with many improvements, most importantly in the top quark reconstruction and in the unfolding technique. This allows for full differential measurements of A_{C} and $A_{\mathrm{C}}^{\mathrm{lep}}$, which are made as a function of $M_{\mathrm{t\bar{t}}}$ as well as the absolute rapidity and the transverse momentum of the $\mathrm{t\bar{t}}$ system in the laboratory frame ($|y_{\mathrm{t\bar{t}}}|$ and $p_{\mathrm{T}}^{\mathrm{t\bar{t}}}$). The larger data sample used here leads to reduced statistical uncertainties.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [14].

3 Event selection and reconstruction

The event selection for this analysis is identical to that used in Ref. [23] and is only briefly described in this section. The particle-flow (PF) method [24, 25] is used to reconstruct final-state particles. Events are required to have exactly two isolated [23] leptons (electrons [26] or muons [27]) of opposite electric charge, with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.4$. The dilepton pair invariant mass $M_{\ell\ell}$ is required to be above 20 GeV. For same-flavor leptons, $M_{\ell\ell}$ must also not be within 15 GeV of the Z boson mass to suppress the Drell–Yan ($\mathrm{Z}/\gamma^{\star}$+jets) background.

The PF objects are clustered to form jets using the anti-k_{T} clustering algorithm [28] with a distance parameter of 0.5, as implemented in the FASTJET package [29, 30]. The contribution to the jet energy from additional interactions in the same bunch crossing (pileup) is estimated on an event-by-event basis using the jet area method [31], and is subtracted from the overall jet p_{T}. The selected events are required to contain at least two jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$. At least one of these jets must be consistent with containing the decay of a heavy-flavor hadron, as identified using the medium operating point of the combined secondary vertex (CSV) b tagging algorithm [32]. We refer to such jets as b-tagged jets.

The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is defined as the negative vector sum of the p_{T} of all PF objects over the full calorimeter coverage ($|\eta| < 5$). Its magnitude is referred to as $E_{\mathrm{T}}^{\mathrm{miss}}$. The calibrations that are applied to the energy measurements of jets are propagated to a correction of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$. The $E_{\mathrm{T}}^{\mathrm{miss}}$ value is required to exceed 40 GeV in events with same-flavor leptons in order to further suppress the Drell–Yan background. There is no $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement for $\mathrm{e}^{\pm}\mu^{\mp}$ events.

The inclusive measurement of A_{C} and all differential measurements presented here require reconstruction of the $\mathrm{t\bar{t}}$ system. Each signal event has two neutrinos, and there is also a twofold ambiguity in combining the b jets with the leptons. In 62% of the events passing the event selection requirements, only one b-tagged jet is identified. In those events the untagged jet with the highest ranking by the CSV algorithm is assumed to be the second b jet. Solutions for the neutrino momenta are found analytically assuming $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$. Each event can have up to 8 possible solutions, and the one with the maximum weight obtained using the matrix weighting technique [33] is chosen as the most probable. For events with no physical solution, we attempt to find a solution for the sum of neutrino p_{T} as close as possible to the measured $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ [34, 35]. Nonetheless, no solution is found for approximately 16% of the events, both in data and simulation. Events with no solutions are used only in the inclusive measurement of $A_{\mathrm{C}}^{\mathrm{lep}}$, although the results do not significantly change if those events are excluded.

4 Event samples and background estimation

The simulated $\mathrm{t\bar{t}}$ events used in this analysis are generated using the MC@NLO 3.41 [36, 37] Monte Carlo event generator, with $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$ and the CTEQ6M parton distribution functions (PDFs) [38]. The parton showering and fragmentation are performed using HERWIG 6.520 [39]. Simulations with different values of m_{t} and the renormalization and factorization scales (μ_{R} and μ_{F}) are used to evaluate the associated systematic uncertainties. Events with dileptonic $\mathrm{t\bar{t}}$ decays, including tau leptons that decay leptonically, are defined as signal, while all other $\mathrm{t\bar{t}}$ decay modes are treated as background. Background events from the W+jets, Drell–Yan, diboson (WW, WZ, and ZZ), triboson, and $\mathrm{t\bar{t}}$+boson processes are generated with MADGRAPH 5.1.3.30 [40, 41], while single top quark events are generated using POWHEG 1.0 [42–46]. The parton showering and fragmentation are done using PYTHIA 6.4.22 [47], which is also used for an alternative $\mathrm{t\bar{t}}$ event sample generated using POWHEG. Cross sections calculated to NLO or NNLO are used to normalize the background samples [48–56].

