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Measurement of the charge asymmetry in highly boosted top-quark pair production in $\sqrt{s} = 8$ TeV pp collision data collected by the ATLAS experiment

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ABSTRACT

In the $pp \to t\bar{t}$ process the angular distributions of top and anti-top quarks are expected to present a subtle difference, which could be enhanced by processes not included in the Standard Model. This Letter presents a measurement of the charge asymmetry in events where the top-quark pair is produced with a large invariant mass. The analysis is performed on 20.3 fb^{-1} of pp collision data at $\sqrt{s} = 8$ TeV collected by the ATLAS experiment at the LHC, using reconstruction techniques specifically designed for the decay topology of highly boosted top quarks. The charge asymmetry in a fiducial region with large invariant mass of the top-quark pair ($m_{t\bar{t}} > 0.75$ TeV) and an absolute rapidity difference of the top and anti-top quark candidates within $-2 < |y_t| - |y_{\bar{t}}| < 2$ is measured to be $4.2 \pm 3.2\%$, in agreement with the Standard Model prediction at next-to-leading order. A differential measurement in three $t\bar{t}$ mass bins is also presented.

1. Introduction

The charge asymmetry [1,2] in top-quark pair production at hadron colliders constitutes one of the more interesting developments in the last decade of top-quark physics. In the Standard Model (SM), a forward–backward asymmetry (A_{FB}), of order α_s, is expected at a proton–antiproton ($p\bar{p}$) collider such as the Tevatron, with a much enhanced asymmetry in certain kinematical regions. Early measurements [3,4] found a larger A_{FB} than predicted by the SM. Later determinations confirmed this deviation and measurements in intervals of the invariant mass, $m_{t\bar{t}}$, of the system formed by the top-quark pair [5–9] found a stronger dependence on $m_{t\bar{t}}$ than anticipated. Recent calculations of electroweak effects [10] and the full next-to-next-to-leading-order (NNLO) corrections [11] to the asymmetry have brought the difference between the observed asymmetry at the Tevatron and the SM prediction down to the 1.5 σ level and reduced the tension with the differential measurements in $m_{t\bar{t}}$ [12,13].

At the Large Hadron Collider (LHC), the forward–backward asymmetry is not present due to the symmetric initial state, but a related charge asymmetry, A_C, is expected in the distribution of the difference of absolute rapidities of the top and anti-top quarks,

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}, \tag{1}$$

where $\Delta|y| = |y_t| - |y_{\bar{t}}|$ and y denotes the rapidity of the top and anti-top quarks.[1] For quark–antiquark ($q\bar{q}$) initial states, the difference in the average momentum carried by valence and sea quarks leads to a positive asymmetry. These quark-initiated processes are strongly diluted by the charge-symmetric gluon-initiated processes, yielding a SM expectation for the charge asymmetry of less than 1%. Many beyond-the-Standard-Model (BSM) scenarios predict an alteration to this asymmetry. Previous measurements at 7 TeV [14–17] and 8 TeV [18–20] by ATLAS and CMS are consistent with the SM prediction.

With a centre-of-mass energy of 8 TeV and a top-quark pair sample of millions of events, the LHC experiments can access the charge asymmetry in a kinematic regime not probed by previous experiments. The development of new techniques involving Lorentz-boosted objects and jet substructure [21–24] and their use in the analysis of LHC data [25,26] have enabled an efficient se-

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis coinciding with the axis of the beam pipe. The x-axis points from the IP towards the centre of the LHC ring, and the y-axis points upward. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The rapidity y is given as $y = -\frac{1}{2}\ln[(E + p_z)/(E - p_z)]$, while the pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln[\tan(\theta/2)]$. The distance in (η, ϕ) coordinates, $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, is used to define cone sizes and the distance between reconstructed objects. Transverse momentum and energy are defined as $p_T = p\sin\theta$ and $E_T = E\sin\theta$, respectively.

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lection of highly boosted objects and an accurate reconstruction of their momentum.

This Letter presents a measurement of the rapidity-dependent charge asymmetry in top-quark pair production that is based on techniques specifically designed to deal with the collimated decay topology of boosted top quarks. Specifically, it is based on the techniques described in Refs. [27–30]. The analysis focuses on the lepton + jets (ℓ + jets) final state, where the hadronic top-quark decay is reconstructed as a single large-radius (large-R) jet and tagged as such using jet substructure variables. The leptonic top-quark decay is reconstructed from a single small-radius (small-R) jet, a single charged lepton (muon or electron), and missing transverse momentum, corresponding to the neutrino from the W boson decay. The event selection and reconstruction follow the prescriptions of Ref. [27], where a detailed description and discussion of their performance can be found.

