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

The CMS Collaboration *

CERN, Switzerland

ABSTRACT

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

1. Introduction

The exceptionally large mass of the top quark, measured by this experiment as $m_{\text{t}} = 172.44 \pm 0.48$ GeV [1], suggests the top quark could have an important connection to physics beyond the standard model (SM), particularly in the mechanism of electroweak (EW) symmetry breaking. Precision measurements of top quark properties have the potential to identify the first hints of new particles, particularly those with stronger couplings to top quarks than to other fundamental particles. The SM predicts a charge asymmetry in tt̄ production at hadron colliders through quark–antiquark annihilation. This asymmetry is caused by the interference between the Born and the box diagrams, as well as between the initial- and final-state radiation diagrams, and is predicted by quantum chromodynamics (QCD) calculations at next-to-leading order (NLO) [2,3]. Early measurements of this asymmetry by the CDF [4] and D0 [5] Collaborations exceeded the NLO predictions [2,3] by about two standard deviations, and the discrepancy was more pronounced in the CDF events with large tt̄ invariant mass ($M_{\text{t}\bar{\text{t}}} > 450$ GeV). These results have led to considerations that the anomalous asymmetry might be generated by tree-level exchanges of new particles or by interference effects from new physics at higher mass scales, not directly observable at the LHC [6]. Recent

developments in experimental techniques [7,8] and theoretical predictions such as the inclusion of EW [9–12] and next-to-next-to-leading-order (NNLO) QCD [13,14] corrections have largely resolved the disagreement between theory and the Tevatron measurements. Nonetheless, the charge asymmetry remains an important probe of new physics.

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

$$A_{\text{C}} = \frac{N(\Delta|y_{\text{t}}| > 0) - N(\Delta|y_{\text{t}}| < 0)}{N(\Delta|y_{\text{t}}| > 0) + N(\Delta|y_{\text{t}}| < 0)}.$$

While the measurement of A_{C} relies on the reconstruction of the top quark and antiquark directions, an advantage of the dilepton final state is that one can alternatively measure the leptonic charge

* *E-mail address:* cms-publication-committee-chair@cern.ch.

asymmetry defined using only the lepton pseudorapidities [15] $\eta_{\ell^\pm}$ as

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

where $\Delta|\eta_\ell| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$. This observable is useful because it is free of the ambiguities associated with the top quark reconstruction, and because the correlation between the direction of a top quark and its decay products transmits an asymmetry in the parent top quarks to the daughter leptons. Furthermore, its dependence on the top quark polarization implies that it is not fully correlated with A_C and provides complementary information [16]. Previous ATLAS and CMS measurements of A_C using data from pp collisions at $\sqrt{s} = 7$ TeV [17,18] and 8 TeV [19–22], and of A_C^{lep} using the 7 TeV data samples [23,24], are consistent with the SM predictions.

In this Letter, measurements are presented of A_C and A_C^{lep} from $t\bar{t}$ events in the dilepton final states, using CMS data from pp collisions at $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 19.5 fb^{-1}. The analysis strategy is similar to that presented in Ref. [23] with many improvements, most importantly in the unfolding technique. This allows for full differential measurements of A_C and A_C^{lep}, which are made as a function of $M_{t\bar{t}}$ as well as the absolute rapidity and the transverse momentum of the $t\bar{t}$ system in the laboratory frame ($|y_{t\bar{t}}|$ and $p_T^{t\bar{t}}$). Furthermore, the larger data sample used here as well as improvements made in the resolution of the top quark reconstruction lead to better statistical precision.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid provide additional measurements of muons. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [15].

3. Event selection and reconstruction

The event selection for this analysis is identical to that used in Ref. [25] and is only briefly described in this section. The particle-flow (PF) method [26,27] is used to reconstruct final-state particles. Events are required to have exactly two isolated [25] leptons (electrons [28] or muons [29]) of opposite electric charge, with $p_T > 20$ GeV and $|\eta| < 2.4$. The dilepton pair invariant mass $M_{\ell\ell}$ is required to be above 20 GeV. For same-flavor leptons, $M_{\ell\ell}$ must also not be within 15 GeV of the Z boson mass to suppress the Drell–Yan ($Z/\gamma^\star +$ jets) background.