For both signal and background events, pileup is simulated with PYTHIA and superimposed on the hard collisions using a pileup multiplicity distribution that reflects the luminosity profile of the analyzed data. The CMS detector response is simulated using a GEANT4-based model [57]. The simulated events are reconstructed and analyzed with the same software used to process the data. The measured trigger efficiencies are used to weight the simulated events to account for the trigger requirement, while the lepton selection efficiencies (reconstruction, identification, and isolation) are consistent between data and simulation [23, 58]. The differences between b tagging efficiencies measured in data and simulation [32] are accounted for using correction factors.

The total contribution from background events to the data sample is expected to be 9%, about half of which comes from single top quark production in association with a W boson (tW), with dileptonic decays. Several control regions (CRs) in data are used to validate and to derive scale factors (SFs) and systematic uncertainties for the background estimates from simulation for tW and Z/γ^{*}+jets production and for events with incorrectly identified leptons. The CRs are selected to have similar kinematic properties to the signal region, but with one or two requirements inverted, thus enriching them in different background contributions [23]. The systematic uncertainties in the SFs are estimated from the envelope of variation in their value using the three dilepton flavor combinations and various CRs. For the tW background we assign a 25% uncertainty based on the recent CMS cross section measurement of $23.4 \pm 5.4\,\mathrm{pb}$ [59].

Other processes, including $\mathrm{t\bar{t}}$ production in association with a boson as well as diboson and triboson production, contribute less than 20% of the total background and are estimated from simulation alone. Recent CMS measurements [60–62] indicate agreement between the predicted and measured cross sections for these processes, and their small yields permit the choice of a conservative systematic uncertainty of 50% with negligible effect on the analysis precision. After subtraction of the predicted background, the remaining yield is assumed to be signal.

5 Unfolding the distributions

The measured distributions are distorted, relative to the true underlying distributions, by the acceptance of the detector, the efficiency of the trigger and event selection, and the finite resolution of the measured kinematic quantities. To correct for these effects, we apply an unfolding procedure that yields the corrected parton-level distributions normalized to unit area. In the context of theoretical calculations and parton shower event generators, the parton-level top quark is defined before it decays and its kinematic properties include the effects of recoil from initial- and final-state radiation in the rest of the event and from final-state radiation from the top quark itself. The parton-level charged lepton, produced from the decay of the intermediate W boson, is defined before the lepton decays or radiates any photons.

We use six bins of varying width in the $\Delta|y_{\mathrm{t}}|$ parton-level distribution that are well matched to the reconstruction resolution and contain approximately equal numbers of events. The $\Delta|\eta_{\ell}|$ distribution depends only on lepton measurements, and the better resolution allows us to use 12 bins. For the reconstruction-level distributions, we use twice as many bins as those used for the parton-level distributions. We employ a regularized unfolding algorithm implemented in the TUNFOLD package [63]. The regularization strength is optimized by minimizing the average global correlation coefficient in the unfolded distribution; the resulting regularization is relatively weak, contributing at the level of 10% to the total χ^2 minimized by the algorithm. We use an analogous unfolding procedure to measure A_{C} and $A_{\mathrm{C}}^{\mathrm{lep}}$ differentially in three bins for each of the $\mathrm{t\bar{t}}$ system kinematic variables $M_{\mathrm{t\bar{t}}}$, $|y_{\mathrm{t\bar{t}}}|$, and $p_{\mathrm{T}}^{\mathrm{t\bar{t}}}$.

6 Systematic uncertainties

Most of the systematic uncertainties concern detector performance and the modeling of the signal and background processes and are estimated from the change in the measurement when varying the simulated event samples used for the unfolding. The uncertainty from the jet energy scale corrections is estimated by varying the jet energies within their uncertainties [64] and propagating this to the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$. Similarly, the jet energy resolution is varied by 2–5%, depending on the η of the jet [64], and the electron energy scale is varied by ±0.6% (±1.5%) for barrel (endcap) electrons, as estimated from comparisons between measured and simulated Z boson events [26]. The uncertainty in muon energies is negligible. The uncertainty in the background subtraction is obtained by varying the normalization of each background component by the corresponding uncertainties.

