Measurement of the top quark pair production charge asymmetry in proton–proton collisions at √s = 7 TeV using the ATLAS detector

The ATLAS Collaboration

Abstract

This paper presents a measurement of the top quark pair (tt) production charge asymmetry AC using 4.7 fb⁻¹ of proton–proton collisions at a centre–of–mass energy √s = 7 TeV collected by the ATLAS detector at the LHC. A tt-enriched sample of events with a single lepton (electron or muon), missing transverse momentum and at least four high transverse momentum jets, of which at least one is tagged as coming from a b–quark, is selected. A likelihood fit is used to reconstruct the tt event kinematics. A Bayesian unfolding procedure is employed to estimate AC at the parton–level. The measured value of the tt production charge asymmetry is AC = 0.006 ± 0.010, where the uncertainty includes both the statistical and the systematic components. Differential AC measurements as a function of the invariant mass, the rapidity and the transverse momentum of the tt–system are also presented. In addition, AC is measured for a subset of events with large tt velocity, where physics beyond the Standard Model could contribute. All measurements are consistent with the Standard Model predictions.
Measurement of the top quark pair production charge asymmetry in proton–proton collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector

The ATLAS Collaboration

*CERN, 1211 Geneva 23, Switzerland

E-mail: atlas.publications@cern.ch

ABSTRACT: This paper presents a measurement of the top quark pair ($t\bar{t}$) production charge asymmetry $A_C$ using 4.7 fb$^{-1}$ of proton–proton collisions at a centre–of–mass energy $\sqrt{s} = 7$ TeV collected by the ATLAS detector at the LHC. A $t\bar{t}$-enriched sample of events with a single lepton (electron or muon), missing transverse momentum and at least four high transverse momentum jets, of which at least one is tagged as coming from a $b$–quark, is selected. A likelihood fit is used to reconstruct the $t\bar{t}$ event kinematics. A Bayesian unfolding procedure is employed to estimate $A_C$ at the parton–level. The measured value of the $t\bar{t}$ production charge asymmetry is $A_C = 0.006 \pm 0.010$, where the uncertainty includes both the statistical and the systematic components. Differential $A_C$ measurements as a function of the invariant mass, the rapidity and the transverse momentum of the $t\bar{t}$–system are also presented. In addition, $A_C$ is measured for a subset of events with large $t\bar{t}$ velocity, where physics beyond the Standard Model could contribute. All measurements are consistent with the Standard Model predictions.

KEYWORDS: Top physics, Top charge asymmetry

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1 Introduction

The measurement of the $t\bar{t}$ production charge asymmetry represents an important test of quantum chromodynamics (QCD) at high energies and is also an ideal place to observe effects of possible new physics processes beyond the Standard Model (BSM). Several BSM processes can alter this asymmetry [1–13], either with anomalous vector or axial–vector couplings (i.e. axigluons) or via interference with the Standard Model (SM). Different models also predict different asymmetries as a function of the invariant mass $m_{t\bar{t}}$ [14], the transverse momentum $p_{T,t\bar{t}}$ and the rapidity $|y_{t\bar{t}}|$ of the $t\bar{t}$-system.

At leading order (LO), $t\bar{t}$ production at hadron colliders is predicted to be symmetric under the exchange of top quark and antiquark. At next–to–leading order (NLO), the process $q\bar{q} \to t\bar{t}g$ exhibits an asymmetry in the rapidity distributions of the top quark and antiquark, due to interference between initial– and final–state gluon emission. In addition, the $q\bar{q} \to t\bar{t}$ process itself possesses an asymmetry due to the interference between the Born and the NLO diagrams. The $qq$ production process is also asymmetric, but its contribution is much smaller than the $q\bar{q}$ one. The production of $t\bar{t}$ events by gluon fusion, $gg \to t\bar{t}$, is symmetric. At the Tevatron proton–antiproton collider, where $t\bar{t}$ events are predominantly produced by $q\bar{q}$ annihilation, top quarks are preferentially emitted in the direction of the incoming quark while the top antiquarks are emitted preferentially in the direction of the incoming antiquark [15–21]. The $t\bar{t}$ asymmetry at the Tevatron is therefore measured as a forward–backward asymmetry,

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)},$$

where $\Delta y \equiv y_t - y_{\bar{t}}$ is the difference in rapidity between top quarks and antiquarks, and $N$ represents the number of events with $\Delta y$ being positive or negative. The interest in this measurement has grown after CDF and D0 collaborations reported $A_{FB}$ measurements significantly larger than the SM predictions, in both the inclusive and differential case as a function of $m_{t\bar{t}}$ and $|y_{t\bar{t}}|$ [22–26].

In proton–proton ($pp$) collisions at the LHC, the dominant mechanism for $t\bar{t}$ production is the $gg$ fusion process, while production via $q\bar{q}$ or $qq$ interactions is small. Since the colliding beams are symmetric, $A_{FB}$ is no longer a useful observable. However, $t\bar{t}$ production via $q\bar{q}$ or $qq$ processes is asymmetric under top quark–antiquark exchange, and, in addition, the valence quarks carry, on average, a larger momentum fraction than antiquarks from the sea. Hence for $q\bar{q}$ or $qq$ production processes at the LHC, QCD predicts a small excess of centrally produced top antiquarks while top quarks are produced, on average, at higher absolute rapidities. Therefore, the $t\bar{t}$ production charge asymmetry $A_C$ is defined as [1, 27]

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

where $\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$ is the difference between the absolute value of the top quark rapidity $|y_t|$ and the absolute value of the top antiquark rapidity $|y_{\bar{t}}|$. The SM prediction for the $t\bar{t}$ production charge asymmetry at the LHC is $A_C^{SM} = 0.0123 \pm 0.0005$ [21], computed at NLO in QCD including electroweak corrections. Recent
asymmetry measurements at the LHC [28–30] did not report any significant deviation from the SM predictions in either the inclusive or differential $A_C$ measurements. Agreement with the SM $A_C$ predictions at the LHC is compatible with the larger than expected $A_{FB}$ values measured at the Tevatron for the most general new physics scenarios [31], but creates a tension between the measurements at the two colliders in specific simple models [8]. This motivates the interest in a more precise measurement of the $t\bar{t}$ production charge asymmetry.

In this paper, a measurement of the $t\bar{t}$ production charge asymmetry in the single–lepton final state is reported. To allow comparisons with theory calculations, a Bayesian unfolding procedure is applied to account for distortions due to acceptance and detector effects, leading to parton–level $A_C$ measurements. Compared with the previous $t\bar{t}$ production charge asymmetry measurement performed by the ATLAS experiment and described in ref. [30], the full 2011 data sample is now used and new differential $A_C$ measurements are performed. In particular, an inclusive $A_C$ measurement and measurements of $A_C$ as a function of $m_{t\bar{t}}$, $p_{T,t\bar{t}}$ and $|y_{t\bar{t}}|$ are presented. The inclusive $A_C$ result and the differential result as a function of $m_{t\bar{t}}$ are also presented with the additional requirement of a minimum velocity $\beta_{z,t\bar{t}}$ of the $t\bar{t}$–system along the beam axis to enhance the sensitivity to BSM effects [32].