Compared to previous analyses [18,20] based on the classical, *resolved* top-quark selection criteria and reconstruction schemes, this approach offers a more precise reconstruction of the $t\bar{t}$ invariant mass and top-quark direction for highly boosted top quarks. It is therefore possible to perform accurate measurements of the charge asymmetry in events with a $t\bar{t}$ invariant mass in the TeV range. This kinematic regime has a higher sensitivity for the SM asymmetry due to a higher fraction of quark-initiated processes, as well as for BSM models that introduce massive new states.

This Letter is structured as follows. The data sample analysed is presented in Section 2, along with a description of the Monte Carlo (MC) simulation samples in Section 3. A brief overview of the reconstructed object definitions and of the event selection and reconstruction is given in Sections 4 and 5. The observed yields and several kinematic distributions are compared to the SM expectations in Section 6. The unfolding technique used to correct the reconstructed $\Delta|y|$ spectrum to the parton level is discussed in Section 7. The estimates of the systematic uncertainties that affect the measurement are described and estimated in Section 8. The results are presented in Section 9, and their impact on several BSM theories is discussed in Section 10. Finally, the conclusions are presented in Section 11.

2. Data sample

The data for this analysis were collected by the ATLAS [31] experiment in the 8 TeV proton–proton (pp) collisions at the CERN LHC in 2012. Collision events are selected using isolated or non-isolated single-lepton triggers, where the isolated triggers have a threshold of 24 GeV on the transverse momentum (p_{T}) of muons or on the transverse energy of electrons. The non-isolated triggers have higher thresholds: 60 GeV for electrons and 36 GeV for muons. The contribution from events with leptons passing only the non-isolated triggers but having p_{T} below these higher thresholds is negligible. The collected data set is limited to periods with stable beam conditions when all sub-systems were operational. The sample corresponds to an integrated luminosity of 20.3 ± 0.6 fb^{-1}.

3. Monte Carlo simulation

Samples of MC simulated events are used to characterise the detector response and efficiency to reconstruct $t\bar{t}$ events, estimate systematic uncertainties, and predict the background contributions from various physics processes. The response of the detector and trigger is simulated [32] using a detailed model implemented in GEANT4 [33]. Simulated events are reconstructed with the same software as the data. Additional pp interactions, simultaneously present in the detector (pile-up), are generated using Pythia 8.1 [34] with the MSTW2008 leading order PDF set [35] and the AUET2 set of tune parameters (tune). The pile-up events are reweighted to the number of interactions per bunch crossing in data (on average 21 in 2012). For some samples used to evaluate systematic uncertainties, the detailed description of the calorimeter response is parameterised using the ATLFAST-II simulation [32]. For all samples the top-quark mass is set to $m_{\mathrm{top}} = 172.5$ GeV.

The nominal signal $t\bar{t}$ sample is produced using the Powheg-Box (version 1, r2330) generator [36], which is based on next-to-leading-order (NLO) QCD matrix elements. The CT10 [37] set of parton distribution functions (PDF) is used. The h_{damp} parameter, which controls the matrix element (ME) to parton shower (PS) matching in Powheg-Box and effectively regulates the high-p_{T} radiation, is set to the top-quark mass. The parton shower, hadronisation, and the underlying event are simulated with Pythia 6.427 [38] using the CTEQ6L1 PDF set and the Perugia 2011 [39] tune. Electroweak corrections are applied to this sample through a reweighting scheme; they are calculated with Hathor 2.1-alpha [40] implementing the theoretical calculations of Refs. [41–43]. Alternative samples are used to evaluate uncertainties in modelling the $t\bar{t}$ signal. These include samples produced with MC@NLO 4.01 [44] interfaced with Herwig 6.520 [45] and Jimmy 4.31 [46], as well as samples generated with Powheg-Box + Herwig/Jimmy and Powheg-Box + Pythia, both with h_{damp} = infinity. Samples are also produced with differing initial- and final-state radiation (ISR/FSR), using the AcerMC generator [47] interfaced with Pythia. All $t\bar{t}$ samples are normalised to cross-section at NNLO + next-to-next-to-leading logarithmic (NNLL) accuracy[2] [49–54]: $\sigma_{t\bar{t}} = 253^{+13}_{-15}$ pb.

Leptonic decays of vector bosons produced in association with several high-p_{T} jets, referred to as W + jets and Z + jets events, with up to five additional final-state partons in the leading-order (LO) matrix-elements, are produced with the Alpgen generator [55] interfaced with Pythia 6.426 for parton fragmentation using the MLM matching scheme [56]. Heavy-flavour quarks are included in the ME calculations to model the $Wb\bar{b}$, $Wc\bar{c}$, Wc, $Zb\bar{b}$ and $Zc\bar{c}$ processes. The W + jets samples are normalised to the inclusive W boson NNLO cross-section [57,58].

