


# Combination of inclusive and differential $t(\bar{t})$ charge asymmetry measurements using ATLAS and CMS data at $\sqrt{s}=7$ and 8 TeV

## Journal Article

### Author(s):

CMS Collaboration; Aaboud, M.Y.; Backhaus, Malte; Bäni, Lukas; Berger, Pirmin; Bianchini, Lorenzo; Casal, Bruno; Dissertori, Günther; Dittmar, Michael; Donegà, Mauro; Dorfer, Christian; Grab, Christoph; Heidegger, Constantin; Hits, Dmitry; Hoss, Jan; Kasieczka, Gregor; Klijnsma, Thomas; Lustermann, Werner; Mangano, Boris; Marionneau, Matthieu; Meinhard, Maren T.; Meister, Daniel; Micheli, Francesco; Musella, Pasquale; Nessi-Tedaldi, Francesca; Pandolfi, Francesco; Pata, Joosep; Paus, Felicitas; Perrin, Gaël; Perrozzi, Luca; Quittnat, Milena; Reichmann, Michael; Sanz Becerra, Diego A.; Schönenberger, Myriam; Shchutska, Lesya; Tavarolo, Vittorio R.; Theofilatos, Konstantinos; Vesterbacka Olsson, Minna L.; [Wallny, Rainer](#) ; Zhu, De Hua; et al.

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# Combination of inclusive and differential $t\bar{t}$ charge asymmetry measurements using ATLAS and CMS data at $\sqrt{s} = 7$ and 8 TeV



## The ATLAS and CMS collaborations

*E-mail:* [atlas.publications@cern.ch](mailto:atlas.publications@cern.ch),  
[cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch)

**ABSTRACT:** This paper presents combinations of inclusive and differential measurements of the charge asymmetry ( $A_C$ ) in top quark pair ( $t\bar{t}$ ) events with a lepton+jets signature by the ATLAS and CMS Collaborations, using data from LHC proton-proton collisions at centre-of-mass energies of 7 and 8 TeV. The data correspond to integrated luminosities of about 5 and 20 fb<sup>-1</sup> for each experiment, respectively. The resulting combined LHC measurements of the inclusive charge asymmetry are  $A_C^{\text{LHC7}} = 0.005 \pm 0.007$  (stat)  $\pm 0.006$  (syst) at 7 TeV and  $A_C^{\text{LHC8}} = 0.0055 \pm 0.0023$  (stat)  $\pm 0.0025$  (syst) at 8 TeV. These values, as well as the combination of  $A_C$  measurements as a function of the invariant mass of the  $t\bar{t}$  system at 8 TeV, are consistent with the respective standard model predictions.

**KEYWORDS:** Hadron-Hadron scattering (experiments), Top physics

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**1 Introduction**

With the large number of top quark pair ( $t\bar{t}$ ) events produced at the CERN LHC, the properties of the most massive elementary particle known to date are studied with ever increasing accuracy. Asymmetries in the angular distributions of top quarks and antiquarks provide powerful probes for physics beyond the standard model (SM). In proton-antiproton

collisions at the Tevatron, it is possible to define a forward-backward asymmetry  $A_{\text{FB}}$  [1–3], while the same underlying physical effects induce a charge asymmetry  $A_{\text{C}}$  in proton-proton (pp) collisions at the LHC [4, 5].

The production of  $t\bar{t}$  pairs via gluon fusion is symmetric with respect to the exchange of the top quark and antiquark. The same is true for the  $q\bar{q} \rightarrow t\bar{t}$  process at leading order (LO) in quantum chromodynamics (QCD). Asymmetries in kinematic observables of top quarks and antiquarks are introduced by higher-order effects in QCD for events produced by quark-antiquark annihilation. Interference effects connect the direction of motion of the top quark to that of the incoming quark, and the direction of motion of the top antiquark to that of the incoming antiquark [6]. Initial quark and antiquark momenta in the protons have different spectra, leading to a measurable difference between the angular distributions of top quark and antiquark in pp collisions. On average, quarks (valence and sea quarks) carry larger momentum than the antiquarks (sea quarks), causing the rapidity distribution of top quarks to be broader than that of top antiquarks.

In proton-proton collisions, the  $t\bar{t}$  charge asymmetry is defined as

$$A_{\text{C}} = \frac{N^{\Delta|y|>0} - N^{\Delta|y|<0}}{N^{\Delta|y|>0} + N^{\Delta|y|<0}}, \quad (1.1)$$

using the difference of the absolute values of the rapidities  $y$  of the top quark and antiquark,  $\Delta|y| = |y_t| - |y_{\bar{t}}|$ , as the sensitive observable. The numbers of events with  $\Delta|y|$  taking positive or negative values are given by  $N^{\Delta|y|>0}$  and  $N^{\Delta|y|<0}$ , respectively.

The ATLAS [7] and CMS [8] Collaborations have measured the inclusive  $t\bar{t}$  charge asymmetry at centre-of-mass energies of 7 and 8 TeV in events with one charged lepton (lepton+jets channel) [9–13] and in events with two charged leptons (dilepton channel) in the final state [14–17], where the leptons are either electrons or muons. The ATLAS Collaboration has also measured the charge asymmetry in highly boosted  $t\bar{t}$  events, where the asymmetry is predicted to be amplified [18]. In addition, both collaborations have measured the charge asymmetry differentially as a function of suitable kinematic variables.

Theoretical predictions from QCD calculations are available at next-to-leading-order (NLO) from refs. [4] and [19] and at next-to-next-to-leading-order (NNLO) [20–23] precision in the strong coupling. These calculations include electroweak (EW) corrections at NLO precision. The two calculations at NLO follow the same approach to evaluate the charge asymmetry but differ in technical details. The calculation in ref. [4] uses a LO parton distribution function (PDF) set to evaluate the asymmetry, while the calculation in ref. [19] uses a NLO PDF set. The factorisation and renormalisation scales are set to the partonic centre-of-mass energy in ref. [4], while the calculation in ref. [19] uses fixed scales and sets both quantities to the top quark mass. The NNLO prediction is based on the methods described in refs. [20, 22], derived using dynamical factorisation and renormalisation scales [21] ( $\mu = H_{\text{T}}/4$ , where  $H_{\text{T}} = \sqrt{m_t^2 + p_{\text{T},t}^2} + \sqrt{m_t^2 + p_{\text{T},\bar{t}}^2}$ , with  $m_t$  being the top quark mass and  $p_{\text{T},t/\bar{t}}$  being the transverse momentum of the top quark or antiquark) and a NNLO PDF set. In the NLO calculations, the ratio in eq. (1.1) is evaluated in powers of the considered couplings (strong and electroweak), taking NLO corrections into account only in the numerator, while the denominator is evaluated with the LO matrix element.

| Inclusive $A_C$         |                        | Centre-of-mass energy       |                                |
|-------------------------|------------------------|-----------------------------|--------------------------------|
|                         |                        | 7 TeV                       | 8 TeV                          |
| Theoretical predictions | QCD NLO + EW NLO [4]   | $0.0115 \pm 0.0006$         | $0.0102 \pm 0.0005$            |
|                         | QCD NLO + EW NLO [19]  | $0.0123 \pm 0.0005$         | $0.0111 \pm 0.0004$            |
|                         | QCD NNLO + EW NLO [23] |                             | $0.0095^{+0.0005}_{-0.0007}$   |
| Experimental results    | ATLAS [9, 11]          | $0.006 \pm 0.010$           | $0.0090 \pm 0.0051$            |
|                         | CMS unfolding [10, 13] | $0.004 \pm 0.010 \pm 0.011$ | $0.0010 \pm 0.0068 \pm 0.0037$ |
|                         | CMS template [12]      |                             | $0.0033 \pm 0.0026 \pm 0.0033$ |

**Table 1.** Overview of the most recent theoretical predictions for the inclusive  $A_C$  at the LHC at  $\sqrt{s} = 7$  and 8 TeV, along with the experimental results from the ATLAS and CMS Collaborations. The uncertainties in all theoretical predictions are dominated by the uncertainties due to scale variations. The uncertainties in the experimental CMS results are given separately as statistical (first contribution) and systematic (second contribution) uncertainties, while for the ATLAS results the total uncertainty is quoted. The ATLAS and CMS experimental results are described in section 2.

For the NNLO prediction, numerator and denominator are calculated at full QCD NNLO precision (and NLO for electroweak corrections) without any expansion in powers of the considered couplings. Although the asymmetry predicted in the SM is small, contributions from beyond the standard model (BSM) could alter its value, especially at high values of the invariant mass of the  $t\bar{t}$  system.

This paper reports the results of combinations of the inclusive  $A_C$  measurements from the ATLAS and CMS Collaborations at  $\sqrt{s} = 7$  and 8 TeV, and the combination of the ATLAS and CMS differential asymmetry measurements as a function of the invariant mass of the  $t\bar{t}$  system at 8 TeV. For the three combinations, only the results in the lepton+jets channel are considered. Including in addition the results in the dilepton channel does not lead to a gain in precision because of their large statistical uncertainty. All these measurements are extrapolated to the full phase space of  $t\bar{t}$  production. Table 1 gives an overview of the recent predictions from theory for both centre-of-mass energies and of the experimental results that serve as input to the combinations described in this paper.

The paper is structured as follows: section 2 and section 3 briefly describe the analyses whose results are used for the combination and the method used to combine the results; section 4 lists the uncertainties and the assumed correlations between the measurements; results and studies on the stability of the combinations are presented in sections 5 and 6.

## 2 Input measurements

### 2.1 The ATLAS measurements

The ATLAS results used for the combinations are based on data recorded at  $\sqrt{s} = 7$  TeV [9] and 8 TeV [11], corresponding to integrated luminosities of 4.7 and 20.3 fb<sup>-1</sup>, respectively.

Very similar analysis strategies are used for the two centre-of-mass energies. The analysis of the 8 TeV data profits from a larger number of selected events and also samples of simulated events generated using higher-order Monte Carlo (MC) event generators than were available for ref. [9]. In the 7 TeV analysis, the  $t\bar{t}$  signal events are simulated us-

ing the LO multi-parton matrix element event generator ALPGEN 2.13 [24] with the LO PDF set CTEQ6L1 [25]. Background events from the production of single-top-quarks are simulated using the LO event generator ACERMC 3.8 [26] ( $t$  channel) or the NLO event generator MC@NLO 4.01 [27–29] ( $tW$  and  $s$  channel). In the 8 TeV analysis, the  $t\bar{t}$  signal events [30] and single-top-quark background events [31, 32] are simulated using the NLO event generator POWHEG-BOX 1.0 [33–35] using the CT10 [36] PDF set. At both centre-of-mass energies, simulated events are produced assuming a top quark mass of 172.5 GeV. Production of a W or Z boson in association with jets, hereafter referred to as W+jets and Z+jets, respectively, is simulated using ALPGEN with the CTEQ6L1 PDF set. For the 7 TeV analysis, the dominant W+jets background is normalised using control samples in data, based on the fact that the production rate of  $W^+$ +jets is larger than that of  $W^-$ +jets. The flavour composition of this background component is also adjusted from data. For the 8 TeV analysis, the W+jets process is normalised *in situ* using data while extracting the asymmetry. Parton showering and the underlying event are modelled in all samples using HERWIG 6.5.20 [37] and JIMMY 4.31 [38] with a set of tuned parameters called the AUET2 tune [39] for the 7 TeV analysis, and PYTHIA 6.4.27 [40] with the Perugia2011C tune [41] for the 8 TeV analysis. The multijet background normalisation and shape are estimated from data using the matrix method [42].

The final state of  $t\bar{t}$  events in the lepton+jets channel features an electron or muon, a neutrino, two b-quarks from the two top quark decays, and two light quarks from the hadronically decaying W boson. Therefore, events with exactly one high- $p_T$  isolated electron or muon candidate and at least four jets are selected. Jets that originated from the hadronisation of a b-quark are identified via a multivariate algorithm [43, 44]. The operation point of the algorithm used for this measurement corresponds to 70% efficiency to tag b-quark jets with a rejection factor of about 130 for light-quark or gluon jets (the rejection factor is equal to the inverse of the probability to erroneously tag jets from light quarks or gluons). For the analysis at 7 TeV, at least one jet is required to be b-tagged, while events without b-tagged jets are kept in the 8 TeV analysis for the *in situ* calibration of the W+jets background.

Events from multijet and Z+jets production rarely feature neutrinos and thus are expected to have only small missing transverse momentum ( $p_T^{\text{miss}}$ ). The missing transverse momentum vector  $\vec{p}_T^{\text{miss}}$  is defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of all reconstructed objects in an event, and  $p_T^{\text{miss}}$  is its magnitude. In order to suppress these backgrounds, requirements are imposed on the  $p_T^{\text{miss}}$  value and the highly correlated transverse mass ( $m_T^W$ ) of the W boson candidate from the semi-leptonically decaying top quark, formed by the lepton and  $\vec{p}_T^{\text{miss}}$ . In the 7 TeV analysis, the  $p_T^{\text{miss}}$  value is required to be larger than 30 (20) GeV in the electron+jets (muon+jets) channel. In addition, the  $m_T^W$  value is required to be larger than 30 GeV in the electron+jets channel while the sum of  $p_T^{\text{miss}}$  and  $m_T^W$  must be larger than 60 GeV in the muon+jets channel. For the 8 TeV analysis, the requirements are slightly different:  $m_T^W + p_T^{\text{miss}} > 60$  GeV for events with exactly zero or one b-tagged jet, and  $p_T^{\text{miss}} > 40$  (20) GeV for events with exactly zero (one) b-tagged jet. In events with two or more b-tagged jets, no requirements on  $p_T^{\text{miss}}$  or  $m_T^W$  are made.

To measure the charge asymmetry, the full  $t\bar{t}$  system is reconstructed and the  $\Delta|y|$  distribution is unfolded to parton level. The reconstruction of the  $t\bar{t}$  system is achieved by using a kinematic fit [45] that assesses the compatibility of the observed event with the kinematic properties of  $t\bar{t}$  events using a likelihood approach. In this approach, the most likely combination out of all possible jet permutations is chosen. The observed  $\Delta|y|$  spectrum is unfolded to correct for acceptance and detector resolution effects using the fully Bayesian unfolding technique [46]. This method estimates the posterior probability density in bins of  $\Delta|y|$ , which is integrated to define the asymmetry in eq. (1.1). The treatment of systematic uncertainties is included by extending the likelihood entering the  $\Delta|y|$  posterior probability density computation with nuisance parameter terms that are marginalised. In the 7 TeV analysis, the charge asymmetry is computed from the unfolded  $\Delta|y|$  distribution. At 8 TeV, a fit that maximises the extended likelihood over six event categories, defined based on the lepton charge and the b-tagged jet multiplicity (zero b-tagged jets, one b-tagged jet, at least two b-tagged jets), is performed. The W+jets calibration factors are fitted during the posterior probability estimation, as the b-tagged jet multiplicity provides information about the heavy- and light-flavour composition of the W+jets background, while the lepton charge asymmetry is used to determine the normalisation of each W+jets component also during the posterior probability estimation. The signal fraction after applying the full selection is estimated to be 78% for both centre-of-mass energies.