2 Data sample, simulated samples and event selection

2.1 Samples

The measurement is performed using 7 TeV $pp$ collisions recorded by the ATLAS detector [33] at the LHC during 2011. The ATLAS detector is composed of inner tracking detectors immersed in a 2 T axial magnetic field provided by a solenoid, surrounded by calorimeters and, as an outer layer, by a muon spectrometer in a magnetic field provided by three large air-core toroid magnet systems. After applying detector and data–quality requirements, the recorded data corresponds to an integrated luminosity of 4.7 fb$^{-1}$ [34].

Simulated $t\bar{t}$ events are modelled using the LO multi–parton matrix–element Monte Carlo (MC) generator ALPGEN [35] with the LO CTEQ6L1 [36] parton distribution function (PDF) for the proton. Parton showering and the underlying event are modelled using HERWIG [37] and JIMMY [38] with the AUET2 parameter settings [39]. The $t\bar{t}$ sample is generated assuming a top quark mass of 172.5 GeV and it is normalised to a total inclusive cross–section of 177$^{+10}_{-11}$ pb computed at next–to–next–to–leading–order (NNLO) in QCD including resummation of next–to–next–to–leading–logarithmic (NNLL) soft gluon terms with Top++2.0 [40–45]. The uncertainties included in the calculation are those related to the choice of the PDF set (following the PDF4LHC prescriptions [46]),

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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 along the beam pipe. The $x$–axis points from the IP to the centre of the LHC ring, and the $y$–axis points upward. Cylindrical coordinates $(r,\phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. Transverse momentum and energy are defined as $p_T = p \sin \theta$ and $E_T = E \sin \theta$, respectively.
the variations of $\alpha_S$ and the choice of renormalisation and factorisation scales. These uncertainties are added in quadrature to give the quoted overall uncertainty.

Single–top events are generated using ACERMC [47] for the $t$–channel and MC@NLO for the $Wt$– and $s$– channels. The production of $W$ and $Z$ bosons in association with jets is simulated using the ALPGEN generator interfaced to HERWIG and JIMMY. Simulated $W$+jets events are reweighted using the NLO PDF set CT10. Pairs of $W/Z$ bosons ($WW$, $WZ$, $ZZ$) are produced using HERWIG.

All simulated samples are generated with multiple $pp$ interactions per bunch crossing (event pile–up). Up to 24 interactions per bunch crossing were observed during the data taking period. The number of interaction vertices in simulated samples is adjusted so that its distribution reproduces the one observed in data. The samples are then processed through the GEANT4 [48] simulation [49] of the ATLAS detector and the same reconstruction software used for data.

2.2 Event selection

Candidate events with the $t\bar{t}$ single–lepton signature are considered. These events are characterised by exactly one high–$p_T$ isolated lepton (electron, muon or tau decaying to electron or muon), missing transverse momentum $E_T^{\text{miss}}$ due to the neutrino from the leptonic $W$ decay, two jets originating from $b$–quarks and two jets originating from light quarks from the hadronic $W$ decay.

Events are required to pass the single–electron or single–muon trigger, with thresholds in transverse energy ($E_T$) at 20 GeV or 22 GeV for electrons (depending on instantaneous luminosity conditions during the different data collection periods) and in transverse momentum ($p_T$) at 18 GeV for muons. Electron candidates are required to have $E_T > 25$ GeV and $|\eta_{\text{cluster}}| < 2.47$, where $\eta_{\text{cluster}}$ is the pseudorapidity of the electromagnetic energy cluster in the calorimeter. Candidates in the transition region $1.37 < |\eta_{\text{cluster}}| < 1.52$ between calorimeter sections are excluded. Muon candidates are required to have $p_T > 20$ GeV and $|\eta| < 2.5$. Electrons and muons are required to be isolated to reduce the backgrounds from hadrons mimicking lepton signatures and heavy–flavour decays inside jets. For electrons, stringent cuts both on the shape of the calorimetric energy deposits and on the tracks used to compute the isolation, in order to reject the tracks related to photon conversions, are applied. Cuts that depend on $\eta$ and $E_T$ leading to a 90% efficiency are used in a cone of $\Delta R = 0.2$ for the energy isolation and in a cone of $\Delta R = 0.3$ for the track isolation around the electron candidate. For muons, the sum of track transverse momenta in a cone of $\Delta R = 0.3$ around the muon is required to be less than 2.5 GeV, while the total energy deposited in a cone of $\Delta R = 0.2$ around the muon is required to be less than 4 GeV.

Jets are reconstructed from topologically connected calorimetric energy clusters using the anti–$k_t$ algorithm [50] with a radius parameter $R = 0.4$. They are first calibrated to the electromagnetic energy scale and then corrected to the hadronic energy scale using energy– and $\eta$–dependent correction factors obtained from simulation and control data analyses [51]. The compatibility of the jets with the primary vertex (defined as the vertex with the highest sum of the square of the transverse momenta of the tracks associated to it) is determined using the tracks associated with the jet (jet vertex fraction). Jets
originating from the hadronisation of $b$–quarks are identified by combining the information from three $b$–tagging algorithms, based on the topology of $b$– and $c$–hadron weak decays inside jets [52] and on the transverse and longitudinal impact parameter significance of each track within the jet [53]. These three tagging algorithms are combined into a single discriminating variable used to make the tagging decision. The operating point chosen corresponds to a 70% tagging efficiency for $b$–quarks. The rejection rate is about 150 for light–quark jets, 5 for charm jets and 14 for hadronically decaying $\tau$ leptons. All these numbers are evaluated in simulated $t\bar{t}$ events.

The missing transverse momentum is reconstructed from clusters of energy deposits in the calorimeters calibrated at the electromagnetic scale and corrected according to the energy scale of the associated physics object. Contributions from muons are included using their momentum measured by the inner tracking and muon spectrometer systems.

Jets within $\Delta R \equiv \sqrt{\Delta \eta^2 + (\Delta \phi)^2} = 0.2$ of an electron candidate are removed to avoid double counting electrons as jets. Subsequently, electrons and muons within $\Delta R = 0.4$ of a jet axis and with $p_T > 20$ GeV are removed in order to reduce the contamination caused by leptons from hadron decays.

In the muon channel, events are required to satisfy $E_T^{\text{miss}} > 20$ GeV and $E_T^{\text{miss}} + m_T(W) > 60$ GeV in order to suppress the multi–jets background. In the electron channel, the multi–jets contamination is larger, and more stringent cuts of $E_T^{\text{miss}} > 30$ GeV and $m_T(W) > 30$ GeV are applied.