Many of the signal modeling and simulation uncertainties are evaluated by using weights to vary the MC@NLO $\mathrm{t\bar{t}}$ sample: the simulated pileup multiplicity distribution is changed within its uncertainty; the correction factors between data and simulation for the b tagging efficiency [32], trigger efficiency, and lepton selection efficiency are shifted up and down by their uncertainties; and the PDFs are varied using the PDF4LHC procedure [65, 66]. Previous CMS studies [67, 68] have shown that the p_{T} distribution of the top quark in data is softer than in the NLO simulation of $\mathrm{t\bar{t}}$ production. Since the origin of the discrepancy is not fully understood, the change in the measurement when reweighting the MC@NLO $\mathrm{t\bar{t}}$ sample to match the top quark p_{T} spectrum in data is taken as a systematic uncertainty associated with signal modeling. Further signal modeling uncertainties are evaluated using the dedicated $\mathrm{t\bar{t}}$ samples: μ_{R} and μ_{F} are simultaneously varied up and down by a factor of 2, m_{t} is varied by $\pm 1\,\mathrm{GeV}$, and the $\mathrm{t\bar{t}}$ sample generated with POWHEG and PYTHIA is used to measure the uncertainty in hadronization modeling from the difference between the HERWIG and PYTHIA descriptions. The systematic uncertainty estimates evaluated using dedicated $\mathrm{t\bar{t}}$ samples have a significant statistical uncertainty governed by the number of events in the simulated samples. To avoid underestimation of these uncertainties, the maximum of the estimated systematic uncertainty and the statistical uncertainty in that estimate is taken as the final systematic uncertainty.

Table 1: Systematic uncertainties in the inclusive values of the asymmetries obtained from the unfolded distributions.

Charge asymmetry variable	A_C	A_C^{lep}
Experimental systematic uncertainties		
Jet energy scale	0.001	$<$0.001
Jet energy resolution	0.002	$<$0.001
Lepton energy scale	0.001	$<$0.001
Background	0.001	0.001
Pileup	$<$0.001	$<$0.001
b tagging efficiency	0.001	$<$0.001
Lepton selection	$<$0.001	$<$0.001
$\mathrm{t\bar{t}}$ modeling uncertainties		
Parton distribution functions	0.001	0.001
Top quark p_T	0.001	$<$0.001
Renormalization and factorization scales	0.003	0.002
Top quark mass	0.001	0.001
Hadronization	0.003	$<$0.001
Unfolding (simulation statistical)	0.005	0.002
Unfolding (regularization)	$<$0.001	$<$0.001
Total systematic uncertainty	0.007	0.003

The uncertainty in the unfolding procedure is dominated by the statistical uncertainty arising from the limited number of events in the MC@NLO $\mathrm{t\bar{t}}$ sample. The uncertainty from the regularization is found to be small in comparison. The systematic uncertainties in the inclusive asymmetry values obtained from the unfolded distributions are summarized in Table 1. The individual terms are added in quadrature to estimate the total systematic uncertainties. For both A_C and A_C^{lep}, the dominant systematic uncertainty is from the limited number of simulated events used for the unfolding.

7 Results

The unfolded normalized differential cross sections for the selected data events are shown in Fig. 1, along with the parton-level predictions for $\mathrm{t\bar{t}}$ production obtained from calculations at NLO in the SM gauge couplings (QCD+EW) [11] and with the MC@NLO generator (which does not include EW corrections). The corresponding asymmetry values are presented in Table 2. Correlations between the contents of different bins, introduced by the unfolding process and from the systematic uncertainties, are accounted for in the calculation of the uncertainties. The measured values are consistent with the expectations from the SM. The asymmetry values as a function of $M_{\mathrm{t\bar{t}}}$, $|y_{\mathrm{t\bar{t}}}|$, and $p_T^{\mathrm{t\bar{t}}}$ are also measured. The results, which are shown in Fig. 2, are consistent with the MC@NLO simulation predictions, as well as with the NLO (QCD+EW) calculations for the $M_{\mathrm{t\bar{t}}}$ and $|y_{\mathrm{t\bar{t}}}|$ dependencies. No comparison is made with NLO calculations for the $p_T^{\mathrm{t\bar{t}}}$ dependencies as it is expected that the effect of the parton shower process on the $p_T^{\mathrm{t\bar{t}}}$ distribution makes fixed-order calculations an inadequate approximation of the data.