Single top-quark production is simulated using Powheg-Box interfaced with Pythia 6.425 using the CTEQ6L1 PDF set and the Perugia 2011 tune. The cross-sections multiplied by the sum of the branching ratios for the leptonic W decay employed for these processes are 28 pb (t-channel) [59], 22 pb (Wt production) [60], and 1.8 pb (s-channel) [61], obtained from NNLO + NNLL calculations.

Diboson production is modelled using Sherpa [62] with the CT10 PDF set, and the yields are normalised to the NLO cross-sections: 23 pb ($WW \to \ell\nu qq$), 0.7 pb ($ZZ \to \ell\ell qq$), 6.0 pb ($WZ \to \ell\nu qq$) and 4.6 pb ($ZW \to \ell\ell qq$).

4. Object definitions

Electron candidates are reconstructed using charged-particle tracks in the inner detector associated with energy deposits in the electromagnetic calorimeter. Muon candidates are identified by matching track segments in the muon spectrometer with tracks in the inner detector. Lepton candidates are required to be isolated using the “mini-isolation” criteria described in Ref. [63].

Jets are reconstructed using the anti-k_t algorithm [64] implemented in the FastJet package [65] with radius parameter $R = 0.4$ (small-R) or $R = 1.0$ (large-R), using as input calibrated topological clusters [66] of energy deposits in the calorimeters. The jet-trimming algorithm [67] is applied to the large-R jets to reduce

[2] The top++2.0 [48] calculation includes the NNLO QCD corrections and resums NNLL soft gluon terms. The quoted cross-section corresponds to a top-quark mass of 172.5 GeV.

the effect of soft and diffuse radiation, such as that from pile-up, multiple parton interactions and initial-state radiation. Large-R jets are trimmed by reclustering the constituents with the k_t algorithm [68,69] with a radius parameter $R_{\text{sub}} = 0.3$ and retaining sub-jets that have a momentum exceeding 5% of that of the large-R jet ($f_{\text{cut}} = 0.05$). For small-R jets, a pile-up correction based on the jet area, the number of primary vertices, the bunch spacing, and jet η is applied. Both jet collections are calibrated to the stable-particle level as a function of p_{T} and η (and mass for large-R jets) [25]. The stable-particle level refers to generator-level jets reconstructed from particles with a lifetime of at least 10 ps. Small-R jets are b-tagged using an algorithm that exploits the relatively large decay time of b-hadrons and their large mass [70,71].

The missing transverse momentum (with magnitude $E_{\text{T}}^{\text{miss}}$) is computed as the negative vector sum of the energy of all calorimeter cells, taking into account the calibration of reconstructed objects, and the presence of muons.

5. Event selection and reconstruction

Each event must have a reconstructed primary vertex with five or more associated tracks of $p_{\text{T}} > 400$ MeV. The events are required to contain exactly one reconstructed lepton candidate, which must then be geometrically matched to the trigger object. To reduce the multi-jet background, the magnitude of the missing transverse momentum and the W-boson transverse mass m_{T}^{W} must satisfy $E_{\text{T}}^{\text{miss}} > 20$ GeV and $E_{\text{T}}^{\text{miss}} + m_{\text{T}}^{W} > 60$ GeV, where

$$m_{\text{T}}^{W} = \sqrt{2 p_{\text{T}}^{\text{lepton}} E_{\text{T}}^{\text{miss}} (1 - \cos \Delta\phi)} \quad (2)$$

and $\Delta\phi$ is the azimuthal angle between the lepton and the missing transverse momentum. At least one small-R jet ($R = 0.4$) must be found close to, but not coincident with, the lepton ($\Delta R(\ell, \text{jet}_{R=0.4}) < 1.5$).

The leptonic top-quark candidate is reconstructed by adding the highest-p_{T} jet among those satisfying the above criteria, the selected charged lepton and the reconstructed neutrino. The longitudinal component of the neutrino momentum is calculated by constraining the lepton-plus-missing-momentum system to have the W boson mass and solving the resulting quadratic equation. If two real solutions are found, the one that yields the smallest longitudinal momentum for the neutrino is used. If no real solution exists, the missing transverse momentum vector is varied by the minimal amount required to produce exactly one real solution.

The hadronically decaying top quark is reconstructed as a single trimmed jet with $R = 1.0$. The selected jet must have $p_{\text{T}} > 300$ GeV, must be well separated from both the charged lepton ($\Delta\phi(\ell, \text{jet}_{R=1.0}) > 2.3$) and the small-$R$ jet associated with the leptonic top-quark candidate ($\Delta R(\text{jet}_{R=1.0}, \text{jet}_{R=0.4}) > 1.5$). A substructure analysis of the large-R jet is used to tag the boosted top-quark candidate: the invariant mass of the jet $m_{\text{jet}}^{\text{trim}}$ after calibration to the particle level [26] must be larger than 100 GeV and the k_t splitting scale[3] $\sqrt{d_{12}^{\text{trim}}}$ must exceed 40 GeV.