Finally, events are required to have at least four jets with $p_T > 25$ GeV and $|\eta| < 2.5$. These requirements define the ‘pretag’ selection. For the ‘tag’ selection, at least one of these jets is required to be $b$–tagged.

### 2.3 Background estimation

The main backgrounds affecting the measurement come from $W$ bosons produced in association with jets ($W$+jets), single–top, $Z$+jets, production of $W/Z$ bosons pairs and multi–jet events with background leptons. The $W$+jets and multi–jets contributions are evaluated using a data–driven approach. Single–top, $Z$+jets and diboson production are evaluated using simulated samples normalised to the approximate NNLO cross section for single–top events, NNLO cross section for inclusive $Z$ events, and NLO cross section for diboson events, respectively.

For reconstructed $t\bar{t}$ candidate events, the dominant $W$+jets background is asymmetric in $\Delta |y|$ and therefore a data–driven technique is used to estimate its normalisation. The approach used is based on the fact that the production rate of $W^+$+jets is larger than that of $W^-$+jets. Since, to a good approximation, processes other than $W$+jets give equal numbers of positively and negatively charged leptons, the formula

$$N_{W^+} + N_{W^-} = \left(\frac{r_{MC} + 1}{r_{MC} - 1}\right) (D^+ - D^-),$$

where $r_{MC}$ is the ratio of the measured transverse mass to the Monte Carlo prediction, $D^+$ and $D^-$ are the distributions of the transverse mass for positively and negatively charged leptons, respectively.

2In events with a leptonic decay of a genuine $W$ boson, $m_T(W)$ is the $W$ boson transverse mass, defined as $\sqrt{2p_T p_\nu (1 - \cos(\phi^l - \phi^\nu))}$, where the measured $E_T^{\text{miss}}$ vector provides the neutrino information.

3The term ‘background (bkgd) leptons’ in this paper refers to hadrons mimicking lepton signatures and to leptons arising from heavy–hadron decays or photon conversions.
is used to estimate the total number of $W$ events in the selected sample, after the numbers of single–top, diboson and $Z$+jets events are evaluated in simulated samples and subtracted. Here, $N_{W\pm}$ is the estimated number of $W^{\pm}$+jets events, $D^+(D^-)$ is the total number of events in data passing the pretag selection described in section 2.2 with positively (negatively) charged leptons, and $r_{MC} = N(pp \rightarrow W^+ + X)/N(pp \rightarrow W^- + X)$ is evaluated from simulation, using the ALPGEN generator with the same event selection. Further details of the method can be found in ref. [30].

The $W$ charge asymmetry depends also on the $W$+jets flavour composition, i.e. on the mixture of $Wbb$+jets, $Wcc$+jets, $Wc$+jets and $W$+light–jets processes in ALPGEN simulated samples. Since this composition cannot be predicted with sufficient precision, data–driven corrections are derived. The relative fractions are estimated in data, after subtracting all non–$W$ contributions, including $t\bar{t}$, applying the tag selection but requiring the presence of exactly two jets in the final state, in order to have a control region dominated by $W$+jets events. The overall number of $W$+jets events is determined simultaneously with the heavy–flavour composition in this region. The heavy–flavour fractions in the simulated $W$+jets samples are then rescaled to the measured fractions. For the electron channel, the scale factors obtained are: $1.4 \pm 0.4$ for $Wbb$+jets and $Wcc$+jets, $0.7 \pm 0.4$ for $Wc$+jets and $1.00 \pm 0.10$ for $W$+light–jets components. For the muon channel, they are: $1.2 \pm 0.4$ for $Wbb$+jets and $Wcc$+jets, $1.0 \pm 0.4$ for $Wc$+jets and $0.97 \pm 0.09$ for $W$+light–jets components. The uncertainties include both the statistical and the systematic components. The sources of systematic uncertainty considered are those described in section 3.3.

With the determined flavour fractions, the $W$+jets normalisation for pretag–selected events using eq. 2.1 is computed and then extrapolated to the tag–selected events using the tagging fractions (i.e. the fraction of events with at least one $b$-jet) computed in simulated samples. The scale factors that are applied to the tag–selected $W$+jets events are $0.83 \pm 0.31$ and $0.94 \pm 0.17$ in the electron and muon channel respectively. The uncertainties include both the statistical and the systematic components, including a particular systematic uncertainty that accounts for differences in the flavour composition between the signal region and the region where the flavour fractions are extracted. It is derived from studies of ALPGEN parameter variations (factorisation and renormalisation scales, angular matching parameters and jet $p_T$ generation thresholds) and it amounts to 15% for the $Wbb/Wcc/Wc$+jets components and 5% for the $W$+light–jets component.

The ‘Matrix Method’ is used to evaluate the multi–jets background with background leptons. The method relies on defining ‘loose’ and ‘tight’ lepton samples [54] and measuring the ‘tight’ selection efficiencies for real ($\epsilon_{real}$) and background ($\epsilon_{bkgd}$) ‘loose’ leptons. The ‘loose’ selection requires less stringent identification and isolation requirements than the ones described in section 2.2, referred here as ‘tight’ selection. The fraction $\epsilon_{real}$ is measured using data control samples of $Z$ boson decays to two leptons. The fraction $\epsilon_{bkgd}$ is measured in control regions where the contribution of background leptons is dominant.

The expected and observed yields are listed in table 1. The number of events in the electron channel is significantly lower than in the muon channel due to the higher lepton $p_T$ threshold, tighter isolation and the more stringent missing transverse momentum requirements. The number of events observed in data and the total predicted yield are
Table 1 Numbers of expected events for the $t\bar{t}$ signal and the various background processes and observed events in data for the pretag and tag samples. The uncertainties include statistical and systematic components.

3 The $t\bar{t}$ production charge asymmetry measurement

After the reconstruction of the $t\bar{t}$–system (section 3.1) and the estimation of the background, the $\Delta|y|$ spectra (section 3.2) are unfolded to obtain inclusive and differential parton–level charge asymmetry measurements (as a function of $m_{t\bar{t}}$, $p_{T,t\bar{t}}$ and $|y_{t\bar{t}}|$), as defined in eq. 1.1.

In addition, an inclusive measurement and a differential measurement as a function of $m_{t\bar{t}}$ are performed for events where the $z$–component of the $t\bar{t}$–system velocity is large, $\beta_{z,t\bar{t}} > 0.6$. Most BSM models introduced to explain the excesses in the CDF and D0 measurements postulate the presence of new particles that can alter the SM prediction for $A_C$. Requiring $\beta_{z,t\bar{t}} > 0.6$ defines a region of phase–space where the effects of these new particles on the asymmetry are enhanced [32].