The anti-k_T clustering algorithm [30] with a distance parameter of 0.5 is used to form jets from the PF objects. The contribution to the jet energy from additional interactions in the same bunch crossing (pileup) is estimated for each event using the jet area method [31], and is subtracted from the overall jet p_T. At least two jets with $p_T > 30$ GeV and $|\eta| < 2.4$ are required in each event. At least one of these jets must be consistent with containing the decay of a heavy-flavor hadron, as identified using the medium operating point of the combined secondary vertex (CSV) b tagging algorithm [32]. We refer to such jets as b-tagged jets.

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

The inclusive measurement of A_C and all differential measurements presented here require reconstruction of the $t\bar{t}$ system. Each signal event has two neutrinos, and there is also a twofold ambiguity in combining the b jets with the leptons. In 62% of the events passing the event selection requirements, only one of the selected jets is b tagged. In those events the untagged jet with the highest ranking by the CSV algorithm is assumed to be the second b jet. Solutions for the neutrino momenta are found analytically assuming $m_t = 172.5$ GeV. Each event can have up to 8 possible solutions, and the one with the maximum weight obtained using the matrix weighting technique [33] is chosen as the most probable. For events with no physical solution, we attempt to find a solution for the sum of neutrino p_T as close as possible to the measured $\vec{p}_T^{\,miss}$ [34,35]. Nonetheless, no solution is found for approximately 16% of the events, both in data and simulation. Events with no solutions are used only in the inclusive measurement of A_C^{lep}, although the results do not significantly change if those events are excluded. The signs of $\Delta|y_t|$ and $\Delta|\eta_\ell|$ are correctly reconstructed in 74.9% and 99.5% of selected simulated $t\bar{t}$ events, respectively.

4. Event samples and background estimation

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

For all MC generated events, pileup is simulated with PYTHIA and superimposed on the hard collisions using a pileup multiplicity distribution that reflects the luminosity profile of the analyzed data. The CMS detector response is simulated using a GEANT4-based model [57], and the events are reconstructed and analyzed with the same software used to process the data. The measured trigger efficiencies are used to weight the simulated events to account for the trigger requirement, while the lepton selection efficiencies (reconstruction, identification, and isolation) are consistent between data and simulation [25,58]. The differences between b tagging efficiencies measured in data and simulation [32] are accounted for using correction factors.

The total contribution from background events to the data sample is expected to be 9%, of which about half comes from single top quark production in association with a W boson (tW), with dileptonic decays. Several control regions (CRs) in data are used to validate the background estimates from simulation for tW and $Z/\gamma^* +$ jets production and for events with incorrectly identified leptons. The CRs are selected to have similar kinematic properties

to the signal region, but with one or two requirements inverted, thus enriching them in different background contributions [25]. Agreement between data and simulation is observed in the tW CR, and we assign a 25% uncertainty in the tW cross section based on the recent CMS measurement of 23.4 ± 5.4 pb [59]. The other CRs are used to derive scale factors (SFs) to multiply the simulated event yields for the corresponding background process, with systematic uncertainties estimated from the envelope of variation in the SF value using the three dilepton flavor combinations and various alternative CRs.

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

A comparison of the observed and predicted distributions of $\Delta|y_t|$ and $\Delta|\eta_\ell|$ can be found in the supplementary material.

5. Unfolding the distributions

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

We use six bins of varying width in the $\Delta|y_t|$ parton-level distribution that are well matched to the reconstruction resolution and contain approximately equal numbers of events. The $\Delta|\eta_\ell|$ distribution depends only on lepton measurements, and the better resolution allows us to use 12 bins. For the reconstruction-level distributions, we use twice as many bins as those used for the parton-level distributions. The unfolding is performed using the TUnfold package [63], using regularization based on the curvature of the simulated signal distribution to suppress statistical fluctuations in the high frequency components of the unfolded distribution. The regularization strength is optimized by minimizing the average global correlation coefficient in the unfolded distribution; the resulting regularization is relatively weak, contributing at the level of 5% to the total χ^2 minimized by the algorithm. An analogous unfolding procedure is used to measure A_C and A_C^{lep} differentially, after introducing a further three bins in each of the $t\bar{t}$ system kinematic variables $M_{t\bar{t}}$, $|y_{t\bar{t}}|$, and $p_T^{t\bar{t}}$.