Finally, at least one of the highest-p_{T} small-R jets associated with the decay of a top-quark candidates ($\Delta R(\ell, \text{jet}_{R=0.4}) < 1.5$ or $\Delta R(\text{jet}_{R=1.0}, \text{jet}_{R=0.4}) < 1.0$) must be b-tagged. Events with a reconstructed $t\bar{t}$ mass of less than 750 GeV are rejected, as the performance of the reconstruction of boosted top quarks is strongly degraded at low mass.

The selection and reconstruction schemes yield good efficiency and $t\bar{t}$ mass determination for high-mass pairs. Detailed MC studies presented in Ref. [27] show that the mass resolution is approximately 6% for a large range of $t\bar{t}$ mass, starting at $m_{t\bar{t}} \sim 1$ TeV. The measurement of the top and anti-top-quark rapidities are nearly unambiguous. The quality of the top quark rapidity reconstruction can be expressed in terms of the dilution factor $D = 2p - 1$, where p is the probability of a correct assignment of the $\Delta|y|$ sign. A dilution factor $D = 1$ indicates perfect charge assignment. The MC simulation predicts a value of approximately $D = 0.75$ for the selected sample. The remaining dilution is largely due to events with small values of the absolute rapidity difference; if events with $|\Delta|y|| < 0.5$ are excluded, the MC simulation predicts a dilution factor greater than 0.9.

Table 1
Observed and expected number of events in the signal region. The two columns correspond to the e + jets and μ + jets selected data samples. The systematic uncertainties of the SM expectation include those from detector-related uncertainties, uncertainties in the normalisation, the luminosity uncertainty and the uncertainty in the cross-section predictions used to normalise the expected yields.

	e + jets	μ + jets
$t\bar{t}$	4100 ± 600	3600 ± 500
W + jets	263 ± 32	264 ± 32
Single top	140 ± 20	138 ± 19
Multi-jet	44 ± 8	4 ± 1
Z + jets	40 ± 27	16 ± 11
Dibosons	20 ± 7	18 ± 7
$t\bar{t}V$	37 ± 19	33 ± 17
Prediction	4600 ± 600	4100 ± 500
Data	4141	3600

6. Comparison of data to the SM template

A template for the expected yield of most SM processes is based on Monte Carlo simulation, where the production rate is normalised using the prediction of the inclusive cross-section specified in Section 3. Exceptions are the W + jets background and the multi-jet background. The W + jets background normalisation and heavy-flavour fractions are corrected with scale factors derived from data, as in Ref. [27], using the observed asymmetry in the yields of positively and negatively charged leptons. The multi-jet background estimate is fully data-driven, using the matrix method. This method uses the selection efficiencies of leptons from prompt and non-prompt sources to predict the number of events with non-prompt leptons in the signal region. These methods and their results are documented in detail in Ref. [27].

The event yields are compared to the SM expectation in Table 1. The distributions of two key observables, the invariant mass of the $t\bar{t}$ system and the difference of the absolute rapidities of the candidate top and anti-top quarks are shown in Fig. 1, for the combination of the e + jets and μ + jets channels. The observed event yield is approximately 10% less than the MC prediction, the result of the softer top-quark p_{T} spectrum in data, which is also reported in Refs. [73–75].

Since A_{C} is measured as a ratio, it is not sensitive to the absolute cross-section. The impact of the differences in the expected and observed shapes of the distributions in Fig. 1 on the measurement is estimated by reweighting the simulated $\Delta|y|$ and top quark p_{T} distributions to match the data and found to be negligible.

[3] The k_t splitting scale [72] is obtained by reclustering the large-R jet components with the k_t algorithm with a radius parameter $R = 0.3$. The first splitting scale $\sqrt{d_{12}^{\text{trim}}}$ corresponds to the scale at which the last two sub-jets are merged into one: $\sqrt{d_{12}^{\text{trim}}} = \min(p_{\text{T},1}, p_{\text{T},2}) \times \Delta R_{1,2}$, where 1 and 2 denote the two sub-jets merged in the last step of the k_t algorithm.