3.1 Reconstruction of the $t\bar{t}$–system

A kinematic fit is used to determine the likelihood for candidate events to be $t\bar{t}$ events as well as to determine the four–vector of the top quark and antiquark to compute $\Delta|y|$. The charge of the lepton is used to determine whether the reconstructed object is a top quark or antiquark. A detailed description of the method and its assumptions can be found in ref. [30]. In simulation studies using $t\bar{t}$ events, the fraction of events reconstructed with the correct $\Delta|y|$ sign was evaluated to be 75%.

For the differential measurements a cut on the likelihood is applied to reject badly reconstructed events, reducing the migrations across the bins. The reconstructed $\Delta|y|$ distribution is shown in figure 1 along with the distributions of $m_{t\bar{t}}$, $p_{T,t\bar{t}}$, $|y_{t\bar{t}}|$ and $\beta_{z,t\bar{t}}$.

3.2 Unfolding procedure

The reconstructed $\Delta|y|$ distributions are distorted by acceptance and detector resolution effects. We use the Fully Bayesian Unfolding (FBU) [55] technique to estimate the parton–
Figure 1. Reconstructed \( \Delta|y| \) (top left), invariant mass \( m_{H} \) (top right), transverse momentum \( p_{T,H} \) (centre left), rapidity \( |y_{H}| \) (centre right) and velocity \( \beta_{z,H} \) (bottom) distributions for the electron and muon channels combined after requiring at least one \( b \)-tagged jet. Data (dots) and SM expectations (solid lines) are shown. The uncertainty on the total prediction includes both the statistical and the systematic components. The overflow is included in the last bin.

level distributions from the measured spectra. This method relies on applying Bayes’ theorem to the unfolding problem, which can be formulated in the following terms.

Given an observed data spectrum \( D \in \mathbb{R}^{N_{D}} \) and a migration matrix \( M \in \mathbb{R}^{N_{r} \times N_{t}} \) \((N_{r} \text{ and } N_{t} \text{ are the number of bins in the measured and true spectra respectively}) that takes into account the distortion effects mentioned above, the posterior probability density of the true spectrum \( T \in \mathbb{R}^{N_{t}} \) follows the probability density

\[
p \left( T | D, M \right) \propto L \left( D | T, M \right) \cdot \pi \left( T \right)
\]

where \( L \left( D | T, M \right) \) is the conditional likelihood for the data \( D \) assuming the true \( T \) and the migration matrix \( M \), and \( \pi \) is the prior probability density for the true \( T \).
Assuming that the data follows a Poisson distribution, the likelihood \( L(D|T,M) \) can be computed starting from the migration matrix \( M \), whose elements \( M_{tr} \) represent the probability and the efficiency of an event produced in the true bin \( t \) to be reconstructed in any bin \( r \). The background in each bin is taken into account when computing \( L(D|T,M) \). While the above quantities can be estimated from simulated samples of signal events, the prior probability density \( \pi(T) \) must be chosen according to what is known about \( T \) before the measurement. In this context, the choice of the prior can be interpreted as the choice of a regularisation in other unfolding techniques (see ref. [56] for instance). After choosing a prior, the posterior probability density \( p(T|D,M) \) is computed by generating uniformly distributed points in the \( N_t \)-dimensional space, and evaluating for each of them \( L(D|T,M) \) and \( \pi(T) \). A weight given by \( L(D|T,M) \cdot \pi(T) \) is then assigned to each point, allowing the posterior probability density of the unfolded spectrum to be determined, for each \( \Delta|y| \) bin and for \( AC \).

The FBU method has two main advantages. Firstly, it gives a precise physical meaning to the regularisation procedure through the choice of a prior built with well-motivated physical quantities. Secondly, systematic uncertainties are accounted for consistently with the Bayesian statistical approach, by reporting credible intervals built by integrating the posterior distribution over the nuisance parameters.

The choice of the prior is arbitrary. With a flat prior, the FBU method has been checked to be equivalent to unregularised matrix inversion. Non–uniform priors favour spectra that have some well–defined features. By assuming that some spectra are more likely than others, information is added to the measurement, reducing the uncertainty but potentially biasing its outcome.

Two different priors are used in the following: a flat prior and a curvature prior. The curvature prior is defined starting from the definition of the curvature \( C(T) \) being the sum of the squares of the second derivatives of the \( \Delta|y| \) distribution \( T \) with \( N_t \) bins:

\[
C(T) = \sum_{i=2}^{N_t-1} (\Delta_{i+1,i} - \Delta_{i,i-1})^2,
\]

where \( \Delta_{a,b} = T_a - T_b \). The curvature prior is then defined as follows:

\[
\pi(T) \propto \begin{cases} 
    e^{\alpha S(T)} & \text{in the integration space, } \forall t \in [1, N_t] \\
    0 & \text{otherwise}
\end{cases}
\]  

(3.1)

where \( \alpha \) is the regularisation parameter and \( S(T) \equiv |C(T) - C(T^*)| \) is a regularisation function, defined, for each generated point, as the difference between the curvature \( C(T) \) of the true \( \Delta|y| \) spectrum \( T \) and that of the estimated spectrum \( T^* \).

The flat prior is used for the differential measurements of \( AC \) as a function of \( m_{t\bar{t}} \) and of \( |y_{t\bar{t}}| \). The curvature prior defined in eq. 3.1 is used for the inclusive measurement and for the differential measurement as a function of \( p_{T,t\bar{t}} \), because it reduces the uncertainty on these measurements. The regularisation strength \( \alpha = 10^{-8} \) is chosen based on the numerical value of the curvature of the true spectrum. It has been checked, by varying \( \alpha \) by one order of magnitude included the \( \alpha = 0 \) unregularised case, that this particular
choice of $\alpha$ does not cause any significant bias in either the unfolded distributions or in the computed asymmetries. The consistency of the FBU method with the iterative scheme [56] has been checked as well.

Four bins are used for the $\Delta|y|$ distribution both for the inclusive and the differential measurements. The $\Delta|y|$ bin ranges are the same in both measurements. The bin ranges for the differential variables are chosen to have approximately the same number of entries in each bin. The $A_C$ posterior probability density is built from the asymmetry in each generated point of the integration space. The value of $A_C$ and its statistical uncertainty are the mean and the RMS of the posterior probability density distribution respectively.

### 3.3 Systematic uncertainties

Several sources of systematic uncertainty are taken into account.

A possible small mis-modelling of the lepton momentum scale and resolution in simulation is corrected by scale factors derived from the comparison of $Z \rightarrow \ell\ell$, $J/\psi \rightarrow \ell\ell$ and $W \rightarrow e\nu$ events in data and simulation. The uncertainty on the scale factors ranges from 1% to 1.5% depending on the $p_T$ and $\eta$ of the leptons.