The inclusive  $t\bar{t}$  charge asymmetries measured at 7 and 8 TeV can be found in table 1. The numbers quoted in table 1 cannot be used directly for the combination, as a breakdown into correlated and uncorrelated components of the total uncertainty is needed. For the 7 TeV analysis, the result before marginalisation is used;  $A_C^{\text{ATLAS}^7} = 0.006 \pm 0.010$  (stat)  $\pm 0.005$  (syst) =  $0.006 \pm 0.011$  (stat  $\oplus$  syst). For the 8 TeV combination, the expected uncertainties after marginalisation are used: the systematic uncertainty from each source is evaluated by building pseudo-data with variations of the predictions and for each one repeating the unfolding procedure, yielding  $A_C^{\text{ATLAS}^8} = 0.0090 \pm 0.0044$  (stat)  $\pm 0.0025$  (syst). The sum in quadrature of these individually estimated uncertainties is equal to the total uncertainty quoted in table 1.

The charge asymmetry is also measured as a function of several kinematic  $t\bar{t}$  variables, including the mass of the  $t\bar{t}$  system.

## 2.2 The CMS measurements

The CMS results used for the combinations are based on data taken at 7 TeV [10] and 8 TeV [12, 13], corresponding to integrated luminosities of 5.0 and 19.6 fb<sup>-1</sup>, respectively. Two different approaches are pursued for these measurements. The two approaches feature similar criteria to select events with a lepton+jets signature, but differ in the procedures to reconstruct the  $t\bar{t}$  pair and to measure the charge asymmetry. In this paper, the analyses are named as follows: “CMS unfolding” [10, 13] refers to the analysis in which the reconstructed distributions are unfolded to parton level and the charge asymmetry is measured in the unfolded distributions, similar to the approach in the ATLAS analysis, while “CMS template” [12] refers to a measurement of the charge asymmetry by fitting the reconstructed

distribution using dedicated templates for symmetric and antisymmetric components of the sensitive observable. The CMS unfolding analysis provides results at both centre-of-mass energies, while the CMS template analysis has only been performed on the data collected at 8 TeV.

For the simulation of the  $t\bar{t}$  signal at the two centre-of-mass energies, the NLO event generator POWHEG-BOX 1.0 is used, together with the CTEQ6M [25] (for 7 TeV) and CT10 (for 8 TeV) NLO PDF sets. Single-top-quark background events are simulated using the LO event generator MADGRAPH [47] 5.1.3 (for 7 TeV) or POWHEG-BOX (for 8 TeV). All events are generated assuming a top quark mass of  $m_t = 172.5$  GeV. The contributions from W and Z boson production in association with jets are simulated using MADGRAPH. The parton shower is simulated using PYTHIA (6.4.24 for 7 TeV and 6.4.26 for 8 TeV) with the Z2 [48] tune for 7 TeV and the Z2\* [49, 50] tune for 8 TeV in all samples. Data events from a sideband region, defined by relaxing the isolation or identification criteria for the lepton, are used to model the multijet background in the signal region.

To select events with a lepton+jets signature, candidate events are required to feature one highly energetic electron or muon, well isolated from other activity in the detector, and at least four jets. One of these jets has to be classified as a b-jet. For that purpose, in the 7 TeV analyses, the TCHE algorithm [51] is used which is based on the track with the second-highest impact parameter significance. At 8 TeV the more sophisticated combined secondary vertex (CSV) tagger [51] is applied. The tagging efficiencies of these algorithms at the chosen working points are 60% (TCHE) and 70% (CSV), with a rejection factor for light-quark and gluon jets of about 100. The selection criteria of the two analyses differ in the required minimum  $p_T$  of the selected jets. The CMS unfolding analysis considers jets with  $p_T > 30$  GeV, while in the CMS template analysis all jets with  $p_T > 20$  GeV are taken into account. As a result, the number of events available for the CMS template analysis is almost twice the number of events analysed in the CMS unfolding measurement.

### 2.2.1 The CMS unfolding analysis

In this analysis, the charge asymmetry is measured both inclusively and differentially as a function of different variables characterising the  $t\bar{t}$  system. In order to calculate the values of  $\Delta|y|$  and the variables used in the differential measurements, the four-momenta of top quarks and antiquarks are reconstructed from the decay products observed in the detector. The leptonically decaying W boson is reconstructed from the electron or muon and  $\vec{p}_T^{\text{miss}}$ . The assignment of the reconstructed jets to the final-state quarks is based on the b-tagging information of the jets and the invariant masses of the reconstructed top quarks and the hadronically decaying W boson.

To suppress the background contributions from multijet and Z+jets production, the events are required to satisfy  $p_T^{\text{miss}} > 40$  GeV in the 7 TeV analysis and  $m_T^W > 50$  GeV in the 8 TeV analysis. The invariant mass of the three-jet combination that yields the largest transverse momentum,  $M_3$ , is highly correlated with the mass of the hadronically decaying top quark. The  $M_3$  variable can therefore be used to distinguish between processes including a top quark and processes that do not contain any top quark. In the 7 TeV analysis,  $p_T^{\text{miss}}$  and  $M_3$  are fitted simultaneously to estimate the background contributions,



while at 8 TeV, the  $m_T^W$  variable and  $M_3$  are used. At both centre-of-mass energies, a signal fraction of 80% is estimated after applying the full selection, with the largest background contribution coming from W+jets production.

The  $\Delta|y|$  distribution, as well as the distributions of the other relevant variables, is corrected for background contributions and migration effects due to the resolution of the reconstruction procedure, and extrapolated from the selected events to the full phase space of  $t\bar{t}$  production. This is done by unfolding with the Tikhonov-based regularised matrix inversion method as implemented in TUnfold [52]. The measured inclusive charge asymmetries at the two centre-of-mass energies are listed in table 1.

## 2.2.2 The CMS template analysis

In this analysis, the reconstruction of the four-vectors of the top quark and antiquark is performed for all jet-parton assignments. For each assignment, the four-momenta of the selected jets are corrected according to the partons to which they are assigned. Flavour-dependent scale factors correcting the jet energies from reconstruction level to parton level are derived from simulated  $t\bar{t}$  events. In each event, one of the possible assignments is chosen based on a likelihood criterion that uses the b-tagging information and the invariant masses of the reconstructed hadronically decaying W boson and top quark. The energy resolution of the selected jets corresponding to the chosen assignment is further improved by applying a kinematic fit under the  $t\bar{t}$  hypothesis.

For the determination of the composition of the selected sample, a likelihood discriminant is constructed from the  $m_T^W$  variable and from the probability that at least one of the possible jet-parton assignments is the correct one. The latter is expressed by the product of two independent probabilities: one based on the invariant masses of the reconstructed hadronically decaying top quark and W boson, and one based on the b-tagging information of the jets assigned to b-quarks and light quarks. A maximum-likelihood fit using the distribution of the resulting discriminant is employed to determine the contributions from  $t\bar{t}$  signal events, W+jets events, and events from multijet production. The contributions from Z+jets processes and single-top-quark production are fixed to their SM predictions. The signal fraction in the selected data, determined with this method, is about 65%.

The charge asymmetry is measured in a second maximum-likelihood fit. The sensitive variable used in this analysis is  $\Upsilon_{t\bar{t}} = \tanh \Delta|y|$ . The hyperbolic tangent preserves the same asymmetry properties as the canonical  $\Delta|y|$ , with the additional feature that it is bounded to the range between  $-1$  and  $1$ . Signal events, simulated with the POWHEG-BOX event generator, are used to construct the symmetric and antisymmetric components of the probability distribution  $\rho(\Upsilon_{t\bar{t}})$  for the variable  $\Upsilon_{t\bar{t}}$ . From a linear combination of these two components a generalised model can be constructed with a single parameter  $\alpha$  that varies the amplitude of the antisymmetric component. The sample composition is fixed to the results of the first likelihood fit, and the charge asymmetry is determined by finding the value of  $\alpha$  for which the  $\Upsilon_{t\bar{t}}$  model best fits the data.

This method is only used to measure the inclusive charge asymmetry with 8 TeV data, and the result is shown in table 1.

### 3 Combination method

Three separate combinations of ATLAS and CMS results are performed: a combination of the inclusive results at 7 TeV, a combination of the inclusive results at 8 TeV, and a combination of the charge asymmetry measured differentially as a function of the invariant mass of the  $t\bar{t}$  system at 8 TeV. For the combination of the inclusive results at 8 TeV, the two most precise measurements are considered: the ATLAS analysis and the CMS template analysis. Because of the large correlation between the two CMS analyses available at 8 TeV, the impact of also adding the result of the 8 TeV CMS unfolding analysis to the combination is negligible (within the quoted precision of  $10^{-4}$ ). For the combination of the differential measurements, the ATLAS result is combined with the result of the CMS unfolding analysis.

In each combination, the two input results are combined by finding the best linear unbiased estimate (BLUE) [53, 54] with the method implemented in ref. [55]. The BLUE method finds the coefficients to be used in a linear combination of the input measurements by minimising the total uncertainty of the combined result, taking into account both the statistical and systematic uncertainties, as well as correlations between the inputs.

### 4 Classification of uncertainties and correlation of measurements

Dedicated studies are performed to estimate the influence of various systematic uncertainties on the results for all analyses considered for the combinations. In the ATLAS analyses, the expected impact of systematic uncertainties is studied with alternative pseudo-data distributions built from the expected signal and background contributions. These alternative pseudo-data sets are generated by varying each source of systematic uncertainty by one standard deviation ( $\pm 1\sigma$ ). The unfolding procedure is then repeated using the baseline background templates and response matrices. At 7 TeV, the impact of the uncertainty on the measured  $A_C$  value is reported as the difference between the mean value of the nominal posterior and the mean value of the varied posterior, and the maximum between the positive and negative variation is chosen as symmetric uncertainty. At 8 TeV, the average asymmetry variation  $|A_C(+1\sigma) - A_C(-1\sigma)|/2$  is quoted as the systematic uncertainty for each source.

In the CMS analyses, the uncertainties are estimated by repeating the analyses on data using simulated samples modified by the variations under study. This includes signal and background templates for the estimation of the signal and background contributions to the selected data set, as well as varied input information for the unfolding and template fitting procedure, respectively. The uncertainty is then defined as the difference between the results obtained using the default simulation and the results obtained using the altered simulation. Where two shifts for the same source of uncertainty are available the absolute value of the larger shift is chosen as the systematic uncertainty.

Although the list of evaluated sources of systematic uncertainty and the actual procedures to estimate their impacts are partially different between the analyses, it is still possible to identify contributions that describe similar physical effects. The classification

of the systematic uncertainties evaluated by the ATLAS and CMS analyses is described in the following, and their assumed correlations across experiments are given in parentheses. In the description below, “—” means that the uncertainty source is considered only either in the ATLAS or the CMS measurement. For some sources of uncertainty, two values are given for the correlation assumptions. In these cases, the first value applies to the combination of inclusive results (ATLAS analysis and CMS template analysis), while the second value applies to the combination of differential results (ATLAS analysis and CMS unfolding analysis). The classification of uncertainties is coarser for the combination of results at 7 TeV. For these analyses, several sources of uncertainty with similar physics origin are grouped together and only the resulting categories are used for the combination. The higher precision of the results at 8 TeV necessitates finer splitting of the various contributions to the overall systematic uncertainty. For a limited number of correlated systematic sources, it was verified that a particular systematic variation induces a change in each measurement in the same direction. The correlation of the measurements for each correlated uncertainty source is assumed to be always positive. The stability of the combinations under variations on the assumptions about the correlations between the systematic uncertainties is checked in section 6. The potential impact on the combination from using different procedures to estimate the systematic uncertainties in the ATLAS and CMS analyses is studied, for selected uncertainty contributions, by varying the correlations and the sizes of these systematic uncertainties. The combination is found to be stable against such variations. Uncertainty sources whose effect on the combined central value is smaller than the quoted precision, i.e. smaller than 0.001 for the combination at 7 TeV and smaller than 0.0001 for the combination at 8 TeV, are considered negligible.

#### 4.1 Uncertainties at 7 TeV

##### **Statistical uncertainty in data** (Correlation: 0)

This category includes the statistical uncertainty in the resulting asymmetry due to the size of the available data set.

##### **Statistical uncertainty in simulation** (Correlation: 0)

In each analysis, the impact of the statistical uncertainty in the extraction of the response matrix from simulation, used for unfolding, is estimated by independently varying the individual elements of the response matrix within their statistical uncertainties.

##### **Detector model** (Correlation: 0)

For each simulated event, scale factors are applied depending on the kinematic properties of the leptons to correct for their mismodelling in the simulation. The uncertainties in these scale factors are propagated to the asymmetry measurement. In addition, the uncertainty from lepton charge misidentification is included in the CMS analysis. Scale factors are also applied to the simulated jets to correct for small differences between the efficiencies for b-jet identification in simulation and data. The impact of the corresponding uncertainties on the measurements is found to be negligible in both analyses. All sources of uncertainty coming from the jet energy calibration, as well as from the modelling of the jet energy resolution in the simulation, are also considered as detector-related uncertainties. All these sources

of systematic uncertainties that are related to the modelling of the detectors are grouped together and assumed to be uncorrelated. Some smaller components of these uncertainties in the jet energy scale (JES) are, however, known to be correlated between the two experiments [56]. As their impact is negligible compared to the uncorrelated components, the assumption of no correlation between the two experiments is still appropriate.

#### **Pile-up and missing transverse momentum** (Correlation: 0)

In both analyses, additional interactions in the same or nearby bunch crossings (pile-up events) are overlaid on the simulated signal and background events. The distribution of pile-up events is adjusted by taking into account the measured instantaneous luminosities per bunch and an effective pp inelastic cross section. The impact on the CMS analysis from the uncertainty in this adjustment is found to be negligible. In the ATLAS analysis, this uncertainty is taken into account in the calculation of  $p_T^{\text{miss}}$ , in addition to propagated uncertainties in lepton and jet momenta.

#### **Signal modelling** (Correlation: 0.5)

In both analyses, the impact of using different MC event generators (POWHEG-BOX instead of ALPGEN in the ATLAS analysis, and MADGRAPH instead of POWHEG-BOX in the CMS analysis) is studied. Also, the difference between the hadronisation and parton shower models implemented in PYTHIA and HERWIG interfaced with the event generators described above is taken as a systematic uncertainty. Variations by a factor 0.5 and 2.0 of the factorisation and renormalisation scales in matrix element calculations, as well as in the parton shower, are also included. The assumed correlations for the different uncertainty sources of this category range from anticorrelated to fully correlated, thus a correlation of 50% is applied in the combination. However, since the impact of these uncertainties on the ATLAS measurement is negligible and taken to be zero in the combination, the actual choice of the correlation value does not affect the result.

#### **PDF** (Correlation: 1)

The systematic uncertainties arising from the choice of PDFs used in the simulation are estimated in both analyses using the eigenvectors of the CTEQ6.6 [57] PDF set. In the ATLAS analysis, two additional sets of PDFs are taken into account (MSTW2008 [58] and NNPDF2.1 [59]) in the estimation of the PDF uncertainty spread, as described in ref. [60]. In both analyses, the uncertainty is evaluated for the signal events, as well as for the main background source, W+jets events.

### **Backgrounds**

- *Modelling of multijet production* (Correlation: 0)

In the ATLAS analysis, both the shape and normalisation uncertainties in the multijet background are estimated through the matrix method [42]. The impact of this uncertainty on the asymmetry measurement is found to be negligible. In the CMS analysis, effects of shape variations on the  $\Delta|y|$  template from the multijet background model based on data are examined by inverting for each event the sign of the  $\Delta|y|$  value to get an alternative shape.