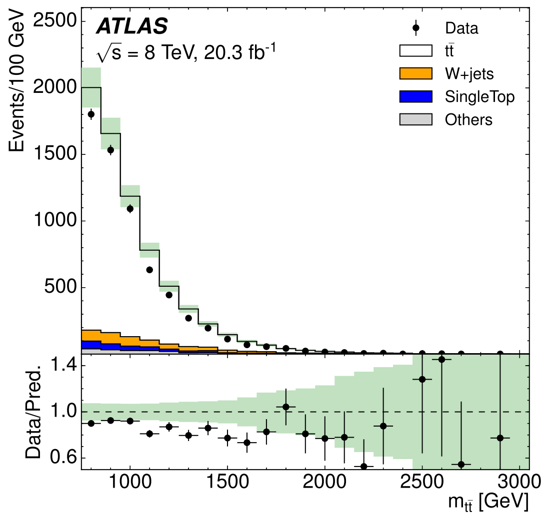


Fig. 1. Detector-level distributions of (a) the invariant mass of the $t\bar{t}$ system and (b) the difference of the absolute rapidities $\Delta|y|$ of top and anti-top-quark candidates, for the combination of the $e+$jets and $\mu+$jets channels. The observed distributions are compared to the SM expectation based on a mixture of data-driven techniques and Monte Carlo simulation. The ratio of data to the SM expectation is shown in the lower plots. Error bars on the data points indicate the statistical uncertainty. The hashed area shows the uncertainty of the SM prediction. This includes the statistical uncertainty, the theory uncertainties in the cross-sections, the effect of detector systematic uncertainties on the expected yield, the luminosity uncertainty, the uncertainty in the normalisations, and the signal modelling uncertainty.

7. Unfolding

An unfolding procedure transforms the observed charge asymmetry into a parton-level result in the phase space covered by the measurement:

$$m_{t\bar{t}} > 750\,\text{GeV},\ -2 < \Delta|y| < 2. \qquad (3)$$

The corrected result can thus be compared directly to fixed-order calculations that implement these constraints.

The unfolding procedure is identical to the one used in a previous ATLAS charge asymmetry measurement [20]. The $e+$jets and $\mu+$jets channels are combined to form a single set of events. The data are corrected for migrations due to detector resolution using a matrix unfolding method based on the open source PyFBU implementation of the fully Bayesian unfolding (FBU) [76] algorithm. A bias in the charge asymmetry introduced by the selection criteria is corrected using a bin-by-bin acceptance correction.

The asymmetry in the full region of Eq. (3) is obtained by correcting the content of four $\Delta|y|$ bins with the following boundaries: $[-2, -0.7, 0, 0.7, 2]$. For simulated events with a reconstructed $\Delta|y|$ that falls within $-2 < \Delta|y| < 2$, but a true $\Delta|y|$ outside this boundary (0.1% of events), the true value is included in the outermost $\Delta|y|$ bin. A differential result in three $m_{t\bar{t}}$ intervals (0.75 TeV $< m_{t\bar{t}} <$ 0.9 TeV, 0.9 TeV $< m_{t\bar{t}} <$ 1.3 TeV, and 1.3 TeV $< m_{t\bar{t}}$) is obtained using a $(1+12)\times 12$ matrix that corrects for mass and $\Delta|y|$ migrations. The extra *underflow* bin keeps track of migrations of selected events from outside of the fiducial volume, $m_{t\bar{t}} <$ 0.75 TeV. The $\Delta|y|$ binning in each mass bin is optimised to yield minimal bias when non-SM asymmetries are injected.

Uncertainties due to limitations in the understanding of object reconstruction and in the calibration of the experiment described in Section 8 are included as nuisance parameters in the unfolding procedure, as well as the normalisation of the backgrounds. In this study, the data sample is too small for FBU to significantly constrain any of the nuisance parameters, and therefore the size of the detector-related and normalisation uncertainties are not reduced by the unfolding process.

8. Systematic uncertainties

Systematic uncertainties are estimated as in Ref. [27] and propagated to the A_C measurement following the procedure of Ref. [20]. The non-negligible uncertainties in the unfolded charge asymmetry measurement are presented in Table 2.

The most important uncertainties among the detector-related and background normalisation uncertainties are the scale and resolution of the jet energy (17 nuisance parameters for large-R jets and 21 for small-R jets) and the b-tagging performance (10 nuisance parameters) [66,77,78]. The impact of uncertainties in the reconstruction of electrons and muons and the missing transverse momentum is negligible. Detector-related uncertainties and background normalisation uncertainties have a small impact on the analysis.

The uncertainty due to imperfections in the MC generator modelling is estimated using a number of alternative generators. The most important effects are the choice of NLO ME and parton shower/hadronisation model. Each alternative sample is unfolded using the nominal procedure. The ME modelling uncertainty is taken as the difference between the results for Powheg-Box + Herwig/Jimmy and MC@NLO + Herwig/Jimmy. The PS/hadronisation modelling uncertainty is evaluated as the difference between Powheg-Box + Pythia and Powheg-Box + Herwig/Jimmy. The results are corrected for the small differences in the prediction of the true A_C among the generators. The ISR/FSR uncertainty is estimated as half the difference between two AcerMC samples with radiation settings varied within the range allowed by data. The uncertainty associated with the choice of PDF is evaluated using the MC@NLO + Herwig/Jimmy sample, by comparing the differences when reweighting the sample to CT10, MSTW 2008 [35], and NNPDF2.1 [79] PDF sets. The three contributions are assumed to be uncorrelated and are added in quadrature, forming the dominant systematic uncertainty in the measurement.