The jet energy scale is derived using information from test-beam data, collision data and simulation. Its uncertainty is between 1% and 2.5% in the central region of the detector, depending on jet $p_T$ and $\eta$ [51]. This value includes uncertainties due to the flavour composition of the sample, mis-measurements due to the effect of nearby jets, influence of pile-up, and a $p_T$-dependent uncertainty for jets arising from the fragmentation of $b$-quarks. The jet energy resolution and reconstruction efficiencies are measured in data using techniques described in refs. [51, 57].

The uncertainties on the lepton and jets are propagated to the missing transverse momentum calculation.

The $b$-tagging efficiencies and light jets mis-tag rates are measured in data. Jet $p_T$-dependent scale factors are applied to simulation to match the efficiencies observed in data. The typical uncertainty on the $b$-tagging scale factors ranges from 6% to 20% (depending on jet $p_T$ and $\eta$) for $b$-jets, from 12% to 22% for $c$-jets and is about 16% for light-jets [53]. The impact of this uncertainty is negligible.

The systematic uncertainty in the modelling of the signal process is assessed by varying the simulation parameters and by using a different Monte Carlo generator (POWHEG [58, 59]). The sources of systematic uncertainty considered are the choice and the functional form of factorisation scale and the choice of parton shower model (PYTHIA or HERWIG). The impact of the choice of PDFs is evaluated following the procedure described in ref. [46]. All these uncertainties have a negligible impact on the asymmetry.

The limited size of the MC simulation samples gives rise to a systematic uncertainty in the response matrix. This is estimated by independently varying the bin content of the response matrix according to Poisson distributions.

Several other sources of systematic uncertainties are considered, namely the uncertainties on: the luminosity determination (1.8%) [34], the lepton and trigger reconstruction and identification scale factors, the lepton charge mis-identification, the jet vertex fraction scale factor, the missing transverse momentum scale and resolution and the $Z+$jets and
multi–jets background normalisations. All of these lead to uncertainties on the asymmetry measurements below 0.001 and are therefore negligible.

Systematic uncertainties related to the different choice of PDFs and to the shape of the $W$+jets distributions are also considered. The former is evaluated as explained above. The latter is estimated in simulated events generated with the same variations of the ALPGEN parameters as described above for the modelling of the signal process.

For each of the systematic uncertainties (except for those related to the modelling of the $t\bar{t}$ signal and for the $W$+jets shape) the $W$+jets normalisation and the heavy–flavour composition are recomputed as described in section 2.3 to take into account the correlation with the various sources of systematic uncertainty considered.

For the systematic uncertainties affecting the background, the posterior probability density with a modified background prediction is computed. For those affecting the signal, the posterior probability density with the modified efficiency and response matrix is evaluated.

Systematic uncertainties are taken into account with a marginalisation procedure. After computing the posterior probability density corresponding to each systematic variation, the likelihood used in the unfolding is marginalised by integrating out its dependence on the nuisance parameters. It is assumed that the priors for all nuisance parameters are Gaussian and that there is no correlation between them. A marginalisation is then performed by transforming the integral over the nuisance parameter into a discrete sum of the posterior probability densities evaluated at three values of the nuisance parameter: the central one and the $1\sigma$ variations. The resulting posterior probability density is finally used to extract the systematic uncertainty on the measurements.

4 Results

4.1 Inclusive and differential measurements

The $t\bar{t}$ production charge asymmetry is measured to be $A_C = 0.006 \pm 0.010$ compatible with the SM prediction $A_C = 0.0123 \pm 0.0005$ [21]. These values are shown in table 2 together with the measurement and prediction for $m_{t\bar{t}} > 600$ GeV. The total systematic uncertainty is computed with the marginalisation procedure described in section 3.3. The uncertainties quoted for all the results in this section include statistical and systematic components. In order to estimate the impact of each source of systematic uncertainty, the marginalisation procedure is repeated removing one such source at a time from the global marginalisation. For each of the systematic uncertainties considered in this analysis and for all the measurements, the impact on the $A_C$ value and its uncertainty is less than 10% of the statistical uncertainty, and thus negligible.

As a cross–check, the systematic uncertainties affecting $A_C$ are computed one by one before the marginalisation procedure described above. For each source, the systematic uncertainty represents the variation of the mean of posterior probability densities corresponding to a $1\sigma$ variation of the nuisance parameter. The statistical uncertainty still dominates the variations in $A_C$ even before the marginalisation procedure. Table 3 summarises the result of this ‘cross–check’ procedure for the inclusive charge asymmetry measurement (left
### Table 2

<table>
<thead>
<tr>
<th>$A_C$</th>
<th>Data</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unfolded</td>
<td>0.006±0.010</td>
<td>0.0123±0.0005</td>
</tr>
<tr>
<td>Unfolded with $m_{t\bar{t}} &gt; 600$ GeV</td>
<td>0.018±0.022</td>
<td>0.0175±0.0003</td>
</tr>
<tr>
<td>Unfolded with $\beta_{z,\bar{t}} &gt; 0.6$</td>
<td>0.011±0.018</td>
<td>0.020±0.007</td>
</tr>
</tbody>
</table>

Measured inclusive charge asymmetry, $A_C$, values for the electron and muon channels combined after unfolding without and with the $\beta_{z,\bar{t}} > 0.6$ cut explained in the text. The $A_C$ measurement with a cut on the $t\bar{t}$ invariant mass $m_{t\bar{t}} > 600$ GeV is also shown. SM predictions, as described in the text, are also reported. The quoted uncertainties include statistical and systematic components after the marginalisation.

### Table 3

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>$\delta A_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inclusive</td>
</tr>
<tr>
<td>Lepton reconstruction/identification</td>
<td>&lt; 0.001</td>
</tr>
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<td>Lepton energy scale and resolution</td>
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</tr>
<tr>
<td>Jet energy scale and resolution</td>
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<tr>
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<tr>
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</tr>
<tr>
<td>$b$–tagging/mis–tag efficiency</td>
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</tr>
<tr>
<td>Signal modelling</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Parton shower/hadronisation</td>
<td>&lt; 0.001</td>
</tr>
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<td>Monte Carlo statistics</td>
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</tr>
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<td>PDF</td>
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<tr>
<td>$W$+jets normalisation and shape</td>
<td>0.002</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>0.010</td>
</tr>
</tbody>
</table>

Systematic uncertainties for the inclusive asymmetry, $A_C$ (second column), the asymmetry for $m_{t\bar{t}} > 600$ GeV (third column) and the inclusive asymmetry, $A_C$, for $\beta_{z,\bar{t}} > 0.6$ (fourth column). For variations resulting in asymmetric uncertainties, the average absolute deviation from the nominal value is reported. The values reported for each systematic uncertainty are the variation of the mean of posteriors computed considering $1\sigma$ variations.