- *Modelling of W+jets* (Correlation: 0.5)

In the ATLAS analysis, the ALPGEN factorisation and renormalisation scales are varied in the W+jets simulation with the same factors as for the signal model uncertainty. In the CMS analysis, a different approach is pursued: the templates for W+jets events with negatively charged leptons are interchanged with the templates for W+jets events with positively charged leptons. As the two methods are only partially correlated, a 50% correlation is assumed between these two systematic uncertainties. As shown in section 6, this particular choice of correlation strength has no significant impact on the combination result.

#### **Model dependence** (Correlation: —)

In both analyses, the potential dependence on the underlying model used to develop the analysis is estimated by using signal samples corresponding to different physical models. The two approaches differ, however, in the type and range of the evaluated variations in the asymmetry. In the ATLAS analysis, relatively small variations in the asymmetry are tested, resulting from different physics models beyond the standard model used for the simulation of the signal sample (*specific physics models*). In the CMS analysis, on the other hand, relatively large variations are tested, regardless of whether or not their realisation is possible in any physics model (*general simplified models*). Because of these differences in the range and motivation of the tested variations, the resulting uncertainties are treated as two different uncertainties, each only evaluated in one of the analyses.

## **4.2 Uncertainties at 8 TeV**

#### **Statistical uncertainty in data** (Correlation: 0)

For the ATLAS analysis and the CMS template analysis, this category includes the statistical uncertainty in the resulting asymmetries. In the ATLAS measurement, the statistical uncertainty is obtained by running the unfolding procedure without taking any systematic effects into account. For the CMS unfolding analysis, this category includes, in addition, the uncertainties in the normalisation of the background processes and the uncertainty due to the number of simulated events in the simulated signal samples. The uncertainties in the normalisation of the background processes and the uncertainty due to the number of simulated events are treated as systematic uncertainties in the ATLAS analysis and the CMS template analysis. The statistical uncertainties are considered to be uncorrelated between the ATLAS and CMS analyses.

#### **Statistical uncertainty in simulation** (Correlation: 0 / —)

In the ATLAS analysis, the impact of the size of the simulated signal event sample is investigated by repeating the unfolding several times on one single pseudo-data set with randomly drawn response matrices. A similar approach is followed in the CMS unfolding analysis, with the only differences being that the unfolding is carried out on the measured data instead of one pseudo-data set, and that the resulting uncertainty is included in the statistical uncertainty of the result. The CMS template analysis uses ensembles of alternative templates, generated by varying the original templates according to Poisson statistics

to estimate the impact of the sample size. This systematic uncertainty is considered to be uncorrelated between the ATLAS analysis and the CMS template analysis.

### Detector model (excluding JES)

- *Leptons* (Correlation: 0)  
This category includes the uncertainty in the scale factors that are used to correct for mismodelling of the trigger response, as well as of the lepton identification and reconstruction efficiency. The resulting uncertainties are considered to be uncorrelated between the ATLAS and CMS analyses.
- *Jet energy resolution* (Correlation: 0)  
This category includes the contributions due to uncertainties in the modelling of the jet energy resolution. These uncertainties are considered to be uncorrelated between the ATLAS and CMS analyses.
- *b-tagging* (Correlation: 0)  
The two collaborations split up the different sources of b-tagging-related systematic uncertainties in a different way. However, as the b-tagging uncertainties in all three analyses are relatively small contributions to the overall uncertainty, the different b-tagging uncertainties for each analysis are combined by adding their contributions in quadrature to obtain only one b-tagging uncertainty per analysis. The resulting uncertainties are assumed to be uncorrelated between the ATLAS and CMS analyses.
- *Missing transverse momentum* (Correlation: —)  
The  $p_T^{\text{miss}}$  reconstruction is affected by uncertainties associated with leptons, jet energy scales and resolutions, which are propagated to the  $p_T^{\text{miss}}$  calculation, as well as by uncertainties associated with the modelling of the underlying event. This was estimated only in the ATLAS analysis and the effect is small; for the CMS analyses, the uncertainties due to the underlying event modelling are studied and found to be negligible compared to other  $p_T^{\text{miss}}$ -related uncertainties. The effects on the  $p_T^{\text{miss}}$  value are, however, not estimated as a separate source of uncertainty but considered implicitly in other uncertainty sources by propagating variations into the calculation of  $p_T^{\text{miss}}$ . Thus, no assumption about the correlation between ATLAS and CMS has to be made.
- *Pile-up* (Correlation: —)  
In the CMS analyses, the impact of a potential mismodelling of the pile-up component overlaid on the simulated events is estimated by varying the number of simulated pile-up events. For the ATLAS analysis, this uncertainty contribution is included in one of the jet energy scale uncertainties described below (*Uncorrelated JES*), and thus not treated as a separate source of uncertainty. Again, no assumption about the correlation between ATLAS and CMS has to be made.

## Jet energy scale

In all three analyses, the same jet clustering algorithm, the anti- $k_T$  algorithm [61], is employed, with different values for the radius parameter  $R$  ( $R = 0.4$  for ATLAS,  $R = 0.5$  for CMS). In the ATLAS analysis, jets are built from energy deposits in the calorimeter, while in the CMS analyses, jets are reconstructed from particle-flow [62] objects. Thus, the calibration procedure and uncertainties in the calibration are quite different. Both collaborations determine a large number of single sources that contribute to the overall uncertainty in the jet energy calibration, which can be grouped into categories with similar ranges of correlation [63].

- *Uncorrelated* JES (Correlation: 0)  
This category includes all components of the JES uncertainties that are uncorrelated between ATLAS and CMS (i.e. statistical and detector-related effects, pile-up, and high- $p_T$  uncertainty components) and uncertainties that do not match between the two experiments.
- *Partially correlated* JES (Correlation: 0.5)  
This category includes the modelling uncertainties of the *in situ* methods used in both collaborations for the determination of the jet energy calibration. While both collaborations measure similar systematic effects, the actual impact has some dependence on the detector itself and on the choices of the technical implementation. The uncertainties of the two analyses are therefore assumed to be partially correlated and the range from 0.0 to 0.5 is scanned. The most conservative result is obtained assuming a correlation of 50%.
- *Mostly correlated* JES (Correlation: 1)  
The calibration of jet energies across  $\eta$  with respect to a well-understood central reference region is sensitive to the modelling of radiation. In both collaborations, similar event generators and techniques are used to estimate the influence of different radiation patterns in the simulation on the jet energy. These uncertainties are expected to be highly correlated, although there are some expected decorrelations from differences in the analysis procedures. As such, the uncertainties assigned to this category are treated as mostly correlated and the range from 0.5 to 1.0 is evaluated. The most conservative result is obtained assuming a correlation of 100%.
- *Fully correlated* JES (Correlation: 1)  
Uncertainties in the JES due to the flavour of jets are grouped into this category. This includes effects due to differences in the jet energy response for various jet flavours and effects from differences in the flavour mixture, compared to the mixture used in the calibration procedures. The assumed correlation between ATLAS and CMS for this uncertainty category is 100%.

## Signal modelling

- *Generator* (Correlation: 1)  
The impact of using a different MC event generator is studied in all three analyses:

MC@NLO instead of POWHEG-BOX in the ATLAS analysis, MADGRAPH instead of POWHEG-BOX in the CMS unfolding analysis, and MC@NLO instead of POWHEG-BOX in the CMS template analysis. These uncertainties are assumed to be fully correlated between the ATLAS and CMS analyses.

- *Parton shower and hadronisation* (Correlation:  $-/1$ )  
The results with different implementations of parton showering and hadronisation in PYTHIA and HERWIG, interfaced with the event generators listed above, are used to estimate the uncertainties in the modelling of the parton shower and hadronisation process. This uncertainty category is assumed to be 100% correlated between the ATLAS analysis and the CMS unfolding analysis, while it has not been evaluated for the CMS template analysis. The impact of an additional uncertainty for the CMS template analysis on the combination was studied by using the parton shower and hadronisation uncertainty of the CMS unfolding analysis, and was found to be small (see section 6.2).
- *Initial-state and final-state radiation and choice of the factorisation and renormalisation scales* (Correlation: 1)  
The uncertainties due to the modelling of additional radiation are assumed to be fully correlated between the ATLAS and CMS analyses, although the two collaborations follow different methods to estimate this impact. In the ATLAS analysis, the uncertainty associated with the modelling of initial-state and final-state radiation is estimated using the ACERMC event generator with varied parameters. In the CMS analyses, a different approach is followed and the factorisation and renormalisation scales are varied in the simulation of the matrix element, as well as in the parton shower, by factors of 0.5 and 2.0.
- *Modelling of the top quark  $p_T$*  (Correlation:  $-$ )  
In the CMS analyses, the simulated  $t\bar{t}$  events are reweighted to correct the  $p_T$  spectrum of the generated top quarks, which was found to be significantly harder than the observed spectra in differential cross section measurements [64]. To estimate the uncertainty related to this mismodelling, the measurement is repeated without the reweighting and the difference with respect to the default result is taken as a measure of the uncertainty. In the ATLAS analysis, the measured  $p_T$  distribution of the reconstructed top quarks is found to agree well with the simulation using the POWHEG-BOX+HERWIG MC sample [65]. Since this sample is used to derive the uncertainty due to parton shower and hadronisation modelling, no additional uncertainty is assigned for the modelling of the  $p_T$  spectrum of top quarks in the ATLAS analysis. For the CMS template analysis, the contribution of this uncertainty is found to be negligible.
- *Parton distribution functions* (Correlation: 1)  
The uncertainties due to the choice of PDFs are considered to be fully correlated between ATLAS and CMS analyses. In the ATLAS analysis and CMS unfolding analysis, the uncertainty in the PDFs is estimated using three different PDF sets (CT10,



MSTW2008, and NNPDF2.1), while in the CMS template analysis the variations of the CT10 eigenvectors are used and variations of the strong coupling parameter are considered independently. In the two CMS analyses, the influence of PDF variations on the modelling of the  $t\bar{t}$  process is estimated, while in the ATLAS analysis the impact of the choice of PDF on the modelling of the W+jets background is also evaluated. The latter is captured in the two CMS analyses by the uncertainty source “Modelling of W+jets” in the category “Backgrounds”.

### **Integrated luminosity** (Correlation: —)

The luminosity used to construct the fit model in the CMS template analysis is varied by  $\pm 4.4\%$ . In the other two analyses, varying the integrated luminosity has negligible effect on the results.

### **Backgrounds**

- *Single-top-quark and Z+jets* (Correlation: 1/—)  
In the ATLAS analysis, an uncertainty arises from the uncertainty in the single-top-quark and Z+jets background normalisations from the theoretical cross sections, as well as an additional normalisation uncertainty for each additional jet. In the CMS template analysis, this uncertainty includes the uncertainties in the single-top-quark and Z+jets production cross sections, as well as the uncertainty in the ratio of single-top-quark to single-top-antiquark production. In the CMS unfolding analysis, the uncertainties in the normalisation of background contributions are considered when subtracting these contributions from the measured data distribution in the unfolding step and are therefore contained in the statistical uncertainty of the result and not treated as a separate systematic uncertainty. For the combination of the ATLAS analysis and CMS template analysis, these uncertainties are considered fully correlated, while they do not apply to the CMS unfolding analysis.
- *Modelling of multijet production* (Correlation: 0)  
In the ATLAS analysis, the uncertainties in the multijet background come from the size of the data sample used in the matrix method, as well as from the uncertainties in the estimation of the misidentified lepton probability in different control regions. In the CMS template analysis, the uncertainty comes mainly from the size of the data sideband sample used for the modelling of the multijet process. In the CMS unfolding analysis, variations in the shapes of the multijet templates derived from sideband regions in data, are used to estimate the uncertainty in the modelling of this background component. These uncertainties are considered to be uncorrelated between the ATLAS and CMS analyses.
- *Modelling of W+jets* (Correlation: —)  
In order to estimate the influence of a possible mismodelling of the simulated W+jets background, the CMS unfolding measurement is repeated using a W+jets template determined from a sideband region in data, defined by requiring exactly zero b-tagged

jets. The CMS template analysis constructs an alternative W+jets template by increasing or decreasing the number of events with heavy-flavour jets. In addition, the uncertainty in the estimated W+jets normalisation is propagated into this uncertainty. The W+jets component of the data set is estimated *in situ* in the ATLAS analysis using separate templates for the different flavours, and therefore no additional uncertainty is taken into account.

**Method** (Correlation:  $-/0$ )

The uncertainty from the unfolding procedure is determined using pseudo-data sets in which the  $t\bar{t}$  signal events are reweighted to simulate different values of the charge asymmetry by applying the default response matrix and comparing the true charge asymmetry values with the values obtained after unfolding. In the ATLAS analysis, a linear fit of the generator-level asymmetry versus the unfolded asymmetry is performed and the uncertainty in the unfolding is calculated from the slope and the offset of this fit. In the CMS unfolding analysis, different scenarios for reweighted  $t\bar{t}$  events are examined and the differences between the unfolded asymmetries and the reweighted true asymmetries are taken to be a measure of the model dependence of the unfolding procedure. The uncertainty is assumed to be uncorrelated between ATLAS measurement and the CMS unfolding measurement. In the CMS template analysis, pseudo-data sets are constructed for different values of  $A_C$  by changing the mixture of symmetric and antisymmetric components in the sample of simulated signal events. The difference between the mean charge asymmetry measured for each alternative model and the actual charge asymmetry is found to be negligible.

Even if the systematic uncertainties for the 7 and 8 TeV results are not fully evaluated in the same way, most of the assigned correlations between the ATLAS and CMS measurements are identical between 7 and 8 TeV. As discussed in section 4.1, the systematic uncertainty in the detector model is assumed to be uncorrelated at 7 TeV since the components that could be considered correlated (for example JES) are small. For the signal modelling uncertainties, the correlation choice of 0.5 at 7 TeV does not affect the result because the signal modelling has a negligible effect on the ATLAS measurement at 7 TeV.

### 4.3 Correlation assumptions in the combination of differential results at 8 TeV

An additional complication in the combination of differential measurements, with respect to inclusive ones, is that the correlations between different bins in the mass distribution of the  $t\bar{t}$  system have to be taken into account in addition to the correlations between categories of systematic uncertainties. The ATLAS analysis and the CMS unfolding analysis use the same number of bins and the same ranges for the bins. The mapping of systematic uncertainties in each bin between the ATLAS analysis and the CMS unfolding analysis is the same as for the combination of the inclusive results.

Bin-to-bin correlations are considered by the analyses for each uncertainty. In the CMS unfolding analysis, the statistical correlations are calculated *in situ* during the unfolding process. To evaluate the bin-to-bin correlations for systematic uncertainties, for each source of systematic uncertainty  $u$ , the measurement is repeated on data using mod-

ified simulated samples, resulting in new values for the charge asymmetries per bin. The changes in unfolded asymmetries are then used to construct a systematic covariance matrix in a loose analogy to statistical covariance matrices. For an uncertainty described by a single systematic shift, a covariance of

$$\text{cov}^u(c_i, c_j) = (A_C^u(c_i) - A_C^{\text{nom}}(c_i)) (A_C^u(c_j) - A_C^{\text{nom}}(c_j)) \quad (4.1)$$

is used, with  $c_i$  and  $c_j$  referring to bins in  $m_{t\bar{t}}$  of the CMS analysis, and  $A_C^u(c_i)$  and  $A_C^u(c_j)$  being the asymmetry values for these bins resulting from the systematic shift, and  $A_C^{\text{nom}}(c_i)$  and  $A_C^{\text{nom}}(c_j)$  being the results of the nominal measurement.