The unfolding uncertainty includes two components. The first component, the uncertainty due to the limited number of events in the Monte Carlo samples used to correct the data, is estimated by propagating the statistical uncertainty of the elements of the

Table 2
The effect on the corrected charge asymmetry, in each $m_{t\bar{t}}$ interval, of systematic uncertainties on the signal and background modelling and the description of the detector response. The uncertainties are given in absolute percentages.

$m_{t\bar{t}}$ interval	>0.75 TeV	0.75–0.9 TeV	0.9–1.3 TeV	>1.3 TeV
Breakdown of detector-related systematic uncertainties				
Jet energy and resolution – $R = 0.4$ jets	0.1%	0.4%	0.3%	0.4%
Jet energy and resolution – $R = 1.0$ jets	0.3%	1.6%	0.6%	1.0%
b-tag/mis-tag efficiency	0.2%	0.2%	0.2%	0.7%
Lepton reconstruction/identification/scale	0.1%	0.2%	0.1%	0.1%
Missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$)	0.1%	<0.1%	<0.1%	0.1%
Background normalization	0.1%	0.2%	0.3%	0.4%
Combined detector-related uncertainties and others				
Statistical + detector-related systematic	2.0%	6.0%	4.1%	11.6%
Signal modelling – matrix element	1.5%	2.4%	0.6%	5.3%
Signal modelling – parton shower	2.0%	3.2%	1.2%	6.2%
Signal modelling – ISR/FSR	0.1%	0.3%	0.1%	3.0%
Signal modelling – PDF	0.4%	0.4%	0.3%	3.3%
Unfolding & MC statistics	0.5%	1.2%	0.8%	2.1%
Total	3.2%	7.3%	4.4%	15.0%

response matrix with pseudo-experiments. To evaluate the second component due to the non-linearity of the unfolding, different charge asymmetry values are injected by reweighting the $t\bar{t}$ Monte Carlo sample according to several functional forms. The uncertainty is taken as the bias estimated for the observed charge asymmetry values. A number of stress tests are performed, where the MC samples are reweighted to mimic the observed differences in the $m_{t\bar{t}}$ and $\Delta|y|$ distributions. The impact on the results of the unfolding procedure is found to be small compared to the unfolding uncertainty and is not taken into account as a separate uncertainty. In addition, the measurement is performed in a more restricted $|\Delta|y||$ region, excluding events with $|\Delta|y|| < 0.5$, where the dilution factor D is smaller. The result is found to be consistent with the nominal measurement, and no uncertainty is assigned.

9. Results

The results for the charge asymmetry in the four $m_{t\bar{t}}$ intervals are presented in Fig. 2 and Table 3. The measurement for $m_{t\bar{t}} > 0.75$ TeV and $|\Delta|y|| < 2$ yields $A_{\mathrm{C}} = (4.2 \pm 3.2)\%$, where the uncertainty is dominated by the modelling uncertainty, followed by the statistical uncertainty of the data. The result is within one standard deviation of the SM expectation. A differential measurement is also presented, in three $m_{t\bar{t}}$ bins: 0.75–0.9 TeV, 0.9–1.3 TeV and $m_{t\bar{t}} > 1.3$ TeV ($|\Delta|y|| < 2$ for all measurements). The largest difference with respect to the SM prediction is observed in the bin with $m_{t\bar{t}} = 0.9$–1.3 TeV, where it reaches 1.6σ.

10. Impact on BSM scenarios

Extensions of the SM with heavy particles can predict a significantly enhanced high-mass charge asymmetry at the LHC. In Fig. 3, BSM predictions of the charge asymmetry in 8 TeV pp collisions with $m_{t\bar{t}} > 0.75$ TeV and $m_{t\bar{t}} > 1.3$ TeV are compared with A_{FB} integrated over $m_{t\bar{t}}$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The measurements presented in this Letter are indicated as horizontal bands. The measurements of A_{FB} integrated over $m_{t\bar{t}}$ in top-quark