### Table 4

For the measurement with the $m_{t\bar{t}} > 600$ GeV requirement after unfolding (central column). Figure 2 shows the charge asymmetry as a function of $m_{t\bar{t}}$, $p_{T, t\bar{t}}$ and $|y_{t\bar{t}}|$ compared with the theoretical SM predictions described in ref. [21] and provided by its authors for the chosen bins. In addition, predictions for two assumed mass values (300 GeV [14] and 7000 GeV), for a heavy axigluon exchanged in the $s$–channel, are also shown. The masses are chosen as benchmarks, taking into account the fact that they would not be visible as resonances in the $m_{t\bar{t}}$ spectrum. The parameters of the model are tuned to give a forward–backward asymmetry compatible with the Tevatron results. The differential distributions and respective asymmetries do not show any significant deviation from the SM prediction. The resulting charge asymmetry $A_C$ is shown in table 4 for the differential measurements as a function of $m_{t\bar{t}}$, $p_{T, t\bar{t}}$ and $|y_{t\bar{t}}|$. The systematic uncertainties, computed before the marginalisation procedure as described above in the cross–check procedure, are listed in table 5 for each of the differential measurements. The correlation matrices for the statistical uncertainties are shown in table 6 for the measurement as a function of $m_{t\bar{t}}$, $p_{T, t\bar{t}}$ and $|y_{t\bar{t}}|$ respectively.
Figure 2. Distributions of $A_C$ as a function of $m_{t\bar{t}}$ (top left), $p_{T,t\bar{t}}$ (top right) and $|y_{t\bar{t}}|$ (bottom left) after unfolding, for the electron and muon channels combined. The $A_C$ distribution as a function of $m_{t\bar{t}}$, after the $\beta_{z,t\bar{t}} > 0.6$ requirement, is also shown (bottom right). The $A_C$ values after the unfolding (points) are compared with the SM predictions (green lines) and the predictions for a colour–octet axigluon with a mass of 300 GeV (red lines) and 7000 GeV (blue lines) respectively, as described in the text. The thickness of the lines represents the factorisation and renormalisation scale uncertainties on the corresponding theoretical predictions. The values plotted are the average $A_C$ in each bin. The error bars include both the statistical and the systematic uncertainties on $A_C$ values. The bins are the same as the ones reported in tables 4 and 7 respectively.

4.2 Measurements for $\beta_{z,t\bar{t}} > 0.6$

An additional requirement on the $z$–component of the $t\bar{t}$–system velocity $\beta_{z,t\bar{t}} > 0.6$ is applied, as explained in section 1, for the inclusive and the differential $\Delta|y|$ distribution as a function of $m_{t\bar{t}}$. It has been verified that resolution effects on the reconstructed $\beta_{z,t\bar{t}}$ did not introduce any bias in the measurement. Hence an unfolding of the $\beta_{z,t\bar{t}}$ distribution was found to be unnecessary. The inclusive asymmetry after this requirement is $A_C = 0.011 \pm 0.018$, as reported in the last row of table 2, to be compared with the SM prediction $A_C^{SM} = 0.020^{+0.009}_{-0.007}$ [21]. Table 3 (right column) shows the list of systematic uncertainties affecting the measurement before the marginalisation procedure.

Figure 2 (bottom right plot) shows the differential $A_C$ measurement as a function of $m_{t\bar{t}}$, while table 7 shows the value of $A_C$ for the different bins, table 8 lists the systematic uncertainties affecting the measurement before the marginalisation and table 9 shows the correlation coefficients among the different bins. These measurements do not deviate significantly from the SM expectations either.
Table 4 Measured charge asymmetry, $A_C$, values for the electron and muon channels combined after unfolding as a function of the $t\bar{t}$ invariant mass, $m_{t\bar{t}}$ (top), the $t\bar{t}$ transverse momentum, $p_{T,t\bar{t}}$ (middle) and the $t\bar{t}$ rapidity, $|y_{t\bar{t}}|$ (bottom). SM predictions, as described in the text, are also reported. The quoted uncertainties include statistical and systematic components after the marginalisation.

4.3 Interpretation

Figure 3 shows the inclusive $A_C$ measurements with and without the additional requirement on the invariant mass of the $t\bar{t}$–system $m_{t\bar{t}} > 600$ GeV described in section 4.1. In the left plot, the $A_C$ measurement without the $m_{t\bar{t}} > 600$ GeV requirement is compared with the corresponding measurement from CMS [29] (horizontal lines) and with the $t\bar{t}$ forward–backward asymmetry $A_{FB}$ measurements made at the Tevatron by CDF, $A_{FB} = 0.164\pm0.045$ [24], and D0, $A_{FB} = 0.196\pm0.065$ [26] (vertical lines). In the right plot, the $A_C$ measurement with the requirement of $m_{t\bar{t}} > 600$ GeV, is compared with the $A_{FB}$ measurement, with the requirement of $m_{t\bar{t}} > 450$ GeV, performed by the CDF experiment at the Tevatron [24].

Predictions given by several new physics models introduced to explain the larger than expected $A_{FB}$ values measured at the Tevatron are also displayed. Details of these models can be found in refs. [8, 30, 60]. For each model, the predictions for $A_{FB}$ and $A_C$ are derived using the PROTOS generator [61] with the constraints described in ref. [30]. The ranges of predicted values for $A_{FB}$ and $A_C$ for a given new physics model are also shown. The new physics contributions are computed using the tree–level SM amplitude plus the one(s) from the new particle(s), to account for the interference between the two contributions. Some of these new physics models seem to be disfavoured by the current measurements.
<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>( m_{tt} ) [GeV]</th>
<th>( m_{tt} ) [GeV]</th>
<th>( m_{tt} ) [GeV]</th>
<th>( m_{tt} ) [GeV]</th>
<th>( m_{tt} ) [GeV]</th>
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</thead>
<tbody>
<tr>
<td>Lepton reconstruction/identification</td>
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<td>420–500</td>
<td>500–600</td>
<td>600–750</td>
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<tr>
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<td>&lt; 0.005</td>
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<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
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<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
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<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
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<tr>
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<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
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<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
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<tr>
<td>PDF</td>
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<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
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<tr>
<td>( W )-jets normalisation and shape</td>
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<td>&lt; 0.005</td>
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<td>Statistical uncertainty</td>
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<table>
<thead>
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<th>( p_{T,tt} ) [GeV]</th>
<th>( p_{T,tt} ) [GeV]</th>
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</thead>
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<td>Lepton reconstruction/identification</td>
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<td>25–60</td>
<td>&gt; 60</td>
</tr>
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<td>Lepton energy scale and resolution</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>0.011</td>
<td>0.013</td>
<td>0.006</td>
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<td>Missing transverse momentum and pile–up modelling</td>
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<td>0.020</td>
<td>0.020</td>
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<td>Multi–jets background normalisation</td>
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<td>0.010</td>
<td>&lt; 0.005</td>
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<tr>
<td>b–tagging/mis–tag efficiency</td>
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<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
</tr>
<tr>
<td>Signal modelling</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
</tr>
<tr>
<td>Parton shower/hadronisation</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
</tr>
<tr>
<td>Monte Carlo sample size</td>
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<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
</tr>
<tr>
<td>PDF</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
</tr>
<tr>
<td>( W )-jets normalisation and shape</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
<td>&lt; 0.005</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>0.052</td>
<td>0.057</td>
<td>0.034</td>
</tr>
</tbody>
</table>