For uncertainties that are determined using exactly two variations (up and down variation, indexed by + and -), the absolute values of the maximal shifts observed in each result bin are determined by

$$\Delta_{\text{max}} A_C(c_i) = \max \left( \left| A_C^{u,+}(c_i) - A_C^{\text{nom}}(c_i) \right|, \left| A_C^{u,-}(c_i) - A_C^{\text{nom}}(c_i) \right| \right),$$

and the covariance is then defined as

$$\begin{aligned} \text{cov}^u(c_i, c_j) = & \Delta_{\text{max}} A_C(c_i) \Delta_{\text{max}} A_C(c_j) \\ & \times \text{sign} \left[ \left( A_C^{u,+}(c_i) - A_C^{u,-}(c_i) \right) \left( A_C^{u,+}(c_j) - A_C^{u,-}(c_j) \right) \right]. \end{aligned}$$

This procedure corresponds to a symmetrisation of the largest observed shifts, and thus constitutes a more conservative uncertainty estimate than an approach based on a direct analogy with statistical covariance definitions. The resulting covariance matrices are transformed into correlation matrices for the combination. For uncertainty sources that are described by a single systematic shift, the covariance matrix in eq. (4.1) corresponds to a correlation matrix with  $\pm 1$  entries only:

$$\text{corr}^u(c_i, c_j) = \text{sign} \left[ \left( A_C^u(c_i) - A_C^{\text{nom}}(c_i) \right) \left( A_C^u(c_j) - A_C^{\text{nom}}(c_j) \right) \right]. \quad (4.2)$$

However, for uncertainties where several shifts are combined, e.g. the uncertainty from the PDF choice, first all covariance matrices are combined, and this combined covariance matrix is then transformed into a correlation matrix, yielding entries in the correlation matrix different from  $\pm 1$ .

In the ATLAS analysis, the correlations between bins  $a_i$  and  $a_j$  for each source of systematic uncertainty that is marginalised are extracted by projecting the posterior probability density into the  $(a_i, a_j)$  plane. The correlation is then computed from the ensemble points that build the probability density in this plane, taking the average between the up and down variations as for the computation of the systematic uncertainty itself. The correlation matrix for the modelling uncertainties that are not marginalised is obtained using eq. (4.2), yielding entries with  $\pm 1$ . The correlation matrix for the systematic uncertainty coming from the size of the simulated samples is taken to be the identity matrix.

For the estimation of the correlations between bins from two different experiments that use the same binning scheme, one can distinguish two cases: the correlations between the same bins of the ATLAS and CMS results, and the correlations between different bins of

the ATLAS and CMS results. In the first case, for each uncertainty source, the correlation assumptions of the inclusive combination are used.

The bin-to-bin correlations for a given uncertainty can be different in the two analyses because of the differences in the unfolding techniques and in the methods used to determine these correlations. This is especially the case for uncertainty categories that include several contributions, e.g. the uncertainty from the PDF choice or the JES uncertainty categories. A straightforward determination of the correlation between different bins in the ATLAS and CMS measurements is therefore not possible. These off-diagonal elements of the correlation matrices are instead calculated by multiplying the assumed correlation of the uncertainty  $u$ ,  $\rho_u$ , with a correction factor depending on the bin-to-bin correlations within the individual experiments.

The correlation for a given uncertainty source  $u$  between  $a_i$  and  $c_j$  can thus be calculated as:

$$\text{corr}^u(a_i, c_j)' = \text{corr}^u(a_i, c_i) \text{corr}^u(c_i, c_j) = \rho_u \text{corr}^u(c_i, c_j). \quad (4.3)$$

Due to symmetry reasons, there is also an alternative way to calculate the correlation, starting from the ATLAS bin-to-bin-correlations instead of the CMS ones:

$$\text{corr}^u(a_i, c_j)'' = \text{corr}^u(a_i, a_j) \text{corr}^u(a_j, c_j) = \text{corr}^u(a_i, a_j) \cdot \rho_u. \quad (4.4)$$

As both methods are valid, the mean of the two estimates  $\text{corr}^u(a_i, c_j)'$  and  $\text{corr}^u(a_i, c_j)''$  is used for the combination

$$\text{corr}^u(a_i, c_j) = \rho_u \frac{\text{corr}^u(c_i, c_j) + \text{corr}^u(a_i, a_j)}{2}, \quad (4.5)$$

while the impact of using either only eq. (4.3) or (4.4) is studied as a check of the stability of the combination.

## 5 Combination of the results

### 5.1 Combination of inclusive results at 7 TeV

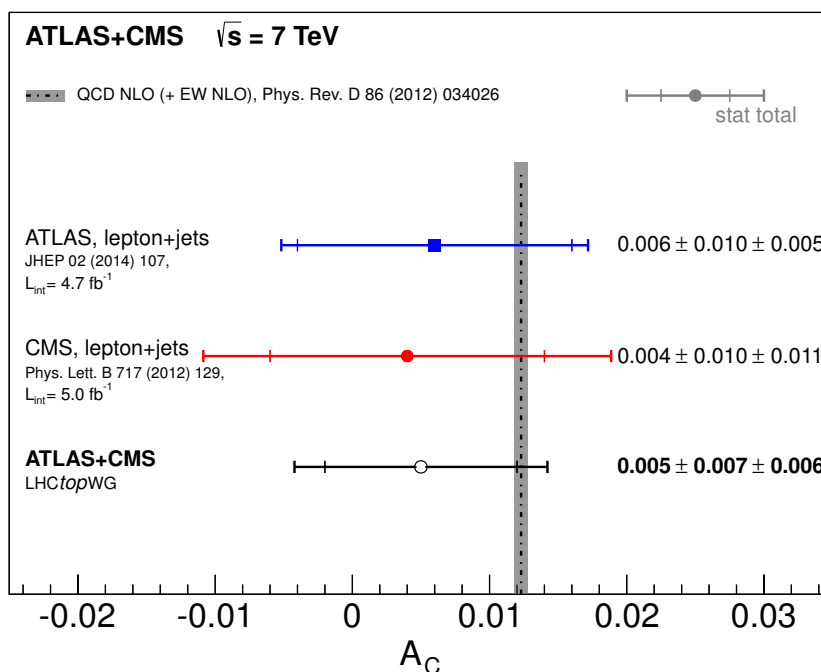
The value resulting from the combination of the inclusive measurements at 7 TeV is

$$A_C^{\text{LHC7}} = 0.005 \pm 0.007 (\text{stat}) \pm 0.006 (\text{syst}).$$

This corresponds to an improvement in the total uncertainty of about 18% with respect to the ATLAS result alone, and an improvement of about 40% with respect to the CMS result. The ATLAS result contributes with a weight of 0.65 to the combined result, while the weight of the CMS result is 0.35. The  $\chi^2$  of the combination is 0.012 (one degree of freedom), corresponding to a  $p$ -value of 0.91. A breakdown of the individual uncertainties and their combined values is provided in table 2. Figure 1 illustrates the two individual inclusive results and their combination, along with the respective uncertainties, and compares them to the prediction from theory [19], calculated at NLO, including electroweak (EW) corrections.

|                              | ATLAS  | CMS    | $\rho$ | Combined |
|------------------------------|--------|--------|--------|----------|
| $A_C$                        | 0.006  | 0.004  | 0.058  | 0.005    |
| Statistical (data)           | 0.010  | 0.010  | 0      | 0.007    |
| Statistical (simulation)     | 0.002  | 0.002  | 0      | 0.001    |
| Detector model               | 0.004  | 0.007  | 0      | 0.004    |
| Pile-up+ $p_T^{\text{miss}}$ | 0.002  | <0.001 | 0      | 0.001    |
| Signal modelling             | <0.001 | 0.002  | 0.5    | 0.001    |
| PDF                          | 0.001  | 0.002  | 1      | 0.001    |
| Multijet                     | <0.001 | 0.001  | 0      | <0.001   |
| W+jets                       | 0.002  | 0.004  | 0.5    | 0.003    |
| Model dependence             |        |        |        |          |
| Specific physics models      | <0.001 | —      | —      | <0.001   |
| General simplified models    | —      | 0.007  | —      | 0.002    |
| Systematic uncertainty       | 0.005  | 0.011  |        | 0.006    |
| Total uncertainty            | 0.011  | 0.015  |        | 0.009    |

**Table 2.** Uncertainties in the input measurements, assumed correlations  $\rho$  between the uncertainties, and the resulting values for the uncertainties in the inclusive combination at  $\sqrt{s} = 7$  TeV. Systematic uncertainties smaller than 0.001 are shown as “<0.001” in the table and are ignored in the combination.



**Figure 1.** Summary of the single inclusive measurements and the LHC combination at  $\sqrt{s} = 7$  TeV compared to the theoretical prediction calculated at NLO precision in the strong coupling constant (including NLO electroweak corrections). The inner bars indicate the statistical uncertainty, while the outer bars indicate the total uncertainty. The uncertainty in the theoretical prediction is dominated by uncertainties due to scale variations.

## 5.2 Combination of inclusive results at 8 TeV

The resulting value of the combination of the inclusive measurements at 8 TeV is

$$A_C^{\text{LHC8}} = 0.0055 \pm 0.0023 (\text{stat}) \pm 0.0025 (\text{syst}).$$

This corresponds to an improvement in the total uncertainty of about 32% with respect to the ATLAS result alone, and an improvement of about 17% with respect to the CMS template result. The ATLAS result contributes with a weight of 0.39 to the combined result, while the weight of the CMS template result is 0.61. The  $\chi^2$  of the combination is 0.88 (one degree of freedom), corresponding to a  $p$ -value of 0.35. A breakdown of the individual uncertainties and their combined values is provided in table 3. Figure 2 illustrates the two individual inclusive results and their combination, along with the respective uncertainties, and compares them to theoretical predictions. Figure 3 compares the  $A_C$  value from the combination described in this article and the  $A_{\text{FB}}$  values measured by the Tevatron experiments with predictions from the SM and from BSM theories (see [5] for a review). The BSM theories include models with charged  $W'$  bosons with right-handed couplings, heavy colour-octet vector gluons  $G_\mu$  with axial couplings, colour-singlet Higgs boson like isodoublets  $\phi$ , colour-triplet scalars  $\omega^4$ , and colour-sextet scalars  $\Omega^4$  with right-handed flavour-violating  $tu$  couplings. Details of these BSM models can be found in refs. [66, 67]. The combined  $A_C$  value uniquely restricts wide regions of the possible BSM parameter space, e.g. for axigluon models.

## 5.3 Combination of differential results at 8 TeV

The values of the combined charge asymmetries in six bins of  $m_{t\bar{t}}$  can be found in table 4. Within their statistical and systematic uncertainties, the combined results agree with the predictions from SM calculations. Depending on the  $m_{t\bar{t}}$  bin, the total uncertainty corresponds to an improvement in precision between 20% (bin 6) and 52% (bin 1) with respect to the ATLAS measurement alone, and to an improvement in precision between 9% (bin 1) and 31% (bin 6) with respect to the CMS measurement alone. Table 5 shows the correlations between the bins of the combined result. Looking only at the leading contributions, the ATLAS measurement contributes, depending on the  $m_{t\bar{t}}$  bin, with a weight between 0.22 (bin 1) and 0.59 (bin 6) to the combined results, while the weights of the CMS results lie in the range from 0.41 (bin 6) to 0.78 (bin 1). The total  $\chi^2$  of the combination is 4.01 (six degrees of freedom), corresponding to a  $p$ -value of 0.69. Figure 4 shows the differential  $A_C$  distributions of the individual measurements and the combination, along with their total uncertainties. In figure 5, the combined result is compared to two predictions for the SM, calculated at NLO [19] and at NNLO [20–22], and to predictions for two versions of a colour-octet model [68]. The latter models are examples that give moderate positive contributions to the forward-backward asymmetry at the Tevatron and a negligible contribution to the inclusive charge asymmetry at the LHC. However, they differ significantly in the asymmetry for the last bin with the difference being similar in size to the uncertainty in the combined LHC result.

|                                       | ATLAS  | CMS    | $\rho$ | Combined |
|---------------------------------------|--------|--------|--------|----------|
| $A_C$                                 | 0.0090 | 0.0033 | 0.13   | 0.0055   |
| Statistical (data)                    | 0.0044 | 0.0026 | 0      | 0.0023   |
| Statistical (simulation)              | 0.0010 | 0.0015 | 0      | 0.0010   |
| <i>Detector model (excluding JES)</i> |        |        |        |          |
| Leptons                               | 0.0003 | 0.0001 | 0      | 0.0001   |
| Jet energy resolution                 | 0.0005 | 0.0004 | 0      | 0.0003   |
| b-tagging                             | 0.0004 | 0.0007 | 0      | 0.0005   |
| Missing transverse momentum           | 0.0002 | —      | —      | 0.0001   |
| Pile-up                               | —      | 0.0003 | —      | 0.0002   |
| <i>Jet energy scale</i>               |        |        |        |          |
| Uncorrelated JES                      | 0.0010 | 0.0004 | 0      | 0.0005   |
| Partially correlated JES              | 0.0009 | 0.0010 | 0.5    | 0.0008   |
| Mostly correlated JES                 | 0.0002 | 0.0004 | 1      | 0.0003   |
| Fully correlated JES                  | 0.0009 | 0.0008 | 1      | 0.0008   |
| <i>Signal modelling</i>               |        |        |        |          |
| Event generator                       | 0.0004 | 0.0002 | 1      | 0.0003   |
| Parton shower and hadronisation       | 0.0004 | —      | —      | 0.0002   |
| Scale/radiation                       | 0.0009 | 0.0014 | 1      | 0.0012   |
| PDF                                   | 0.0007 | 0.0002 | 1      | 0.0004   |
| Integrated luminosity                 | —      | 0.0001 | —      | 0.0001   |
| <i>Backgrounds</i>                    |        |        |        |          |
| Single-top-quark / Z+jets             | 0.0001 | 0.0004 | 1      | 0.0003   |
| Multijet                              | 0.0005 | 0.0018 | 0      | 0.0011   |
| W+jets                                | —      | 0.0002 | —      | 0.0001   |
| Method                                | 0.0003 | —      | —      | 0.0001   |
| Systematic uncertainty                | 0.0025 | 0.0033 |        | 0.0025   |
| Total uncertainty                     | 0.0051 | 0.0041 |        | 0.0034   |

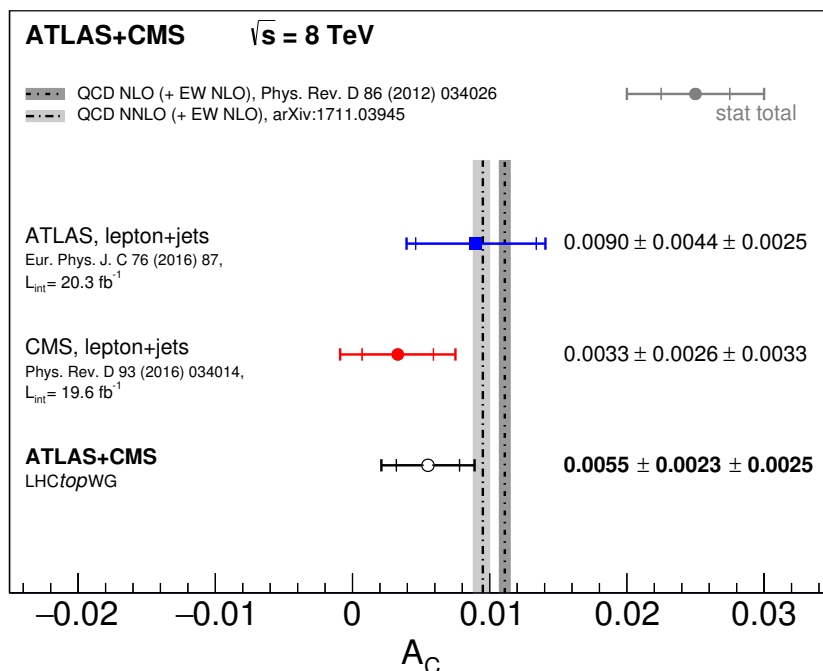
**Table 3.** Uncertainties in the input measurements, assumed correlations  $\rho$  between the uncertainties, and the resulting values for the uncertainties in the inclusive combination at  $\sqrt{s} = 8$  TeV. The breakdown of the systematic uncertainties of the ATLAS analysis (for the systematic uncertainties that are marginalised) corresponds to the expected uncertainties after marginalisation.