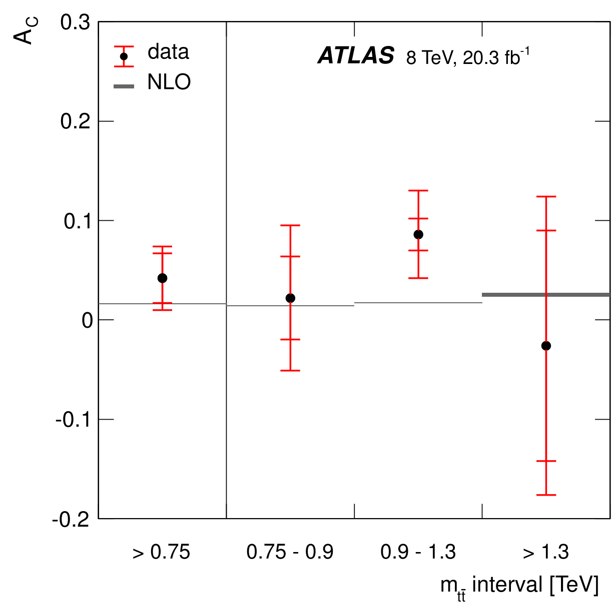


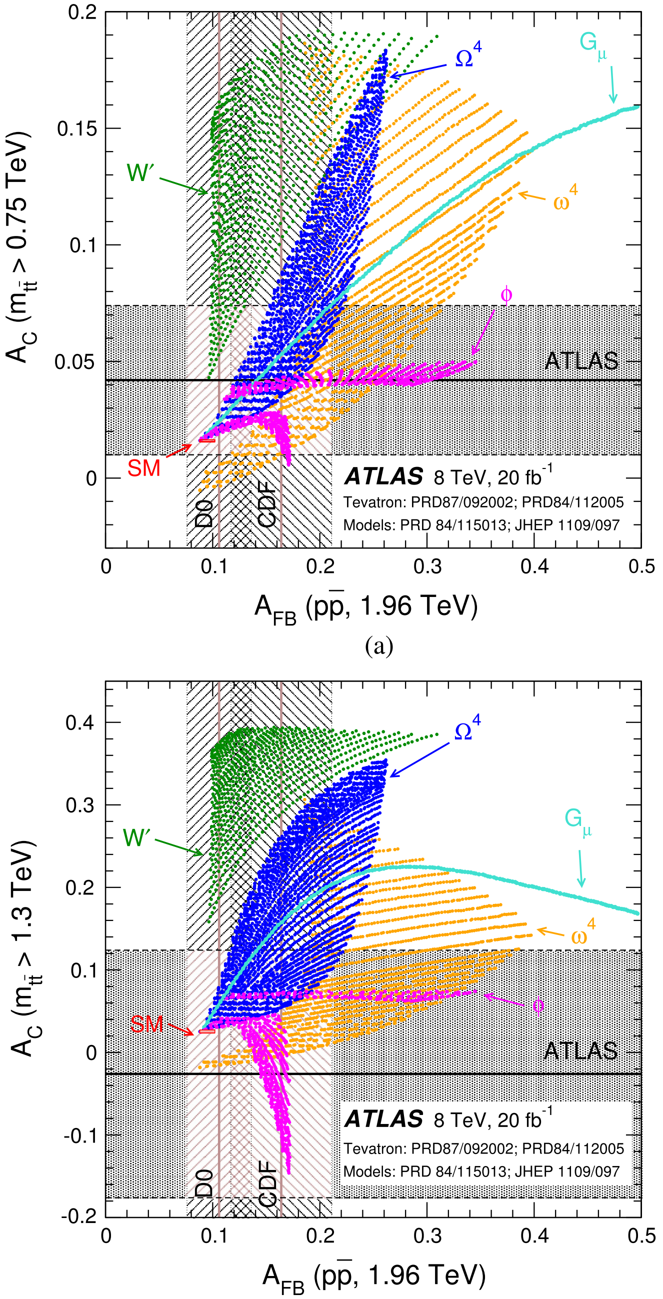
Fig. 2. A summary of the charge asymmetry measurements. The error bars on the data indicate the modelling and unfolding systematic uncertainties, shown as the inner bar, and the total uncertainty, which includes the statistical uncertainty and the experimental systematic uncertainties. The SM prediction of the NLO calculation in Ref. [13] for the charge asymmetry of top-quark pairs with $|\Delta|y|| < 2$ is indicated as a shaded horizontal bar in each $m_{t\bar{t}}$ bin, where the width of the bar indicates the uncertainty.

pair production at 1.96 TeV in $p\bar{p}$ collisions by CDF [7] and D0 [8] are shown as vertical bands.

The clouds of points in Fig. 3 correspond to a number of models in Refs. [80,81]: a heavy W' boson exchanged in the t-channel, a heavy axi-gluon G_{μ} exchanged in the s-channel, and doublet (ϕ), triplet (ω^4) or sextet (Ω^4) scalars. Each point corresponds to a choice of the new particle's mass, in the range between 100 GeV and 10 TeV, and of the couplings to SM particles, where all values

Table 3
The measured charge asymmetry after the unfolding to parton level in four intervals of the invariant mass of the $t\bar{t}$ system. The result is compared to the SM prediction using the NLO calculation in Ref. [13]. The phase space is limited to $|(\Delta|y|)| < 2$. The uncertainties correspond to the sum in quadrature of statistical and systematic uncertainties (for the data) or to the theory uncertainty (for the SM prediction).