6. Systematic uncertainties

Most of the systematic uncertainties concern detector performance and the modeling of the signal and background processes and are estimated from the change in the measurement when varying the simulated event samples used for the unfolding. The uncertainty from the jet energy scale corrections is estimated by varying the jet energies within their uncertainties [64] and propagating this to the $\vec{p}_T^{\text{miss}}$. Similarly, the jet energy resolution is

Table 1
Systematic uncertainties in the inclusive values of the charge asymmetries obtained from the unfolded distributions. Uncertainties of less than 0.0005 are marked by a dash (−).

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

varied by 2–5%, depending on the η of the jet [64], and the electron energy scale is varied by $\pm 0.6\%$ ($\pm 1.5\%$) for barrel (endcap) electrons, as estimated from comparisons between measured and simulated Z boson events [28]. The uncertainty in muon energies is negligible. The uncertainty in the background subtraction is obtained by varying the normalization of each background component by the uncertainties described in Section 4.

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

The uncertainty in the unfolding procedure is dominated by the statistical uncertainty arising from the limited number of events in the MC@NLO $t\bar{t}$ sample. The uncertainty from the regularization is found to be small in comparison. The systematic uncertainties in the inclusive charge asymmetry values obtained from the unfolded distributions are summarized in Table 1. The individual terms are added in quadrature to estimate the total systematic uncertainties. For both A_C and A_C^{lep}, the dominant systematic uncertainty arises from the limited number of simulated events used for the unfolding.
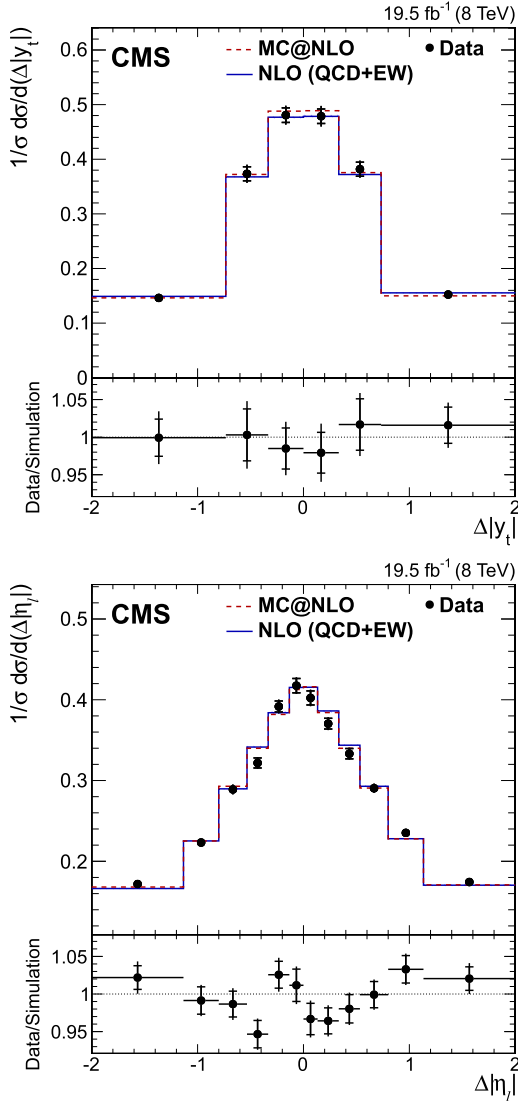
Fig. 1. Background-subtracted and unfolded distributions of $\Delta|y_t|$ (top) and $\Delta|\eta_\ell|$ (bottom) from data (points), normalized to unit area. Parton-level predictions from the MC@NLO simulation and calculations at NLO (QCD + EW) [12] are shown by dashed and solid histograms, respectively. The ratio of the measured bin values to the MC@NLO prediction is shown in the bottom panel. The vertical bars show the total uncertainty, the statistical component of which is marked by a horizontal tick. The first and last bins of each plot include underflow and overflow events, respectively.