## 6 Stability studies

The stability of the combinations with respect to the assumptions made about the correlations between the systematic uncertainties is studied by varying the input assumptions. The resulting central value and total uncertainty are then compared to the result obtained using the default settings.

### 6.1 Stability checks at 7 TeV

At  $\sqrt{s} = 7$  TeV, for uncertainties with an assumed default correlation of 100% or of zero, the assumption of 50% correlation is tried. For the uncertainty in the modelling of the W+jets background, for which the nominal assumption is 50% correlation, both zero and 100% correlation are tested. Changing the correlation assumptions in the described way

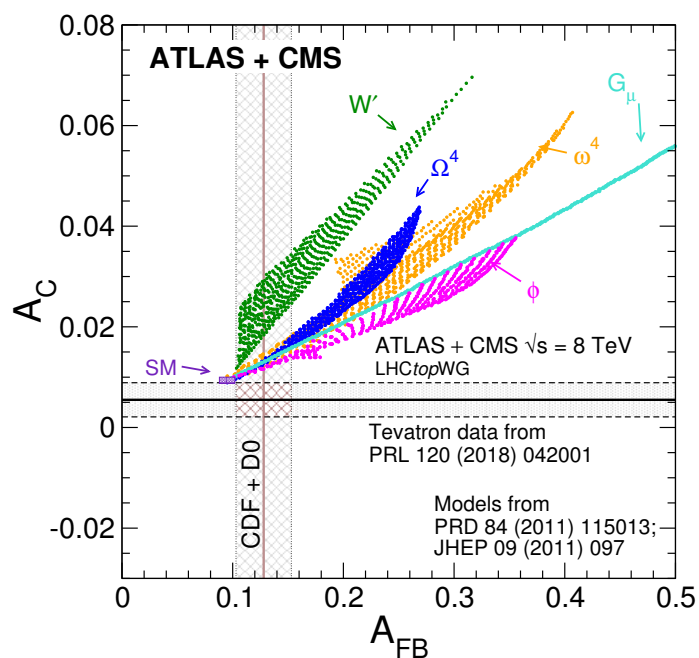


**Figure 2.** Summary of the single inclusive measurements and the LHC combination at  $\sqrt{s} = 8$  TeV compared to theoretical predictions at NLO [19] and NNLO [23] precision in the strong coupling constant (including NLO electroweak corrections). The inner bars indicate the statistical uncertainty, while the outer bars indicate the total uncertainty. The uncertainty in the theoretical predictions is dominated by uncertainties due to scale variations.

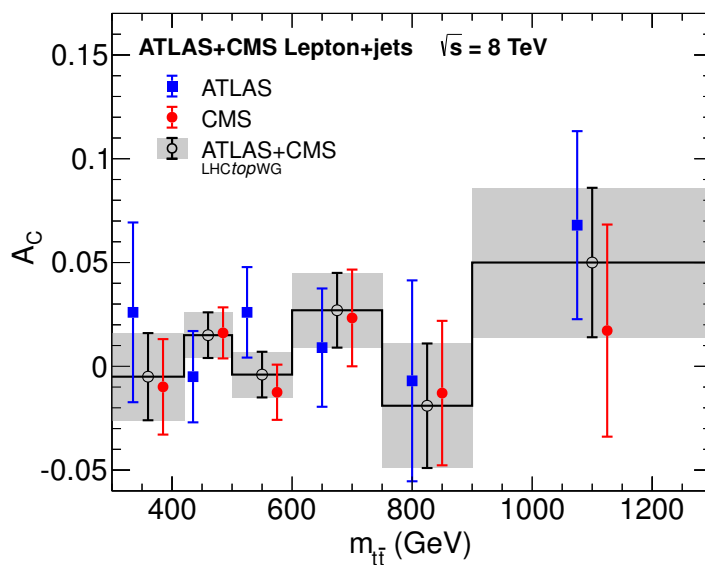
|                         | $m_{t\bar{t}}$ bin (GeV) |          |          |          |          |          |
|-------------------------|--------------------------|----------|----------|----------|----------|----------|
|                         | <420                     | 420–500  | 500–600  | 600–750  | 750–900  | >900     |
| ATLAS $A_C$             | 0.026                    | −0.005   | 0.026    | 0.009    | −0.007   | 0.068    |
| statistical uncertainty | 0.025                    | 0.017    | 0.018    | 0.023    | 0.042    | 0.037    |
| systematic uncertainty  | 0.036                    | 0.015    | 0.012    | 0.017    | 0.025    | 0.026    |
| CMS $A_C$               | −0.010                   | 0.016    | −0.013   | 0.023    | −0.013   | 0.017    |
| statistical uncertainty | 0.020                    | 0.011    | 0.012    | 0.015    | 0.026    | 0.038    |
| systematic uncertainty  | 0.012                    | 0.006    | 0.006    | 0.018    | 0.023    | 0.035    |
| Combined $A_C$          | −0.005                   | 0.015    | −0.004   | 0.027    | −0.019   | 0.050    |
| statistical uncertainty | 0.017                    | 0.009    | 0.009    | 0.012    | 0.022    | 0.027    |
| systematic uncertainty  | 0.013                    | 0.006    | 0.007    | 0.014    | 0.020    | 0.024    |
| QCD NLO + EW NLO        | 0.00809                  | 0.01117  | 0.01138  | 0.01335  | 0.01671  | 0.02100  |
| uncertainty             | 0.00036                  | 0.00053  | 0.00039  | 0.00038  | 0.00058  | 0.00025  |
| QCD NNLO + EW NLO       | 0.00690                  | 0.00950  | 0.01095  | 0.01219  | 0.01327  | 0.01286  |
| uncertainty             | +0.00061                 | +0.00081 | +0.00079 | +0.00054 | +0.00075 | +0.00083 |
|                         | −0.00058                 | −0.00087 | −0.00095 | −0.00081 | −0.00101 | −0.00231 |

**Table 4.** ATLAS and CMS charge asymmetry results at 8 TeV in six bins of  $m_{t\bar{t}}$  and the combined values along with statistical and systematic uncertainties. In addition the predictions from QCD calculations at NLO [19] and NNLO [23] are given.

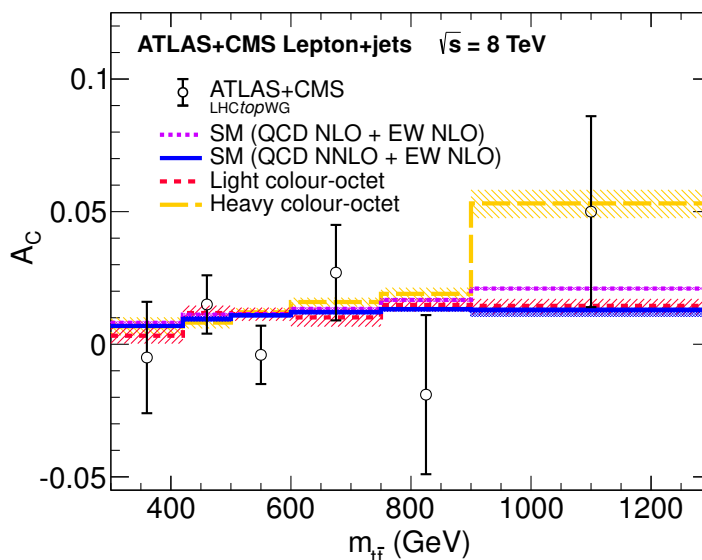




**Figure 3.** Measured inclusive charge asymmetry  $A_C$  at the LHC at  $\sqrt{s} = 8$  TeV (horizontal line) versus forward-backward asymmetry  $A_{FB}$  (vertical lines) at the Tevatron [3], compared with the SM prediction at QCD NNLO (+EW NLO) [20–22] and predictions incorporating various potential BSM contributions [66, 67]: a  $W'$  boson, a heavy axigluon ( $G_\mu$ ), a scalar isodoublet ( $\phi$ ), a colour triplet scalar ( $\omega^4$ ), and a colour sextet scalar ( $\Omega^4$ ).



**Figure 4.** Charge asymmetry in six bins of the invariant mass of the  $t\bar{t}$  system as measured in the ATLAS and CMS analyses and the combined results. The last bin includes the overflow. The gray band indicates the uncertainty in the combined result.



**Figure 5.** The combined ATLAS+CMS charge asymmetry in six bins of the invariant mass of the  $t\bar{t}$  system in comparison with theoretical predictions for the SM [19, 23] and two versions of a colour-octet model [68]. The last bin includes the overflow, both for the combination and the theory predictions. The uncertainties, indicated by the shaded areas, reported for the SM predictions are dominated by scale variations and are small, while the uncertainties reported for the colour-octet model are statistical uncertainties in the simulation.

| Bins | 1      | 2      | 3      | 4      | 5      | 6     |
|------|--------|--------|--------|--------|--------|-------|
| 1    | 1.000  |        |        |        |        |       |
| 2    | -0.129 | 1.000  |        |        |        |       |
| 3    | -0.100 | 0.015  | 1.000  |        |        |       |
| 4    | -0.018 | -0.060 | -0.098 | 1.000  |        |       |
| 5    | -0.009 | -0.074 | 0.067  | -0.342 | 1.000  |       |
| 6    | -0.088 | -0.040 | 0.012  | 0.199  | -0.188 | 1.000 |

**Table 5.** Correlation matrix for the six correlated bins of the combined result.

has neither an effect on the central value of the combination nor on its total uncertainty within the quoted precision ( $10^{-3}$ ).

## 6.2 Stability checks at 8 TeV

Several studies are performed to assess the stability of the inclusive and differential combinations at  $\sqrt{s} = 8$  TeV. In a first check, the combinations are repeated taking only the statistical uncertainties into account to investigate the impact of systematic uncertainties on the combination results. The variations in the central values of the inclusive and differential combinations, and thus the impact of systematic uncertainties, are below  $0.5\sigma_{\text{stat}}$ , where  $\sigma_{\text{stat}}$  is the statistical uncertainty of the central values. Therefore, the impact of the assumptions about the correlations between the sources of systematic uncertainties can be expected to also be modest in size.

As in the combination at 7 TeV, the correlation assumptions are varied one by one and the results are compared with the nominal results. These studies are performed for the combination of the inclusive measurements as well as for the combination of the differential measurements. For the inclusive combination, none of the described changes in the correlation assumption has an impact on the central value of the combination or the total uncertainty larger than the quoted precision ( $10^{-4}$ ). The differential combination is also found to be robust against such changes. The impacts, if any, on the central values or the total uncertainties of single bins are found to be below  $0.1\sigma_{\text{tot}}$ , where  $\sigma_{\text{tot}}$  is the total uncertainty in that bin.

### 6.2.1 Additional stability checks for the differential combination

Two additional studies are performed for the combination of the differential results. The first study concerns the different ways of building the correlation matrix in the ATLAS analysis and evaluates their impact on the central values and uncertainties of the combination results. In the ATLAS analysis, the bin-to-bin correlations for all systematic uncertainties that are not marginalised are set to  $\pm 1$ , and the correlations for systematic uncertainties that are marginalised are derived directly from the unfolding. This nominal method to construct the correlation matrix is compared to a scenario where the correlations are all set to  $+1$ , and a scenario where the correlations for the marginalised uncertainties are set to either  $+1$  or  $-1$  depending on whether the value of the correlation derived from the unfolding takes positive or negative values. These checks of ignoring the correlations extracted from the unfolding represent a conservative test for the case where it would not be known how to compute these correlations. The differences in the central values between the nominal scenario and these two different approaches are below  $0.4\sigma_{\text{tot}}$  in each  $m_{t\bar{t}}$  bin, where  $\sigma_{\text{tot}}$  is the total uncertainty in that bin. The impact on the total uncertainties in all six bins is at most 0.002.

In the second study, the procedure to estimate the bin-to-bin inter-experiment correlations as defined in eq. (4.5) is changed to using the bin-to-bin correlations either only from ATLAS or only from CMS:

$$\begin{aligned} \text{corr}^u(a_i, c_j) &= \rho_u \text{corr}^u(c_i, c_j), \quad \text{or} \\ \text{corr}^u(a_i, c_j) &= \rho_u \text{corr}^u(a_i, a_j). \end{aligned}$$

Using only the bin-to-bin correlations from the ATLAS (CMS) analysis changes the central values by at most  $0.3\sigma_{\text{tot}}$  ( $0.2\sigma_{\text{tot}}$ ), with  $\sigma_{\text{tot}}$  being the total uncertainty for the respective bin. The total uncertainties remain stable or increase by no more than 0.002 in the case of using only the bin-to-bin correlations from the ATLAS analysis. Overall, the changes in the central values in all the bins are well inside the range given by the total uncertainty in each bin.

### 6.2.2 Impact of the parton shower and hadronisation systematic uncertainty in the inclusive combination

The CMS template analysis does not take into account an uncertainty due to the modelling of parton showers and hadronisation. As a further test, the impact of such an additional

uncertainty on the inclusive combination results is estimated by using the corresponding uncertainty values from the CMS unfolding analysis (0.0011), scaled by a factor of 2 as an approximation. The factor 2 is motivated by looking at the ratios of the other signal-modelling-related uncertainties between the two CMS analyses. In this study, the central value of the combination increases by  $0.16\sigma_{\text{tot}}$ , and the total uncertainty increases by 12% (relative). These variations are small and similar in size to variations obtained in the other stability tests.

## 7 Summary

Combinations of ATLAS and CMS measurements of the  $t\bar{t}$  charge asymmetry in lepton+jets final states are reported using proton-proton collision data collected at the LHC at centre-of-mass energies of 7 and 8 TeV and corresponding to integrated luminosities for each experiment of up to 5 and  $20\text{ fb}^{-1}$ , respectively. Inclusive charge asymmetry results are combined at 7 and 8 TeV, and differential measurements of the charge asymmetry as a function of the invariant mass of the  $t\bar{t}$  system at 8 TeV are combined. Detailed studies of the correlations between the different measurements and systematic uncertainties have been performed. The precision of the resulting combinations is significantly improved with respect to the corresponding individual measurements. The individual results and the combinations are in agreement with standard model calculations at next-to-leading-order and next-to-next-to-leading-order precision and also compatible with zero asymmetry. They uniquely restrict the phase space of possible new physics phenomena which would produce asymmetries larger than the standard model ones.