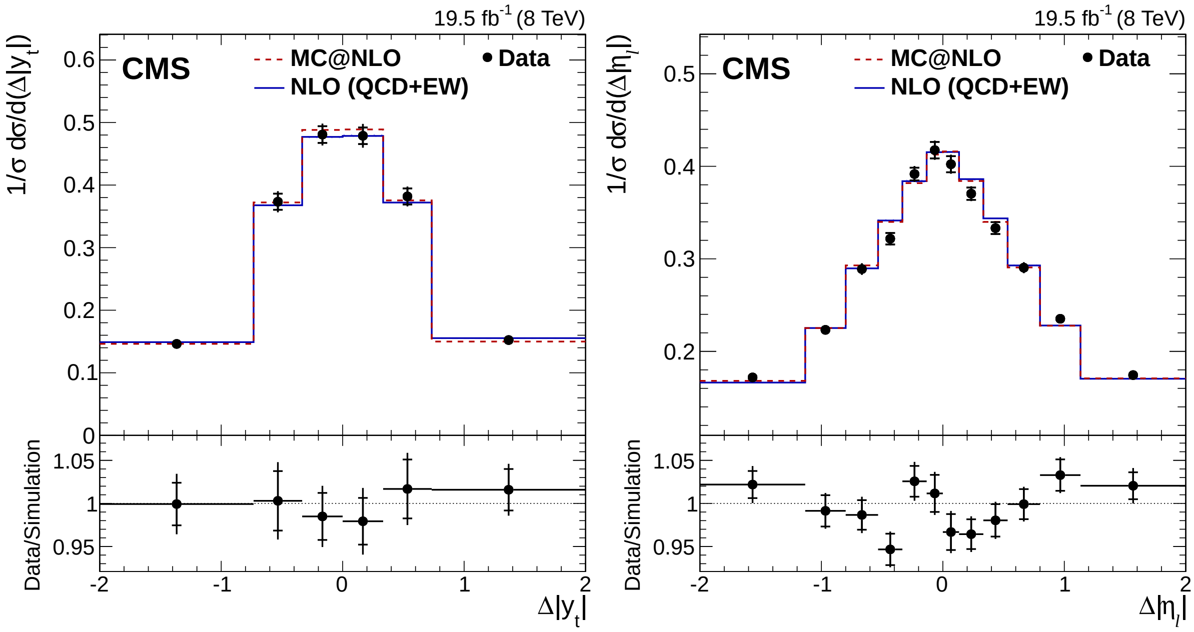

Figure 1: Background-subtracted and unfolded distributions of $\Delta|y_t|$ (left) and $\Delta|\eta_\ell|$ (right) from data (points), normalized to unit area. Parton-level predictions from the MC@NLO simulation and calculations at NLO (QCD+EW) [11] are shown by dashed and solid histograms, respectively. The ratio of the measured bin values to the MC@NLO prediction is shown in the bottom panel. The vertical bars show the total uncertainty, the statistical component of which is marked by a horizonal tick. The first and last bins of each plot include underflow and overflow events, respectively.