7. Results

The unfolded normalized differential cross section from the selected events in data is shown as a function of $\Delta|y_t|$ and $\Delta|\eta_\ell|$ in Fig. 1, along with the parton-level predictions for $t\bar{t}$ production obtained from calculations at NLO in the SM gauge couplings (QCD + EW) [12] and with the MC@NLO generator (which does not include EW corrections). The corresponding A_C and A_C^{lep} values are presented in Table 2. Correlations between the contents of different bins, introduced by the unfolding process and from the systematic uncertainties, are accounted for in the calculation of the uncertainties. The measured values are consistent with the expectations from the SM. The charge asymmetries as a function of $M_{t\bar{t}}$, $|y_{t\bar{t}}|$, and $p_T^{t\bar{t}}$ are also measured. The results, which are shown in Fig. 2, are consistent with the MC@NLO simulation predictions, as well as with the NLO (QCD + EW) calculations for the $M_{t\bar{t}}$ and

Table 2

The inclusive charge asymmetry measurements obtained from the unfolded distributions and the parton-level predictions from the MC@NLO simulation and calculations at NLO (QCD + EW) [12]. For the data, the first uncertainty is statistical and the second is systematic. The uncertainties in the MC@NLO results are statistical and the uncertainties in the NLO calculations come from varying together μ_R and μ_F up and down by a factor of two.

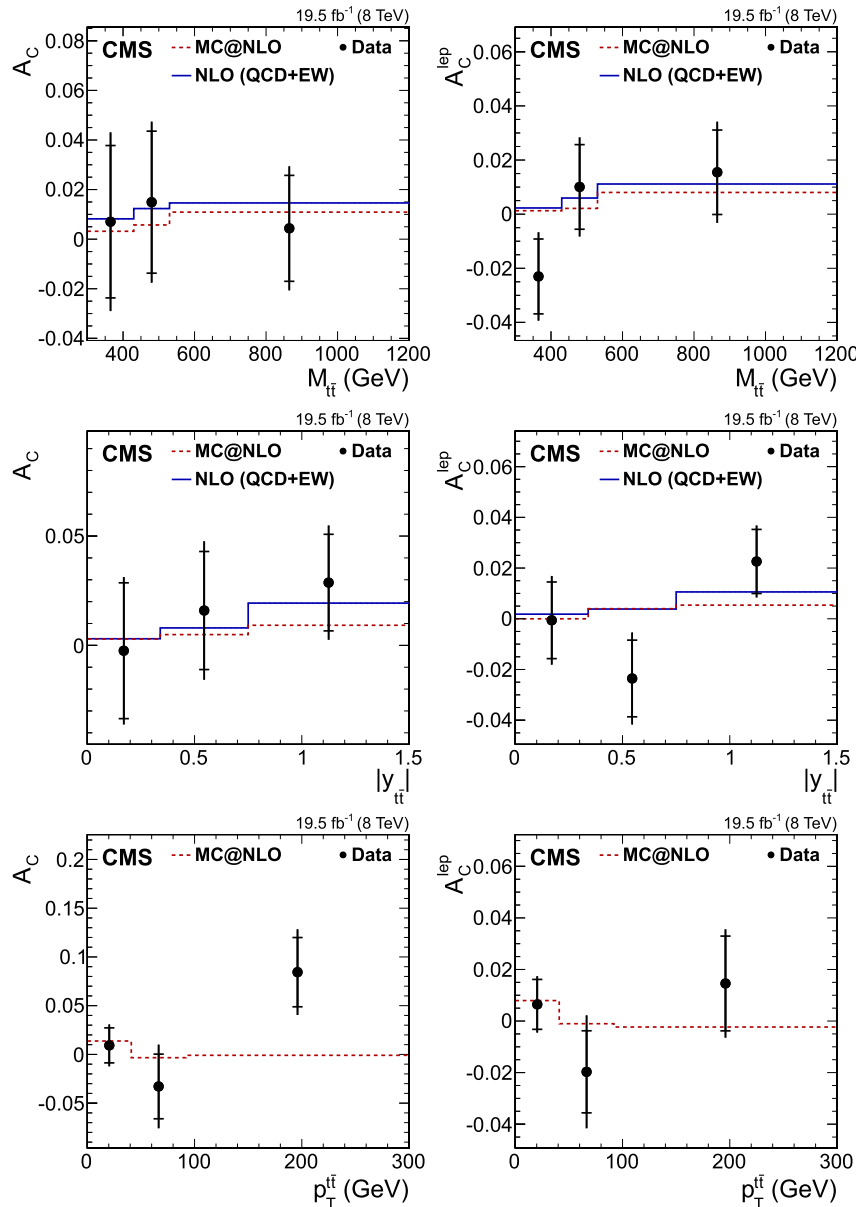| Variable	Data	MC@NLO	NLO (QCD + EW)
A_C	$0.011 \pm 0.011 \pm 0.007$	0.006 ± 0.001	0.0111 ± 0.0004
A_C^{lep}	$0.003 \pm 0.006 \pm 0.003$	0.004 ± 0.001	0.0064 ± 0.0003