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M. Aaboud<sup>137d</sup>, G. Aad<sup>88</sup>, B. Abbott<sup>115</sup>, O. Abidinov<sup>12,\*</sup>, B. Abeloos<sup>119</sup>, S.H. Abidi<sup>161</sup>, O.S. AbouZeid<sup>139</sup>, N.L. Abraham<sup>151</sup>, H. Abramowicz<sup>155</sup>, H. Abreu<sup>154</sup>, Y. Abulaiti<sup>148a,148b</sup>, B.S. Acharya<sup>167a,167b,a</sup>, S. Adachi<sup>157</sup>, L. Adamczyk<sup>41a</sup>, J. Adelman<sup>110</sup>, M. Adersberger<sup>102</sup>, T. Adye<sup>133</sup>, A.A. Affolder<sup>139</sup>, Y. Afik<sup>154</sup>, C. Agheorghiesei<sup>28c</sup>, J.A. Aguilar-Saavedra<sup>128a,128f</sup>, S.P. Ahlen<sup>24</sup>, F. Ahmadov<sup>68,b</sup>, G. Aielli<sup>135a,135b</sup>, S. Akatsuka<sup>71</sup>, T.P.A. Åkesson<sup>84</sup>, E. Akilli<sup>52</sup>, A.V. Akimov<sup>98</sup>, G.L. Alberghi<sup>22a,22b</sup>, J. Albert<sup>172</sup>, P. Albicocco<sup>50</sup>, M.J. Alconada Verzini<sup>74</sup>, S.C. Alderweireldt<sup>108</sup>, M. Aleksa<sup>32</sup>, I.N. Aleksandrov<sup>68</sup>, C. 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Andrei<sup>60a</sup>, S. Angelidakis<sup>37</sup>, I. Angelozzi<sup>109</sup>, A. Angerami<sup>38</sup>, A.V. Anisenkov<sup>111,c</sup>, A. Annovi<sup>126a</sup>, C. Antel<sup>60a</sup>, M. Antonelli<sup>50</sup>, A. Antonov<sup>100,\*</sup>, D.J. Antrim<sup>166</sup>, F. Anulli<sup>134a</sup>, M. Aoki<sup>69</sup>, L. Aperio Bella<sup>32</sup>, G. Arabidze<sup>93</sup>, Y. Arai<sup>69</sup>, J.P. Araque<sup>128a</sup>, V. Araujo Ferraz<sup>26a</sup>, A.T.H. Arce<sup>48</sup>, R.E. Ardell<sup>80</sup>, F.A. Arduh<sup>74</sup>, J-F. Arguin<sup>97</sup>, S. Argyropoulos<sup>66</sup>, A.J. Armbruster<sup>32</sup>, L.J. Armitage<sup>79</sup>, O. Arnaez<sup>161</sup>, H. Arnold<sup>51</sup>, M. Arratia<sup>30</sup>, O. Arslan<sup>23</sup>, A. Artamonov<sup>99,\*</sup>, G. Artoni<sup>122</sup>, S. Artz<sup>86</sup>, S. Asai<sup>157</sup>, N. Asbah<sup>45</sup>, A. Ashkenazi<sup>155</sup>, L. Asquith<sup>151</sup>, K. Assamagan<sup>27</sup>, R. Astalos<sup>146a</sup>, M. 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 G. Chiarelli<sup>126a</sup>, G. Chiodini<sup>76a</sup>, A.S. Chisholm<sup>32</sup>, A. Chitan<sup>28b</sup>, Y.H. Chiu<sup>172</sup>, M.V. Chizhov<sup>68</sup>,  
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 J. Chudoba<sup>129</sup>, A.J. Chuinard<sup>90</sup>, J.J. Chwastowski<sup>42</sup>, L. Chytka<sup>117</sup>, D. Cinca<sup>46</sup>, V. Cindro<sup>78</sup>,  
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I. Yusuff<sup>30,ay</sup>, B. Zabinski<sup>42</sup>, G. Zacharis<sup>10</sup>, R. Zaidan<sup>13</sup>, A.M. Zaitsev<sup>132,ak</sup>, N. Zakharchuk<sup>45</sup>, J. Zalieckas<sup>15</sup>, A. Zaman<sup>150</sup>, S. Zambito<sup>59</sup>, D. Zanzi<sup>32</sup>, C. Zeitnitz<sup>178</sup>, G. Zemaityte<sup>122</sup>, J.C. Zeng<sup>169</sup>, Q. Zeng<sup>145</sup>, O. Zenin<sup>132</sup>, T. Ženiš<sup>146a</sup>, D. Zerwas<sup>119</sup>, D. Zhang<sup>36b</sup>, D. Zhang<sup>92</sup>, F. Zhang<sup>176</sup>, G. Zhang<sup>36a,ax</sup>, H. Zhang<sup>119</sup>, J. Zhang<sup>6</sup>, L. Zhang<sup>51</sup>, L. Zhang<sup>36a</sup>, M. Zhang<sup>169</sup>, P. Zhang<sup>35b</sup>, R. Zhang<sup>23</sup>, R. Zhang<sup>36a,av</sup>, X. Zhang<sup>36b</sup>, Y. Zhang<sup>35a,35d</sup>, Z. Zhang<sup>119</sup>, X. Zhao<sup>43</sup>, Y. Zhao<sup>36b,x</sup>, Z. Zhao<sup>36a</sup>, A. Zhemchugov<sup>68</sup>, B. Zhou<sup>92</sup>, C. Zhou<sup>176</sup>, L. Zhou<sup>43</sup>, M. Zhou<sup>35a,35d</sup>, M. Zhou<sup>150</sup>, N. Zhou<sup>36c</sup>, Y. Zhou<sup>7</sup>, C.G. Zhu<sup>36b</sup>, H. Zhu<sup>35a</sup>, J. Zhu<sup>92</sup>, Y. Zhu<sup>36a</sup>, X. Zhuang<sup>35a</sup>, K. Zhukov<sup>98</sup>, A. Zibell<sup>177</sup>, D. Zieminska<sup>64</sup>, N.I. Zimine<sup>68</sup>, S. Zimmermann<sup>51</sup>, Z. Zinonos<sup>103</sup>, M. Zinser<sup>86</sup>, M. Ziolkowski<sup>143</sup>, L. Živković<sup>14</sup>, G. Zobernig<sup>176</sup>, A. Zoccoli<sup>22a,22b</sup>, R. Zou<sup>33</sup>, M. zur Nedden<sup>17</sup>, L. Zwalinski<sup>32</sup>.

<sup>1</sup> *Department of Physics, University of Adelaide, Adelaide, Australia*

<sup>2</sup> *Physics Department, SUNY Albany, Albany NY, United States of America*

<sup>3</sup> *Department of Physics, University of Alberta, Edmonton AB, Canada*

<sup>4</sup> <sup>(a)</sup> *Department of Physics, Ankara University, Ankara;* <sup>(b)</sup> *Istanbul Aydin University, Istanbul;* <sup>(c)</sup> *Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*

<sup>5</sup> *LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France*

<sup>6</sup> *High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America*

<sup>7</sup> *Department of Physics, University of Arizona, Tucson AZ, United States of America*

<sup>8</sup> *Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America*

<sup>9</sup> *Physics Department, National and Kapodistrian University of Athens, Athens, Greece*

<sup>10</sup> *Physics Department, National Technical University of Athens, Zografou, Greece*

<sup>11</sup> *Department of Physics, The University of Texas at Austin, Austin TX, United States of America*

<sup>12</sup> *Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*

<sup>13</sup> *Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain*

<sup>14</sup> *Institute of Physics, University of Belgrade, Belgrade, Serbia*

<sup>15</sup> *Department for Physics and Technology, University of Bergen, Bergen, Norway*

<sup>16</sup> *Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America*

<sup>17</sup> *Department of Physics, Humboldt University, Berlin, Germany*

<sup>18</sup> *Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*

<sup>19</sup> *School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*

<sup>20</sup> <sup>(a)</sup> *Department of Physics, Bogazici University, Istanbul;* <sup>(b)</sup> *Department of Physics Engineering, Gaziantep University, Gaziantep;* <sup>(d)</sup> *Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul;* <sup>(e)</sup> *Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*

<sup>21</sup> *Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*

<sup>22</sup> <sup>(a)</sup> *INFN Sezione di Bologna;* <sup>(b)</sup> *Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy*

<sup>23</sup> *Physikalisches Institut, University of Bonn, Bonn, Germany*

<sup>24</sup> *Department of Physics, Boston University, Boston MA, United States of America*

<sup>25</sup> *Department of Physics, Brandeis University, Waltham MA, United States of America*

<sup>26</sup> <sup>(a)</sup> *Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;* <sup>(b)</sup> *Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora;* <sup>(c)</sup> *Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei;* <sup>(d)</sup> *Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*

<sup>27</sup> *Physics Department, Brookhaven National Laboratory, Upton NY, United States of America*

<sup>28</sup> <sup>(a)</sup> *Transilvania University of Brasov, Brasov;* <sup>(b)</sup> *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;* <sup>(c)</sup> *Department of Physics, Alexandru Ioan Cuza University of*

- Iasi, Iasi; <sup>(d)</sup> National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; <sup>(e)</sup> University Politehnica Bucharest, Bucharest; <sup>(f)</sup> West University in Timisoara, Timisoara, Romania
- <sup>29</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- <sup>30</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- <sup>31</sup> Department of Physics, Carleton University, Ottawa ON, Canada
- <sup>32</sup> CERN, Geneva, Switzerland
- <sup>33</sup> Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- <sup>34</sup> <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- <sup>35</sup> <sup>(a)</sup> Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; <sup>(b)</sup> Department of Physics, Nanjing University, Jiangsu; <sup>(c)</sup> Physics Department, Tsinghua University, Beijing 100084; <sup>(d)</sup> University of Chinese Academy of Science (UCAS), Beijing, China
- <sup>36</sup> <sup>(a)</sup> Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui; <sup>(b)</sup> School of Physics, Shandong University, Shandong; <sup>(c)</sup> School of Physics and Astronomy, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, China
- <sup>37</sup> Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
- <sup>38</sup> Nevis Laboratory, Columbia University, Irvington NY, United States of America
- <sup>39</sup> Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- <sup>40</sup> <sup>(a)</sup> INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; <sup>(b)</sup> Dipartimento di Fisica, Università della Calabria, Rende, Italy
- <sup>41</sup> <sup>(a)</sup> AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; <sup>(b)</sup> Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- <sup>42</sup> Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- <sup>43</sup> Physics Department, Southern Methodist University, Dallas TX, United States of America
- <sup>44</sup> Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- <sup>45</sup> DESY, Hamburg and Zeuthen, Germany
- <sup>46</sup> Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- <sup>47</sup> Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- <sup>48</sup> Department of Physics, Duke University, Durham NC, United States of America
- <sup>49</sup> SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- <sup>50</sup> INFN e Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>51</sup> Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- <sup>52</sup> Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland
- <sup>53</sup> <sup>(a)</sup> INFN Sezione di Genova; <sup>(b)</sup> Dipartimento di Fisica, Università di Genova, Genova, Italy
- <sup>54</sup> <sup>(a)</sup> E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- <sup>55</sup> II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- <sup>56</sup> SUPA — School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- <sup>57</sup> II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- <sup>58</sup> Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- <sup>59</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
- <sup>60</sup> <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>61</sup> Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- <sup>62</sup> <sup>(a)</sup> Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; <sup>(b)</sup> Department of Physics, The University of Hong Kong, Hong Kong; <sup>(c)</sup> Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

- 63 *Department of Physics, National Tsing Hua University, Taiwan, Taiwan*
- 64 *Department of Physics, Indiana University, Bloomington IN, United States of America*
- 65 *Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
- 66 *University of Iowa, Iowa City IA, United States of America*
- 67 *Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America*
- 68 *Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia*
- 69 *KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
- 70 *Graduate School of Science, Kobe University, Kobe, Japan*
- 71 *Faculty of Science, Kyoto University, Kyoto, Japan*
- 72 *Kyoto University of Education, Kyoto, Japan*
- 73 *Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
- 74 *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
- 75 *Physics Department, Lancaster University, Lancaster, United Kingdom*
- 76 <sup>(a)</sup> *INFN Sezione di Lecce;* <sup>(b)</sup> *Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
- 77 *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- 78 *Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
- 79 *School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
- 80 *Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*
- 81 *Department of Physics and Astronomy, University College London, London, United Kingdom*
- 82 *Louisiana Tech University, Ruston LA, United States of America*
- 83 *Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
- 84 *Fysiska institutionen, Lunds universitet, Lund, Sweden*
- 85 *Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain*
- 86 *Institut für Physik, Universität Mainz, Mainz, Germany*
- 87 *School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- 88 *CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*
- 89 *Department of Physics, University of Massachusetts, Amherst MA, United States of America*
- 90 *Department of Physics, McGill University, Montreal QC, Canada*
- 91 *School of Physics, University of Melbourne, Victoria, Australia*
- 92 *Department of Physics, The University of Michigan, Ann Arbor MI, United States of America*
- 93 *Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America*
- 94 <sup>(a)</sup> *INFN Sezione di Milano;* <sup>(b)</sup> *Dipartimento di Fisica, Università di Milano, Milano, Italy*
- 95 *B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus*
- 96 *Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus*
- 97 *Group of Particle Physics, University of Montreal, Montreal QC, Canada*
- 98 *P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
- 99 *Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
- 100 *National Research Nuclear University MEPhI, Moscow, Russia*
- 101 *D.V. Skobel'syn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
- 102 *Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- 103 *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- 104 *Nagasaki Institute of Applied Science, Nagasaki, Japan*
- 105 *Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
- 106 <sup>(a)</sup> *INFN Sezione di Napoli;* <sup>(b)</sup> *Dipartimento di Fisica, Università di Napoli, Napoli, Italy*

- 107 *Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America*
- 108 *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
- 109 *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- 110 *Department of Physics, Northern Illinois University, DeKalb IL, United States of America*
- 111 *Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*
- 112 *Department of Physics, New York University, New York NY, United States of America*
- 113 *Ohio State University, Columbus OH, United States of America*
- 114 *Faculty of Science, Okayama University, Okayama, Japan*
- 115 *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America*
- 116 *Department of Physics, Oklahoma State University, Stillwater OK, United States of America*
- 117 *Palacký University, RCPTM, Olomouc, Czech Republic*
- 118 *Center for High Energy Physics, University of Oregon, Eugene OR, United States of America*
- 119 *LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
- 120 *Graduate School of Science, Osaka University, Osaka, Japan*
- 121 *Department of Physics, University of Oslo, Oslo, Norway*
- 122 *Department of Physics, Oxford University, Oxford, United Kingdom*
- 123 <sup>(a)</sup> *INFN Sezione di Pavia;* <sup>(b)</sup> *Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- 124 *Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America*
- 125 *National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
- 126 <sup>(a)</sup> *INFN Sezione di Pisa;* <sup>(b)</sup> *Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- 127 *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America*
- 128 <sup>(a)</sup> *Laboratório de Instrumentação e Física Experimental de Partículas — LIP, Lisboa;* <sup>(b)</sup> *Faculdade de Ciências, Universidade de Lisboa, Lisboa;* <sup>(c)</sup> *Department of Physics, University of Coimbra, Coimbra;* <sup>(d)</sup> *Centro de Física Nuclear da Universidade de Lisboa, Lisboa;* <sup>(e)</sup> *Departamento de Física, Universidade do Minho, Braga;* <sup>(f)</sup> *Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada;* <sup>(g)</sup> *Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal*
- 129 *Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
- 130 *Czech Technical University in Prague, Praha, Czech Republic*
- 131 *Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
- 132 *State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia*
- 133 *Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
- 134 <sup>(a)</sup> *INFN Sezione di Roma;* <sup>(b)</sup> *Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
- 135 <sup>(a)</sup> *INFN Sezione di Roma Tor Vergata;* <sup>(b)</sup> *Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- 136 <sup>(a)</sup> *INFN Sezione di Roma Tre;* <sup>(b)</sup> *Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
- 137 <sup>(a)</sup> *Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;* <sup>(b)</sup> *Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat;* <sup>(c)</sup> *Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;* <sup>(d)</sup> *Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;* <sup>(e)</sup> *Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- 138 *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*
- 139 *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America*