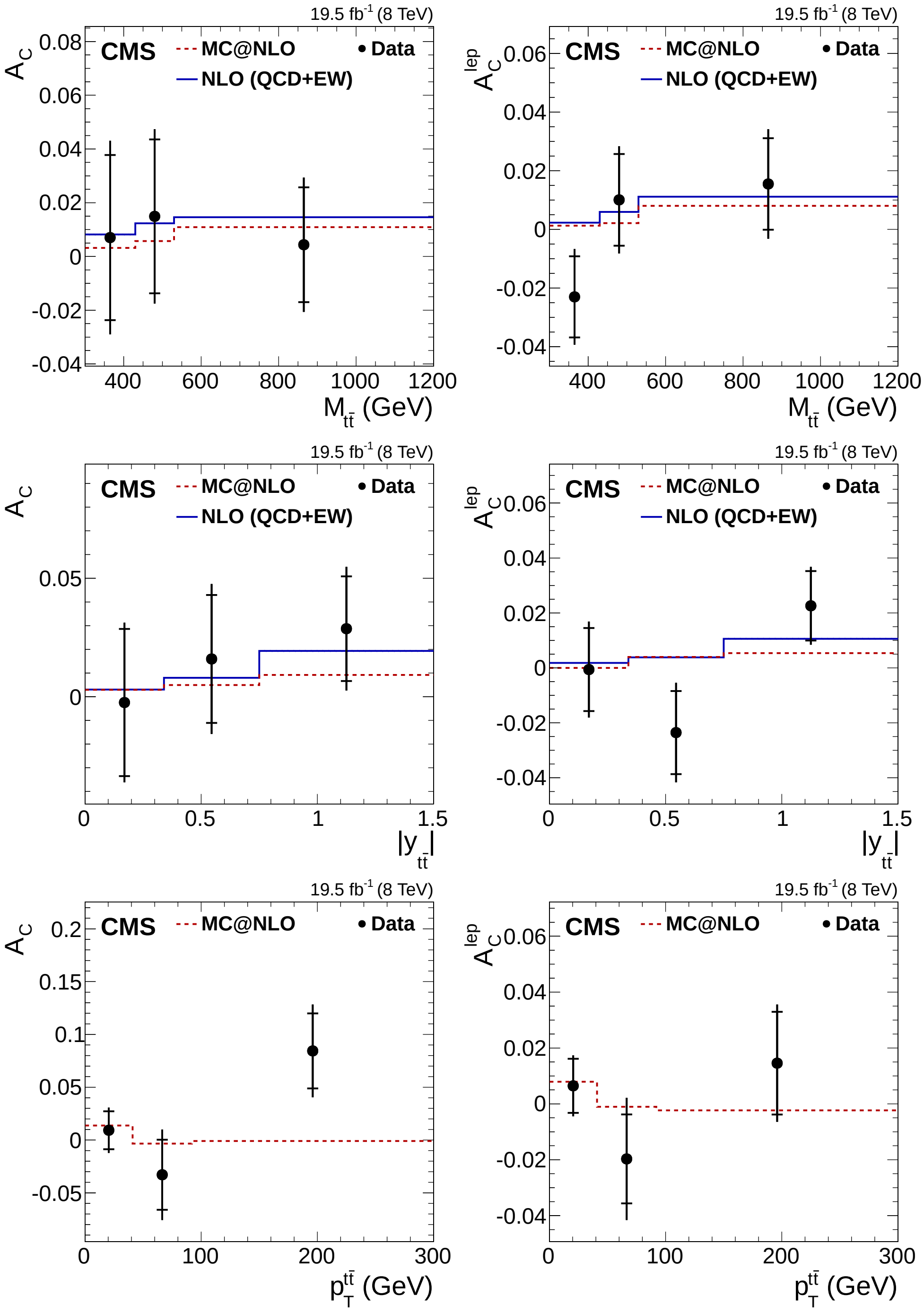

Figure 2: Dependence of the charge asymmetries A_C (left) and A_C^{lep} (right) obtained from the unfolded distributions in data (points) on $M_{t\bar{t}}$ (upper), $|y_{t\bar{t}}|$ (middle), and $p_T^{t\bar{t}}$ (lower). Parton-level predictions from the MC@NLO simulation and calculations at NLO (QCD+EW) [11] are shown by dashed and solid histograms, respectively. The vertical bars show the total uncertainty, the statistical component of which is marked by a horizonal tick. The last bin of each plot includes overflow events.

Table 2: The inclusive asymmetry measurements obtained from the unfolded distributions and the parton-level predictions from the MC@NLO simulation and calculations at NLO (QCD+EW) [11]. For the data, the first uncertainty is statistical and the second is systematic. The uncertainties in the MC@NLO results are statistical and the uncertainties in the NLO calculations come from varying together μ_R and μ_F up and down by a factor of two.

Variable	Data	MC@NLO	NLO (QCD+EW)
A_C	$0.011 \pm 0.011 \pm 0.007$	0.006 ± 0.001	0.0111 ± 0.0004
A_C^{lep}	$0.003 \pm 0.006 \pm 0.003$	0.004 ± 0.001	0.0064 ± 0.0003

8 Summary

Measurements are presented of the charge asymmetry in $\mathrm{t\bar{t}}$ dilepton final states from distributions, unfolded to the parton level, of the absolute rapidity (pseudorapidity) difference of top quarks (leptons) with positive and negative charge. The data sample corresponds to an integrated luminosity of $19.5\,\mathrm{fb}^{-1}$ from pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$, collected by the CMS experiment at the LHC. The $\mathrm{t\bar{t}}$ and leptonic charge asymmetries are found to be, respectively, $0.011 \pm 0.011\,(\text{stat}) \pm 0.007\,(\text{syst})$ and $0.003 \pm 0.006\,(\text{stat}) \pm 0.003\,(\text{syst})$ when measured inclusively. The charge asymmetries are also measured as a function of the invariant mass, absolute rapidity, and transverse momentum of the $\mathrm{t\bar{t}}$ system in the laboratory frame. All measurements are in agreement with the standard model predictions, and can help constrain new theories [13].

Acknowledgements

We would like to thank W. Bernreuther and Z.-G. Si for calculating the theoretical distributions shown in this paper. We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for

Polish Science, cofinanced from European Union, Regional Development Fund; the OPUS programme of the National Science Center (Poland); the Compagnia di San Paolo (Torino); MIUR project 20108T4XTM (Italy); the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

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