| Source of systematic uncertainty | \( |y_{tt}| \) | \( |y_{tt}| \) | \( |y_{tt}| \) |
|----------------------------------|-------------|-------------|-------------|
| Lepton reconstruction/identification | < 0.005 | < 0.005 | < 0.005 |
| Lepton energy scale and resolution | 0.022 | 0.014 | 0.008 |
| Jet energy scale and resolution | 0.013 | 0.007 | < 0.005 |
| Missing transverse momentum and pile–up modelling | < 0.005 | 0.006 | < 0.005 |
| Multi–jets background normalisation | < 0.005 | < 0.005 | < 0.005 |
| b–tagging/mis–tag efficiency | < 0.005 | < 0.005 | < 0.005 |
| Signal modelling | < 0.005 | < 0.005 | < 0.005 |
| Parton shower/hadronisation | < 0.005 | < 0.005 | < 0.005 |
| Monte Carlo sample size | < 0.005 | < 0.005 | < 0.005 |
| PDF | < 0.005 | < 0.005 | < 0.005 |
| \( W \)-jets normalisation and shape | < 0.005 | < 0.005 | < 0.005 |
| Statistical uncertainty | 0.042 | 0.030 | 0.025 |

Table 5: Systematic uncertainties for the charge asymmetry, \( A_C \), measurement for the electron and muon channels combined after unfolding as a function of the \( tt \) invariant mass, \( m_{tt} \) (top), the \( tt \) transverse momentum, \( p_{T,tt} \) (middle) and the \( tt \) rapidity, \( |y_{tt}| \) (bottom). For variations resulting in asymmetric uncertainties, the average absolute deviation from the nominal value is reported. The values reported for each systematic uncertainty are the variation of the mean of posterior probability densities computed considering 1\( \sigma \) variations.
<table>
<thead>
<tr>
<th>$\rho_{i,j}$</th>
<th>$m_{t\bar{t}}$ [GeV]</th>
<th>0–420</th>
<th>420–500</th>
<th>500–600</th>
<th>600–750</th>
<th>&gt; 750</th>
</tr>
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<tbody>
<tr>
<td>0–420</td>
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<td>-0.05</td>
<td>0.01</td>
<td></td>
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</tr>
<tr>
<td>&gt; 750</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
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</table>

Table 6 Correlation coefficients $\rho_{i,j}$ for the statistical uncertainties between the $i$–th and $j$–th bin of the differential $A_C$ measurement as a function of the $t\bar{t}$ invariant mass, $m_{t\bar{t}}$ (top), the transverse momentum, $p_{T,t\bar{t}}$ (middle) and the $t\bar{t}$ rapidity, $|y_{t\bar{t}}|$ (bottom).

<table>
<thead>
<tr>
<th>$\rho_{i,j}$</th>
<th>$p_{T,t\bar{t}}$ [GeV]</th>
<th>0–25</th>
<th>25–60</th>
<th>&gt; 60</th>
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</thead>
<tbody>
<tr>
<td>0–25</td>
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<td></td>
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</tr>
<tr>
<td>25–60</td>
<td>-0.79</td>
<td>1</td>
<td>-0.60</td>
<td></td>
</tr>
<tr>
<td>&gt; 60</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

| $\rho_{i,j}$ | $|y_{t\bar{t}}|$ | 0–0.3 | 0.3–0.7 | > 0.7 |
|------------|----------------|------|--------|------|
| 0–0.3      | 1               |      | -0.33  | 0.05 |
| 0.3–0.7    |                 | 1    | -0.21  |      |
| > 0.7      |                 |      | 1      |      |

Table 7 Measured charge asymmetry, $A_C$, values for the electron and muon channels combined after unfolding as a function of the $t\bar{t}$ invariant mass, $m_{t\bar{t}}$, for $\beta_{z,t\bar{t}} > 0.6$. SM predictions, as described in the text, are also reported. The quoted uncertainties include statistical and systematic components after the marginalisation.
Table 8 Systematic uncertainties for the charge asymmetry, $A_C$, measurement for the electron and muon channels combined after unfolding as a function of the $t\bar{t}$ invariant mass, $m_{t\bar{t}}$, for $\beta_{z,t}\bar{t} > 0.6$. For variations resulting in asymmetric uncertainties, the average absolute deviation from the nominal value is reported. The values reported for each systematic uncertainty are the variation of the mean of posterior probability densities computed considering 1σ variations.

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>$m_{t\bar{t}}$ [GeV] for $\beta_{z,t}\bar{t} &gt; 0.6$</th>
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<td>PDF</td>
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<td>$W$-jets normalisation and shape</td>
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<tr>
<td>Statistical uncertainty</td>
<td>0.078</td>
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</tbody>
</table>

Table 9 Correlation coefficients $\rho_{i,j}$ for the statistical uncertainties between the $i$-th and $j$-th bin of the differential $A_C$ measurement as a function of the $t\bar{t}$ invariant mass, $m_{t\bar{t}}$, for $\beta_{z,t}\bar{t} > 0.6$.
Figure 3. Measured forward–backward asymmetries $A_{FB}$ at Tevatron and charge asymmetries $A_C$ at LHC, compared with the SM predictions (black box) as well as predictions incorporating various potential new physics contributions (as described in the figure) [8, 60]. In both plots, where present, the horizontal bands and lines correspond to the ATLAS (light green) and CMS (dark green) measurements, while the vertical ones correspond to the CDF (orange) and D0 (yellow) measurements. The inclusive $A_C$ measurements are reported in the left plot. In the right plot a comparison is reported between the $A_{FB}$ measurement by CDF for $m_{tt} > 450$ GeV and the $A_C$ measurement for $m_{tt} > 600$ GeV.

5 Conclusion

This paper has presented a measurement of the $t\bar{t}$ production charge asymmetry measurement in $t\bar{t}$–events with a single lepton (electron or muon), at least four jets, of which at least one is tagged as a $b$–jet, and large missing transverse momentum, using an integrated luminosity of 4.7 fb$^{-1}$ recorded by the ATLAS experiment in $pp$ collisions at a centre–of–mass energy of $\sqrt{s} = 7$ TeV at the LHC. The inclusive $t\bar{t}$ production charge asymmetry $A_C$ and its differential distributions, as a function of $m_{tt}$, $p_T, t\bar{t}$ and $|y_{t\bar{t}}|$, have been unfolded to parton–level. The measured inclusive $t\bar{t}$ production charge asymmetry is $A_C = 0.006 \pm 0.010$, to be compared with the SM prediction $A_{SM}^{C} = 0.0123 \pm 0.0005$. All measurements presented are statistically limited and are found to be compatible with the SM prediction within the uncertainties.