- 140 *Department of Physics, University of Washington, Seattle WA, United States of America*  
 141 *Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*  
 142 *Department of Physics, Shinshu University, Nagano, Japan*  
 143 *Department Physik, Universität Siegen, Siegen, Germany*  
 144 *Department of Physics, Simon Fraser University, Burnaby BC, Canada*  
 145 *SLAC National Accelerator Laboratory, Stanford CA, United States of America*  
 146 <sup>(a)</sup> *Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava;* <sup>(b)</sup>  
*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of*  
*Sciences, Kosice, Slovak Republic*  
 147 <sup>(a)</sup> *Department of Physics, University of Cape Town, Cape Town;* <sup>(b)</sup> *Department of Physics,*  
*University of Johannesburg, Johannesburg;* <sup>(c)</sup> *School of Physics, University of the Witwatersrand,*  
*Johannesburg, South Africa*  
 148 <sup>(a)</sup> *Department of Physics, Stockholm University;* <sup>(b)</sup> *The Oskar Klein Centre, Stockholm, Sweden*  
 149 *Physics Department, Royal Institute of Technology, Stockholm, Sweden*  
 150 *Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY,*  
*United States of America*  
 151 *Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*  
 152 *School of Physics, University of Sydney, Sydney, Australia*  
 153 *Institute of Physics, Academia Sinica, Taipei, Taiwan*  
 154 *Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel*  
 155 *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv,*  
*Israel*  
 156 *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*  
 157 *International Center for Elementary Particle Physics and Department of Physics, The University*  
*of Tokyo, Tokyo, Japan*  
 158 *Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*  
 159 *Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*  
 160 *Tomsk State University, Tomsk, Russia*  
 161 *Department of Physics, University of Toronto, Toronto ON, Canada*  
 162 <sup>(a)</sup> *INFN-TIFPA;* <sup>(b)</sup> *University of Trento, Trento, Italy*  
 163 <sup>(a)</sup> *TRIUMF, Vancouver BC;* <sup>(b)</sup> *Department of Physics and Astronomy, York University, Toronto*  
*ON, Canada*  
 164 *Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science*  
*and Engineering, University of Tsukuba, Tsukuba, Japan*  
 165 *Department of Physics and Astronomy, Tufts University, Medford MA, United States of America*  
 166 *Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of*  
*America*  
 167 <sup>(a)</sup> *INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;* <sup>(b)</sup> *ICTP, Trieste;* <sup>(c)</sup>  
*Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*  
 168 *Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*  
 169 *Department of Physics, University of Illinois, Urbana IL, United States of America*  
 170 *Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain*  
 171 *Department of Physics, University of British Columbia, Vancouver BC, Canada*  
 172 *Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada*  
 173 *Department of Physics, University of Warwick, Coventry, United Kingdom*  
 174 *Waseda University, Tokyo, Japan*  
 175 *Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*  
 176 *Department of Physics, University of Wisconsin, Madison WI, United States of America*  
 177 *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*  
 178 *Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität*  
*Wuppertal, Wuppertal, Germany*  
 179 *Department of Physics, Yale University, New Haven CT, United States of America*



- <sup>180</sup> *Yerevan Physics Institute, Yerevan, Armenia*
- <sup>181</sup> *Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*
- <sup>182</sup> *Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan*
- <sup>a</sup> *Also at Department of Physics, King's College London, London, United Kingdom*
- <sup>b</sup> *Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
- <sup>c</sup> *Also at Novosibirsk State University, Novosibirsk, Russia*
- <sup>d</sup> *Also at TRIUMF, Vancouver BC, Canada*
- <sup>e</sup> *Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States of America*
- <sup>f</sup> *Also at Physics Department, An-Najah National University, Nablus, Palestine*
- <sup>g</sup> *Also at Department of Physics, California State University, Fresno CA, United States of America*
- <sup>h</sup> *Also at Department of Physics, University of Fribourg, Fribourg, Switzerland*
- <sup>i</sup> *Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany*
- <sup>j</sup> *Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain*
- <sup>k</sup> *Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal*
- <sup>l</sup> *Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia*
- <sup>m</sup> *Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China*
- <sup>n</sup> *Also at Università di Napoli Parthenope, Napoli, Italy*
- <sup>o</sup> *Also at Institute of Particle Physics (IPP), Canada*
- <sup>p</sup> *Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
- <sup>q</sup> *Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia*
- <sup>r</sup> *Also at Borough of Manhattan Community College, City University of New York, New York City, United States of America*
- <sup>s</sup> *Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece*
- <sup>t</sup> *Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa*
- <sup>u</sup> *Also at Louisiana Tech University, Ruston LA, United States of America*
- <sup>v</sup> *Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain*
- <sup>w</sup> *Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America*
- <sup>x</sup> *Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
- <sup>y</sup> *Also at Graduate School of Science, Osaka University, Osaka, Japan*
- <sup>z</sup> *Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany*
- <sup>aa</sup> *Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
- <sup>ab</sup> *Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia*
- <sup>ac</sup> *Also at CERN, Geneva, Switzerland*
- <sup>ad</sup> *Also at Georgian Technical University (GTU), Tbilisi, Georgia*
- <sup>ae</sup> *Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan*
- <sup>af</sup> *Also at Manhattan College, New York NY, United States of America*
- <sup>ag</sup> *Also at Hellenic Open University, Patras, Greece*
- <sup>ah</sup> *Also at The City College of New York, New York NY, United States of America*
- <sup>ai</sup> *Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Portugal*
- <sup>aj</sup> *Also at Department of Physics, California State University, Sacramento CA, United States of America*
- <sup>ak</sup> *Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia*
- <sup>al</sup> *Also at Departement de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland*

- <sup>am</sup> Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
- <sup>an</sup> Also at Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
- <sup>ao</sup> Also at School of Physics, Sun Yat-sen University, Guangzhou, China
- <sup>ap</sup> Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria
- <sup>aq</sup> Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- <sup>ar</sup> Also at National Research Nuclear University MEPhI, Moscow, Russia
- <sup>as</sup> Also at Department of Physics, Stanford University, Stanford CA, United States of America
- <sup>at</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- <sup>au</sup> Also at Giresun University, Faculty of Engineering, Turkey
- <sup>av</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- <sup>aw</sup> Also at Department of Physics, Nanjing University, Jiangsu, China
- <sup>ax</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>ay</sup> Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
- \* Deceased

## The CMS collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

### Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler<sup>1</sup>, A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, N. Rad, H. Rohringer, J. Schieck<sup>1</sup>, R. Schöffbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz<sup>1</sup>, M. Zarucki

### Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

### Universiteit Antwerpen, Antwerpen, Belgium

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

### Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskiy, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

### Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, T. Seva, E. Starling, C. Vander Velde, P. Vanlaer, D. Van-nerom, R. Yonamine, F. Zenoni

### Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov<sup>2</sup>, D. Poyraz, C. Roskas, S. Salva, M. Tytgat, W. Verbeke, N. Zaganidis

### Université Catholique de Louvain, Louvain-la-Neuve, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, A. Caudron, P. David, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

### Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

### Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>3</sup>, E. Coelho, E.M. Da Costa, G.G. Da Silveira<sup>4</sup>, D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas

Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote<sup>3</sup>, F. Torres Da Silva De Araujo, A. Vilela Pereira

**Universidade Estadual Paulista <sup>a</sup>, Universidade Federal do ABC <sup>b</sup>, São Paulo, Brazil**

S. Ahuja<sup>a</sup>, C.A. Bernardes<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>b</sup>, P.G. Mercadante<sup>b</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>, D. Romero Abad<sup>b</sup>, J.C. Ruiz Vargas<sup>a</sup>

**Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria**

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

**University of Sofia, Sofia, Bulgaria**

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

**Beihang University, Beijing, China**

W. Fang<sup>5</sup>, X. Gao<sup>5</sup>, L. Yuan

**Institute of High Energy Physics, Beijing, China**

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, T. Yu, H. Zhang, S. Zhang, J. Zhao

**State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**

Y. Ban, G. Chen, J. Li, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, F. Zhang<sup>5</sup>

**Tsinghua University, Beijing, China**

Y. Wang

**Universidad de Los Andes, Bogota, Colombia**

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez, M.A. Segura Delgado

**University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

**University of Split, Faculty of Science, Split, Croatia**

Z. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov<sup>6</sup>, T. Susa

**University of Cyprus, Nicosia, Cyprus**

M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

**Charles University, Prague, Czech Republic**

M. Finger<sup>7</sup>, M. Finger Jr.<sup>7</sup>

**Universidad San Francisco de Quito, Quito, Ecuador**

E. Carrera Jarrin

**Academy of Scientific Research and Technology of the Arab Republic of Egypt,  
Egyptian Network of High Energy Physics, Cairo, Egypt**

Y. Assran<sup>8,9</sup>, S. Elgammal<sup>9</sup>, A. Mahrous<sup>10</sup>

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

S. Bhowmik, R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

**Department of Physics, University of Helsinki, Helsinki, Finland**

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén,  
K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen,  
E. Tuominen, J. Tuominiemi

**Lappeenranta University of Technology, Lappeenranta, Finland**

T. Tuuva

**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour,  
S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, C. Leloup,  
E. Locci, M. Mached, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

**Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France**

A. Abdulsalam<sup>11</sup>, C. Amendola, I. Antropov, S. Baffioni, F. Beaudette, P. Busson,  
L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov,  
J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, R. Salerno,  
J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

**Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France**

J.-L. Agram<sup>12</sup>, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon,  
C. Collard, E. Conte<sup>12</sup>, X. Coubez, F. Drouhin<sup>12</sup>, J.-C. Fontaine<sup>12</sup>, D. Gelé, U. Goerlach,  
M. Jansová, P. Juillot, A.-C. Le Bihan, N. Tonon, P. Van Hove

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique  
des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France**

S. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov<sup>13</sup>, V. Sordini, M. Vander Donckt, S. Viret

**Georgian Technical University, Tbilisi, Georgia**

T. Toriashvili<sup>14</sup>

**Tbilisi State University, Tbilisi, Georgia**

Z. Tsamalaidze<sup>7</sup>

**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov<sup>13</sup>

**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

A. Albert, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

**RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**

G. Flügge, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl<sup>15</sup>

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras<sup>16</sup>, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo<sup>17</sup>, J. Garay Garcia, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel<sup>18</sup>, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann<sup>18</sup>, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, R. Shevchenko, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

**University of Hamburg, Hamburg, Germany**

R. Aggleton, S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo<sup>15</sup>, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, R. Friese, M. Giffels, M.A. Harrendorf, F. Hartmann<sup>15</sup>, S.M. Heindl, U. Husemann, F. Kassel<sup>15</sup>, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

**Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece**

G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, I. Topsis-Giotis

**National and Kapodistrian University of Athens, Athens, Greece**

G. Karathanasis, S. Kesisoglou, A. Panagiotou, N. Saoulidou

**National Technical University of Athens, Athens, Greece**

K. Kousouris

**University of Ioánnina, Ioánnina, Greece**

I. Evangelou, C. Foudas, P. Giannelos, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

**MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary**

M. Csanad, N. Filipovic, G. Pasztor, O. Surányi, G.I. Veres<sup>19</sup>

**Wigner Research Centre for Physics, Budapest, Hungary**

G. Bencze, C. Hajdu, D. Horvath<sup>20</sup>, Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>19</sup>

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

N. Beni, S. Czellar, J. Karancsi<sup>21</sup>, A. Makovec, J. Molnar, Z. Szillasi

**Institute of Physics, University of Debrecen, Debrecen, Hungary**

M. Bartók<sup>19</sup>, P. Raics, Z.L. Trocsanyi, B. Ujvari

**Indian Institute of Science (IISc), Bangalore, India**

S. Choudhury, J.R. Komaragiri

**National Institute of Science Education and Research, Bhubaneswar, India**

S. Bahinipati<sup>22</sup>, P. Mal, K. Mandal, A. Nayak<sup>23</sup>, D.K. Sahoo<sup>22</sup>, N. Sahoo, S.K. Swain

**Panjab University, Chandigarh, India**

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, N. Dhingra, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, A. Mehta, J.B. Singh, G. Walia

**University of Delhi, Delhi, India**

Ashok Kumar, Aashaq Shah, A. Bhardwaj, S. Chauhan, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma

**Saha Institute of Nuclear Physics, HBNI, Kolkata, India**

R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

**Indian Institute of Technology Madras, Madras, India**

P.K. Behera

**Bhabha Atomic Research Centre, Mumbai, India**

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty<sup>15</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

**Tata Institute of Fundamental Research-A, Mumbai, India**

T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

**Tata Institute of Fundamental Research-B, Mumbai, India**

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity<sup>24</sup>, G. Majumder, K. Mazumdar, T. Sarkar<sup>24</sup>, N. Wickramage<sup>25</sup>

**Indian Institute of Science Education and Research (IISER), Pune, India**

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**

S. Chenarani<sup>26</sup>, E. Eskandari Tadavani, S.M. Etesami<sup>26</sup>, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi<sup>27</sup>, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>28</sup>, M. Zeinali

**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

**INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, F. Errico<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, S. Lezki<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, B. Marangelli<sup>a,b</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, A. Sharma<sup>a</sup>, L. Silvestris<sup>a,15</sup>, R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup>, G. Zito<sup>a</sup>

**INFN Sezione di Bologna <sup>a</sup>, Università di Bologna <sup>b</sup>, Bologna, Italy**

G. Abbiendi<sup>a</sup>, C. Battilana<sup>a,b</sup>, D. Bonacorsi<sup>a,b</sup>, L. Borgonovi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, S.S. Chhibra<sup>a</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a</sup>

**INFN Sezione di Catania <sup>a</sup>, Università di Catania <sup>b</sup>, Catania, Italy**

S. Albergo<sup>a,b</sup>, S. Costa<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, F. Giordano<sup>a,b</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>



**INFN Sezione di Firenze <sup>a</sup>, Università di Firenze <sup>b</sup>, Firenze, Italy**

G. Barbagli<sup>a</sup>, K. Chatterjee<sup>a,b</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, L. Russo<sup>a,29</sup>, G. Sguazzoni<sup>a</sup>, D. Strom<sup>a</sup>, L. Viliani<sup>a</sup>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera<sup>15</sup>

**INFN Sezione di Genova <sup>a</sup>, Università di Genova <sup>b</sup>, Genova, Italy**

V. Calvelli<sup>a,b</sup>, F. Ferro<sup>a</sup>, F. Ravera<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

**INFN Sezione di Milano-Bicocca <sup>a</sup>, Università di Milano-Bicocca <sup>b</sup>, Milano, Italy**

A. Benaglia<sup>a</sup>, A. Beschi<sup>b</sup>, L. Brianza<sup>a,b</sup>, F. Brivio<sup>a,b</sup>, V. Ciriolo<sup>a,b,15</sup>, M.E. Dinardo<sup>a,b</sup>, S. Fiorendi<sup>a,b</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, M. Malberti<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, K. Pauwels<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Pigazzini<sup>a,b,30</sup>, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

**INFN Sezione di Napoli <sup>a</sup>, Università di Napoli 'Federico II' <sup>b</sup>, Napoli, Italy, Università della Basilicata <sup>c</sup>, Potenza, Italy, Università G. Marconi <sup>d</sup>, Roma, Italy**

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, S. Di Guida<sup>a,d,15</sup>, F. Fabozzi<sup>a,c</sup>, F. Fienga<sup>a,b</sup>, A.O.M. Iorio<sup>a,b</sup>, W.A. Khan<sup>a</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,d,15</sup>, P. Paolucci<sup>a,15</sup>, C. Sciacca<sup>a,b</sup>, F. Thyssen<sup>a</sup>

**INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Padova, Italy, Università di Trento <sup>c</sup>, Trento, Italy**

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, L. Benato<sup>a,b</sup>, D. Bisello<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, A. Carvalho Antunes De Oliveira<sup>a,b</sup>, P. Checchia<sup>a</sup>, M. Dall'Osso<sup>a,b</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino<sup>a</sup>, S. Lacaprara<sup>a</sup>, P. Lujan, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, S. Ventura<sup>a</sup>, M. Zanetti<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

**INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy**

A. Braghieri<sup>a</sup>, A. Magnani<sup>a</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, M. Ressegotti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a,b</sup>, P. Vitulo<sup>a,b</sup>

**INFN Sezione di Perugia <sup>a</sup>, Università di Perugia <sup>b</sup>, Perugia, Italy**

L. Alunni Solestizi<sup>a,b</sup>, M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, C. Cecchi<sup>a,b</sup>, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, R. Leonardi<sup>a,b</sup>, E. Manoni<sup>a</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Rossi<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, D. Spiga<sup>a</sup>

**INFN Sezione di Pisa <sup>a</sup>, Università di Pisa <sup>b</sup>, Scuola Normale Superiore di Pisa <sup>c</sup>, Pisa, Italy**

K. Androsov<sup>a</sup>, P. Azzurri<sup>a,15</sup>, G. Bagliesi<sup>a</sup>, T. Boccali<sup>a</sup>, L. Borrello, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,b</sup>, R. Dell'Orso<sup>a</sup>, G. Fedi<sup>a</sup>, L. Giannini<sup>a,c</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a,29</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, E. Manca<sup>a,c</sup>, G. Mandorli<sup>a,c</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, A. Savoy-Navarro<sup>a,31</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

**INFN Sezione di Roma <sup>a</sup>, Sapienza Università di Roma <sup>b</sup>, Rome, Italy**

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, M. Cipriani<sup>a,b</sup>, N. Daci<sup>a</sup>, D. Del Re<sup>a,b,15</sup>, E. Di Marco<sup>a,b</sup>, M. Diemoz<sup>a</sup>, S. Gelli<sup>a,b</sup>, E. Longo<sup>a,b</sup>, F. Margaroli<sup>a,b</sup>, B. Marzocchi<sup>a,b</sup>, P. Meridiani<sup>a</sup>, G. Organtini<sup>a,b</sup>, R. Paramatti<sup>a,b</sup>, F. Preiato<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>

**INFN Sezione di Torino <sup>a</sup>, Università di Torino <sup>b</sup>, Torino, Italy, Università del Piemonte Orientale <sup>c</sup>, Novara, Italy**

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, N. Bartosik<sup>a</sup>, R. Bellan<sup>a,b</sup>, C. Biino<sup>a</sup>, N. Cartiglia<sup>a</sup>, F. Cenna<sup>a,b</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, A. Degano<sup>a,b</sup>, N. Demaria<sup>a</sup>, B. Kiani<sup>a,b</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. Monteno<sup>a</sup>, M.M. Obertino<sup>a,b</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, K. Shchelina<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>, P. Traczyk<sup>a,b</sup>

**INFN Sezione di Trieste <sup>a</sup>, Università di Trieste <sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, A. Zanetti<sup>a</sup>

**Kyungpook National University, Daegu, Korea**

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

**Chonbuk National University, Jeonju, Korea**

A. Lee

**Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea**

H. Kim, D.H. Moon, G. Oh

**Hanyang University, Seoul, Korea**

J.A. Brochero Cifuentes, J. Goh, T.J. Kim

**Korea University, Seoul, Korea**

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**University of Seoul, Seoul, Korea**

H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

**Sungkyunkwan University, Suwon, Korea**

Y. Choi, C. Hwang, J. Lee, I. Yu

**Vilnius University, Vilnius, Lithuania**

V. Dudenias, A. Juodagalvis, J. Vaitkus

**National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali<sup>32</sup>, F. Mohamad Idris<sup>33</sup>, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**

Reyes-Almanza, R, Ramirez-Sanchez, G., Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz<sup>34</sup>, Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

**Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico**

A. Morelos Pineda

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

P.H. Butler

**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**

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**National Centre for Nuclear Research, Swierk, Poland**

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Zalewski

**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**

K. Bunkowski, A. Byszuk<sup>35</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

**Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadrucchio, J. Varela

**Joint Institute for Nuclear Research, Dubna, Russia**

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev<sup>36,37</sup>, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

**Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia**

Y. Ivanov, V. Kim<sup>38</sup>, E. Kuznetsova<sup>39</sup>, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

**Institute for Nuclear Research, Moscow, Russia**

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyev, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

**Institute for Theoretical and Experimental Physics, Moscow, Russia**

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

**Moscow Institute of Physics and Technology, Moscow, Russia**

T. Aushev, A. Bylinkin<sup>37</sup>

**National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia**

M. Chadeeva<sup>40</sup>, P. Parygin, D. Philippov, S. Polikarpov, E. Popova, V. Rusinov

**P.N. Lebedev Physical Institute, Moscow, Russia**

V. Andreev, M. Azarkin<sup>37</sup>, I. Dremin<sup>37</sup>, M. Kirakosyan<sup>37</sup>, S.V. Rusakov, A. Terkulov

**Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia**

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin<sup>41</sup>, L. Dudko, A. Ershov, V. Klyukhin, N. Korneeva, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, V. Savrin, P. Volkov

**Novosibirsk State University (NSU), Novosibirsk, Russia**

V. Blinov<sup>42</sup>, D. Shtol<sup>42</sup>, Y. Skovpen<sup>42</sup>

**State Research Center of Russian Federation, Institute for High Energy Physics of NRC &quot;Kurchatov Institute&quot;;, Protvino, Russia**

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

**University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia**

P. Adzic<sup>43</sup>, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**

J. Alcaraz Maestre, I. Bachiller, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares, A. Álvarez Fernández

**Universidad Autónoma de Madrid, Madrid, Spain**

C. Albajar, J.F. de Trocóniz, M. Missiroli

**Universidad de Oviedo, Oviedo, Spain**

J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, P. Vischia, J.M. Vizán García

**Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain**

I.J. Cabrillo, A. Calderon, B. Chazin Quero, E. Curras, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, P. Harris, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban<sup>18</sup>, J. Kieseler, V. Knünz, A. Kornmayer, M.J. Kortelainen, M. Krammer<sup>1</sup>, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic<sup>44</sup>, F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Rabadý, A. Racz, T. Reis, G. Rolandi<sup>45</sup>, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas<sup>46</sup>, A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns<sup>47</sup>, M. Verweij, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

W. Bertl<sup>†</sup>, L. Caminada<sup>48</sup>, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

**ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland**

M. Backhaus, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Klijnsma, W. Lustermann, B. Mangano, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quitnat, M. Reichmann, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

**Universität Zürich, Zurich, Switzerland**

T.K. Aarrestad, C. Amsler<sup>49</sup>, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, D. Pinna, G. Rauco, P. Robmann, D. Salerno,

K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

**National Central University, Chung-Li, Taiwan**

V. Candelise, Y.H. Chang, K.y. Cheng, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

**National Taiwan University (NTU), Taipei, Taiwan**

Arun Kumar, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

**Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand**

B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas

**Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey**

A. Bat, F. Boran, S. Cerci<sup>50</sup>, S. Damarseekin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos<sup>51</sup>, E.E. Kangal<sup>52</sup>, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut<sup>53</sup>, K. Ozdemir<sup>54</sup>, D. Sunar Cerci<sup>50</sup>, B. Tali<sup>50</sup>, U.G. Tok, S. Turkecapar, I.S. Zorbakir, C. Zorbilmez

**Middle East Technical University, Physics Department, Ankara, Turkey**

G. Karapinar<sup>55</sup>, K. Ocalan<sup>56</sup>, M. Yalvac, M. Zeyrek

**Bogazici University, Istanbul, Turkey**

E. Gülmez, M. Kaya<sup>57</sup>, O. Kaya<sup>58</sup>, S. Tekten, E.A. Yetkin<sup>59</sup>

**Istanbul Technical University, Istanbul, Turkey**

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu

**Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine**

B. Grynyov

**National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine**

L. Levchuk

**University of Bristol, Bristol, United Kingdom**

F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold<sup>60</sup>, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

**Rutherford Appleton Laboratory, Didcot, United Kingdom**

K.W. Bell, A. Belyaev<sup>61</sup>, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

**Imperial College, London, United Kingdom**

G. Auzinger, R. Bainbridge, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash, A. Nikitenko<sup>6</sup>, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta<sup>62</sup>, T. Virdee<sup>15</sup>, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

**Brunel University, Uxbridge, United Kingdom**

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, L. Teodorescu, S. Zahid

**Baylor University, Waco, U.S.A.**

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

**Catholic University of America, Washington DC, U.S.A.**

R. Bartek, A. Dominguez

**The University of Alabama, Tuscaloosa, U.S.A.**

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

**Boston University, Boston, U.S.A.**

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

**Brown University, Providence, U.S.A.**

G. Benelli, D. Cutts, A. Garabedian, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

**University of California, Davis, Davis, U.S.A.**

R. Band, C. Brainerd, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, D. Stolp, K. Tos, M. Tripathi, Z. Wang

**University of California, Los Angeles, U.S.A.**

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

**University of California, Riverside, Riverside, U.S.A.**

E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, G. Karapostoli, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B. R. Yates

**University of California, San Diego, La Jolla, U.S.A.**

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi,

M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech<sup>63</sup>, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

**University of California, Santa Barbara - Department of Physics, Santa Barbara, U.S.A.**

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

**California Institute of Technology, Pasadena, U.S.A.**

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**Carnegie Mellon University, Pittsburgh, U.S.A.**

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

**University of Colorado Boulder, Boulder, U.S.A.**

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S.R. Wagner

**Cornell University, Ithaca, U.S.A.**

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

**Fermi National Accelerator Laboratory, Batavia, U.S.A.**

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla<sup>†</sup>, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck, W. Wu

**University of Florida, Gainesville, U.S.A.**

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, I.K. Furic, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

**Florida International University, Miami, U.S.A.**

Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez



**Florida State University, Tallahassee, U.S.A.**

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

**Florida Institute of Technology, Melbourne, U.S.A.**

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

**University of Illinois at Chicago (UIC), Chicago, U.S.A.**

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

**The University of Iowa, Iowa City, U.S.A.**

B. Bilki<sup>64</sup>, W. Clarida, K. Dilsiz<sup>65</sup>, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>66</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul<sup>67</sup>, Y. Onel, F. Ozok<sup>68</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

**Johns Hopkins University, Baltimore, U.S.A.**

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

**The University of Kansas, Lawrence, U.S.A.**

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

**Kansas State University, Manhattan, U.S.A.**

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze

**Lawrence Livermore National Laboratory, Livermore, U.S.A.**

F. Rebassoo, D. Wright

**University of Maryland, College Park, U.S.A.**

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

**Massachusetts Institute of Technology, Cambridge, U.S.A.**

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

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A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

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J.G. Acosta, S. Oliveros

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J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

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G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, A. Massironi, D.M. Morse, T. Ori moto, R. Teixeira De Lima, D. Trocino, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

**Northwestern University, Evanston, U.S.A.**

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

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R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>36</sup>, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

**The Ohio State University, Columbus, U.S.A.**

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, B. Liu, W. Luo, B.L. Winer, H.W. Wulsin

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S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, A. Kalogeropoulos, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

**University of Puerto Rico, Mayaguez, U.S.A.**

S. Malik, S. Norberg

**Purdue University, West Lafayette, U.S.A.**

A. Barker, V.E. Barnes, S. Das, S. Folgueras, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

**Purdue University Northwest, Hammond, U.S.A.**

T. Cheng, N. Parashar, J. Stupak

**Rice University, Houston, U.S.A.**

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Guilbaud, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

**University of Rochester, Rochester, U.S.A.**

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

**The Rockefeller University, New York, U.S.A.**

R. Ciesielski, K. Goulios, C. Mesropian

**Rutgers, The State University of New Jersey, Piscataway, U.S.A.**

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

**University of Tennessee, Knoxville, U.S.A.**

A.G. Delannoy, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

**Texas A&M University, College Station, U.S.A.**

O. Bouhali<sup>69</sup>, A. Castaneda Hernandez<sup>69</sup>, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>70</sup>, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

**Texas Tech University, Lubbock, U.S.A.**

N. Akchurin, J. Damgov, F. De Guio, P.R. Duderø, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

**Vanderbilt University, Nashville, U.S.A.**

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

**University of Virginia, Charlottesville, U.S.A.**

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

**Wayne State University, Detroit, U.S.A.**

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

**University of Wisconsin - Madison, Madison, WI, U.S.A.**

M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

- 2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- 3: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- 5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 6: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 7: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 8: Also at Suez University, Suez, Egypt
- 9: Now at British University in Egypt, Cairo, Egypt
- 10: Now at Helwan University, Cairo, Egypt
- 11: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
- 12: Also at Université de Haute Alsace, Mulhouse, France
- 13: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 14: Also at Tbilisi State University, Tbilisi, Georgia
- 15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 17: Also at University of Hamburg, Hamburg, Germany
- 18: Also at Brandenburg University of Technology, Cottbus, Germany
- 19: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- 22: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
- 23: Also at Institute of Physics, Bhubaneswar, India
- 24: Also at University of Visva-Bharati, Santiniketan, India
- 25: Also at University of Ruhuna, Matara, Sri Lanka
- 26: Also at Isfahan University of Technology, Isfahan, Iran
- 27: Also at Yazd University, Yazd, Iran
- 28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 29: Also at Università degli Studi di Siena, Siena, Italy
- 30: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy
- 31: Also at Purdue University, West Lafayette, U.S.A.
- 32: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 34: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
- 35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 36: Also at Institute for Nuclear Research, Moscow, Russia
- 37: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 39: Also at University of Florida, Gainesville, U.S.A.
- 40: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 41: Also at California Institute of Technology, Pasadena, U.S.A.
- 42: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 43: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 44: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

- 45: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 46: Also at National and Kapodistrian University of Athens, Athens, Greece
- 47: Also at Riga Technical University, Riga, Latvia
- 48: Also at Universität Zürich, Zurich, Switzerland
- 49: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 50: Also at Adiyaman University, Adiyaman, Turkey
- 51: Also at Istanbul Aydin University, Istanbul, Turkey
- 52: Also at Mersin University, Mersin, Turkey
- 53: Also at Cag University, Mersin, Turkey
- 54: Also at Piri Reis University, Istanbul, Turkey
- 55: Also at Izmir Institute of Technology, Izmir, Turkey
- 56: Also at Necmettin Erbakan University, Konya, Turkey
- 57: Also at Marmara University, Istanbul, Turkey
- 58: Also at Kafkas University, Kars, Turkey
- 59: Also at Istanbul Bilgi University, Istanbul, Turkey
- 60: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 61: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 62: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 63: Also at Utah Valley University, Orem, U.S.A.
- 64: Also at Beykent University, Istanbul, Turkey
- 65: Also at Bingol University, Bingol, Turkey
- 66: Also at Erzincan University, Erzincan, Turkey
- 67: Also at Sinop University, Sinop, Turkey
- 68: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 69: Also at Texas A&M University at Qatar, Doha, Qatar
- 70: Also at Kyungpook National University, Daegu, Korea