$|y_{t\bar{t}}|$ dependencies. No comparison is made with NLO calculations for the $p_T^{t\bar{t}}$ dependencies as it is expected that the effect of the parton shower process on the $p_T^{t\bar{t}}$ distribution makes fixed-order calculations an inadequate approximation of the data.

8. Summary

Measurements are presented of the charge asymmetry in $t\bar{t}$ dilepton final states from distributions, unfolded to the parton level, of the absolute rapidity (pseudorapidity) difference of top quarks (leptons) with positive and negative charge. The data sample corresponds to an integrated luminosity of $19.5\,\text{fb}^{-1}$ from pp collisions at $\sqrt{s} = 8\,\text{TeV}$, collected by the CMS experiment at the LHC. The $t\bar{t}$ and leptonic inclusive charge asymmetries are found to be, respectively, $0.011 \pm 0.011\,(\text{stat}) \pm 0.007\,(\text{syst})$ and $0.003 \pm 0.006\,(\text{stat}) \pm 0.003\,(\text{syst})$ when measured inclusively. The charge asymmetries are also measured as a function of the invariant mass, absolute rapidity, and transverse momentum of the $t\bar{t}$ system in the laboratory frame. Although statistically limited, all measurements are in agreement with the standard model predictions. Future measurements at $\sqrt{s} = 13\,\text{TeV}$ with larger data sets are expected to have better statistical precision outweighing the dilution of the charge asymmetry from the decreased fraction of events with the quark–antiquark initial state.

Fig. 2. Dependence of the $t\bar{t}$ and leptonic charge asymmetries A_C (left) and A_C^{lep} (right) obtained from the unfolded distributions in data (points) on $M_{t\bar{t}}$ (upper), $|y_{t\bar{t}}|$ (middle), and $p_T^{t\bar{t}}$ (lower). Parton-level predictions from the MC@NLO simulation and calculations at NLO (QCD + EW) [12] are shown by dashed and solid histograms, respectively. The vertical bars show the total uncertainty, the statistical component of which is marked by a horizontal tick. The last bin of each plot includes overflow events.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.physletb.2016.07.006.

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CMS Collaboration

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth [1], V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler [1], A. König, M. Krammer [1], I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck [1], R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz [1]

Institut für Hochenergiephysik der OeAW, Wien, Austria

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

National Centre for Particle and High Energy Physics, Minsk, Belarus

S. Alderweireldt, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang [2]

Université Libre de Bruxelles, Bruxelles, Belgium

L. Benucci, A. Cimmino, S. Crucy, D. Dobur, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, C. Beluffi [3], O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Ceard, S. De Visscher, C. Delaere, M. Delcourt, D. Favart, L. Forthomme, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, M. Musich, C. Nuttens, L. Perrini, K. Piotrzkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono

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

N. Beliy, G.H. Hammad

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato [4], A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote [4], A. Vilela Pereira

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

S. Ahuja [a], C.A. Bernardes [b], A. De Souza Santos [b], S. Dogra [a], T.R. Fernandez Perez Tomei [a], E.M. Gregores [b], P.G. Mercadante [b], C.S. Moon [a,5], S.F. Novaes [a], Sandra S. Padula [a], D. Romero Abad [b], J.C. Ruiz Vargas