$m_{t\bar{t}}$ interval	>0.75 TeV	0.75–0.9 TeV	0.9–1.3 TeV	>1.3 TeV
Measurement	(4.2 ± 3.2)%	(2.2 ± 7.3)%	(8.6 ± 4.4)%	(−2.9 ± 15.0)%
SM prediction	(1.60 ± 0.04)%	(1.42 ± 0.04)%	(1.75 ± 0.05)%	(2.55 ± 0.18)%



(b)

Fig. 3. Predictions from a number of extensions of the SM from Refs. [80,81], for the forward–backward asymmetry integrated over $m_{t\bar{t}}$ at the Tevatron (on the x-axis in both plots) and two high-mass charge asymmetry measurements at the LHC. The y-axis in both figures represents the measurement for (a) $m_{t\bar{t}} > 0.75$ TeV and for (b) $m_{t\bar{t}} > 1.3$ TeV. The SM predictions of both the forward–backward asymmetry at the Tevatron and the charge asymmetry at the LHC are also shown [11,82].

allowed give a total cross-section for top-quark pair production at the Tevatron compatible with observations and a high-mass $t\bar{t}$ production cross-section ($m_{t\bar{t}} > 1$ TeV) at the LHC that is at most three times the SM prediction. The contribution from new physics to the Tevatron A_{FB} is moreover required to be positive. The predictions of the Tevatron forward–backward asymmetry and the LHC high-mass charge asymmetry are calculated using PROTOS [83], which includes the tree-level SM amplitude plus the one(s) from the new particle(s), taking into account the interference between the two contributions. This measurement extends the reach of previous ATLAS and CMS measurements to beyond 1 TeV (adding a bin with $m_{t\bar{t}} = 0.9$–1.3 TeV). The BSM sensitivity of this measurement is also complementary to that of the most recently published ATLAS measurement [20] and can be seen to disfavour the t-channel W' boson model in the highest $m_{t\bar{t}}$ bin.

11. Conclusions

The charge asymmetry in the rapidity distribution of top-quark pairs produced at large $t\bar{t}$ invariant mass has been measured in a sample of $\sqrt{s} = 8$ TeV pp collisions corresponding to an integrated luminosity of 20.3 fb^{-1}, collected with the ATLAS experiment at the LHC in 2012. The selection criteria and the reconstruction algorithm designed for $\ell +$ jets events with the decay topology of highly boosted top quarks are found to give good control over the sign of the absolute rapidity difference of top and anti-top quarks, with a dilution factor that reaches 0.75, significantly higher than more traditional methods.

The observed asymmetry is corrected to the fiducial space $m_{t\bar{t}} > 0.75$ TeV and $-2 < \Delta|y| < 2$. The result, $A_{\mathrm{C}} = (4.2 \pm 3.2)\%$, is less than one standard deviation from the SM prediction of $1.60 \pm 0.04\%$. The charge asymmetry is also determined in three $t\bar{t}$ mass intervals. The most significant deviation from the SM prediction, 1.6σ, is observed in the mass bin that ranges from 0.9 TeV to 1.3 TeV: $A_{\mathrm{C}} = (8.6 \pm 4.4)\%$. The other two mass bins yield values compatible with the SM prediction within 1σ. These measurements provide a constraint on extensions of the SM, some of which predict a very sizeable charge asymmetry at large $t\bar{t}$ mass.

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Chomont [35], S. Chouridou [9], B.K.B. Chow [101], V. Christodoulou [80], D. Chromek-Burckhart [31], J. Chudoba [128], A.J. Chuinard [89], J.J. Chwastowski [40], L. Chytka [116], G. Ciapetti [133a,133b], A.K. Ciftci [4a], D. Cinca [54], V. Cindro [77], I.A. Cioara [22], A. Ciocio [15], F. Cirotto [105a,105b], Z.H. Citron [171], M. Ciubancan [27b], A. Clark [50], B.L. Clark [58], P.J. Clark [47], R.N. Clarke [15], C. Clement [147a,147b], Y. Coadou [87], M. Cobal [163a,163c], A. Coccaro [50], J. Cochran [65], L. Coffey [24], L. Colasurdo [107], B. Cole [36], S. Cole [109], A.P. Colijn [108], J. Collot [56], T. Colombo [31], G. Compostella [102], P. Conde Muiño [127a,127b], E. Coniavitis [49], S.H. Connell [146b], I.A. Connelly [79], V. Consorti [49], S. Constantinescu [27b], C. Conta [122a,122b], G. Conti [31], F. Conventi [105a,k], M. Cooke [15], B.D. Cooper [80], A.M. Cooper-Sarkar [121], T. Cornelissen [174], M. Corradi [133a,133b], F. Corriveau [89,l], A. Corso-Radu [66], A. 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