Acknowledgments

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

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NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNRSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNI SW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZˇS, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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The ATLAS Collaboration

W. Verkerke,106 J.C. Vermeulen,106 A. Vest,44 M.C. Vetterli,143, f, O. Viazlo,80
I. Vichou,166, T. Vickery,146,an, O.E. Vickery Boeriu,146c, G.H.A. Viehhauser,119, S. Viel,169
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A. Zoccoli$^{20a,20b}$, M. zur Nedden$^{16}$, G. Zurzolo$^{103a,103b}$, V. Zutshi$^{107}$, L. Zwalinski$^{30}$.

1 School of Chemistry and Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany NY, United States of America
3 Department of Physics, University of Alberta, Edmonton AB, Canada
4 (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Gazi University, Ankara; (c) Division of Physics, TOBB University of Economics and Technology, Ankara; (d) Turkish Atomic Energy Authority, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
7 Department of Physics, University of Arizona, Tucson AZ, United States of America
8 Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13 (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
26 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Physics Department, Shanghai Jiao Tong University, Shanghai, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington NY, United States of America
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
39 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas TX, United States of America
41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham NC, United States of America
46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova,
Italy
51 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 Department of Physics, Indiana University, Bloomington IN, United States of America
61 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
62 University of Iowa, Iowa City IA, United States of America
63 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
64 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
65 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
66 Graduate School of Science, Kobe University, Kobe, Japan
67 Faculty of Science, Kyoto University, Kyoto, Japan
68 Kyoto University of Education, Kyoto, Japan
69 Department of Physics, Kyushu University, Fukuoka, Japan
70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
77 Department of Physics and Astronomy, University College London, London, United Kingdom

– 38 –
Louisiana Tech University, Ruston LA, United States of America

Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

Fysiska institutionen, Lunds universitet, Lund, Sweden

Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain

Institut für Physik, Universität Mainz, Mainz, Germany

School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

Department of Physics, University of Massachusetts, Amherst MA, United States of America

Department of Physics, McGill University, Montreal QC, Canada

School of Physics, University of Melbourne, Victoria, Australia

Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

(a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus

Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America

Group of Particle Physics, University of Montreal, Montreal QC, Canada

P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia

Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia

D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia

Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

Nagasaki Institute of Applied Science, Nagasaki, Japan

Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan

(a) INFN Sezione di Napoli; (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy

Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America

Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb IL, United States of America
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York NY, United States of America
Ohio State University, Columbus OH, United States of America
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
Department of Physics, Oklahoma State University, Stillwater OK, United States of America
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
\( (a) \) INFN Sezione di Pavia; \( (b) \) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
Petersburg Nuclear Physics Institute, Gatchina, Russia
\( (a) \) INFN Sezione di Pisa; \( (b) \) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
\( (a) \) Laboratorio de Instrumentacion e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; \( (b) \) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Physics Department, University of Regina, Regina SK, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan
\( (a) \) INFN Sezione di Roma I; \( (b) \) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
\( (a) \) INFN Sezione di Roma Tor Vergata; \( (b) \) Dipartimento di Fisica, Università di
Roma Tor Vergata, Roma, Italy
135 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università
Roma Tre, Roma, Italy
136 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes
Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences
Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad,
LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM,
Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA
Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette,
France
138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa
Cruz CA, United States of America
139 Department of Physics, University of Washington, Seattle WA, United States of
America
140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United
Kingdom
141 Department of Physics, Shinshu University, Nagano, Japan
142 Fachbereich Physik, Universität Siegen, Siegen, Germany
143 Department of Physics, Simon Fraser University, Burnaby BC, Canada
144 SLAC National Accelerator Laboratory, Stanford CA, United States of America
145 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava;
(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak
Academy of Sciences, Kosice, Slovak Republic
146 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of
Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of
the Witwatersrand, Johannesburg, South Africa
147 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre,
Stockholm, Sweden
148 Physics Department, Royal Institute of Technology, Stockholm, Sweden
149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony
Brook NY, United States of America
150 Department of Physics and Astronomy, University of Sussex, Brighton, United
Kingdom
151 School of Physics, University of Sydney, Sydney, Australia
152 Institute of Physics, Academia Sinica, Taipei, Taiwan
153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University,
Tel Aviv, Israel
155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
156 International Center for Elementary Particle Physics and Department of Physics, The
University of Tokyo, Tokyo, Japan
157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo,
Japan
158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
159 Department of Physics, University of Toronto, Toronto ON, Canada
160 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
161 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
162 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
164 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
165 (a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
166 Department of Physics, University of Illinois, Urbana IL, United States of America
167 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
168 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
169 Department of Physics, University of British Columbia, Vancouver BC, Canada
170 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
171 Department of Physics, University of Warwick, Coventry, United Kingdom
172 Waseda University, Tokyo, Japan
173 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
174 Department of Physics, University of Wisconsin, Madison WI, United States of America
175 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
176 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
177 Department of Physics, Yale University, New Haven CT, United States of America
178 Yerevan Physics Institute, Yerevan, Armenia
179 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
\(^a\) Also at Department of Physics, King’s College London, London, United Kingdom
\(^b\) Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
\(^c\) Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
\(^d\) Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
\(^e\) Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
\(^f\) Also at TRIUMF, Vancouver BC, Canada
\(^g\) Also at Department of Physics, California State University, Fresno CA, United States of America

– 42 –
h Also at Novosibirsk State University, Novosibirsk, Russia
i Also at Department of Physics, University of Coimbra, Coimbra, Portugal
j Also at Università di Napoli Parthenope, Napoli, Italy
k Also at Institute of Particle Physics (IPP), Canada
l Also at Department of Physics, Middle East Technical University, Ankara, Turkey
m Also at Louisiana Tech University, Ruston LA, United States of America
n Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
o Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
p Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
q Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
r Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
s Also at Department of Physics, University of Cape Town, Cape Town, South Africa
t Also at CERN, Geneva, Switzerland
u Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
v Also at Manhattan College, New York NY, United States of America
w Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
x Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
y Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
z Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
aa Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India
ab Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy
ac Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
ad Also at Section de Physique, Université de Genève, Geneva, Switzerland
ae Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal
af Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
ag Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
ah Also at DESY, Hamburg and Zeuthen, Germany
ai Also at International School for Advanced Studies (SISSA), Trieste, Italy
aj Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
ak Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
al Also at Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
am Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
an Also at Department of Physics, Oxford University, Oxford, United Kingdom
ao Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
ap Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
aq Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
ar Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
* Deceased