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

W. Fang [6]

Beihang University, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, D. Leggat, R. Plestina [7], F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger [8], M. Finger Jr. [8]

Charles University, Prague, Czech Republic

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

Y. Assran [9,10], A. Ellithi Kamel [11], A. Mahrous [12], A. Radi [10,13]

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

B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Peltola, J. Tuominiemi, E. Tuovinen, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, N. Filipovic, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France

J.-L. Agram [14], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte [14], X. Coubez, J.-C. Fontaine [14], D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin [15], K. Skovpen, P. Van Hove

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov [16], J.D. Ruiz Alvarez, D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

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

T. Toriashvili [17]

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze [8]

Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, J.F. Schulte, T. Verlage, H. Weber, V. Zhukov [16]

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

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

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, A. Nehrkorn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl [15]

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

M. Aldaya Martin, I. Asin, N. Bartosik, K. Beernaert, O. Behnke, U. Behrens, K. Borras [18], A. Burgmeier, A. Campbell, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Gallo [19], J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel [20], H. Jung, A. Kalogeropoulos, O. Karacheban [20], M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann [20], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, A. Nayak, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, K.D. Trippkewitz, G.P. Van Onsem, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, J. Ott, F. Pantaleo [15], T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, C. Sander, C. Scharf, P. Schleper, E. Schlieckau, A. Schmidt, S. Schumann, J. Schwandt, V. Sola, H. Stadie, G. Steinbrück, F.M. Stober, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, S. Fink, F. Frensch, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann [15], S.M. Heindl, U. Husemann, I. Katkov [16], A. Kornmayer [15], P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, G. Sieber, H.J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

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

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

National and Kapodistrian University of Athens, Athens, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, P. Hidas, D. Horvath [21], F. Sikler, V. Veszpremi, G. Vesztergombi [22], A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [23], J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók [22], A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

S. Choudhury [24], P. Mal, K. Mandal, D.K. Sahoo, N. Sahoo, S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, J.B. Singh, G. Walia

Panjab University, Chandigarh, India

Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

University of Delhi, Delhi, India

R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty [15], L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik [25], R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu [26], Sa. Jain, G. Kole, S. Kumar, B. Mahakud, M. Maity [25], G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar [25], N. Sur, B. Sutar, N. Wickramage [27]

Tata Institute of Fundamental Research, Mumbai, India

S. Chauhan, S. Dube, A. Kapoor, K. Kothekar, A. Rane, S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami [28], A. Fahim [29], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh [30], M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], C. Calabria [a,b], C. Caputo [a,b], A. Colaleo [a], D. Creanza [a,c], L. Cristella [a,b], N. De Filippis [a,c], M. De Palma [a,b], L. Fiore [a], G. Iaselli [a,c], G. Maggi [a,c], M. Maggi [a], G. Miniello [a,b], S. My [a,b], S. Nuzzo [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a,b], A. Ranieri [a], G. Selvaggi [a,b], L. Silvestris [a,15], R. Venditti [a,b]

[a] *INFN Sezione di Bari, Bari, Italy*

[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], C. Battilana [15], D. Bonacorsi [a,b], S. Braibant-Giacomelli [a,b], L. Brigliadori [a,b], R. Campanini [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], S.S. Chhibra [a,b], G. Codispoti [a,b], M. Cuffiani [a,b], G.M. Dallavalle [a], F. Fabbri [a], A. Fanfani [a,b], D. Fasanella [a,b], P. Giacomelli [a], C. Grandi [a], L. Guiducci [a,b], S. Marcellini [a], G. Masetti [a], A. Montanari [a], F.L. Navarria [a,b], A. Perrotta [a], A.M. Rossi [a,b], T. Rovelli [a,b], G.P. Siroli [a,b], N. Tosi [a,b,15]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

G. Cappello [b], M. Chiorboli [a,b], S. Costa [a,b], A. Di Mattia [a], F. Giordano [a,b], R. Potenza [a,b], A. Tricomi [a,b], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

G. Barbagli [a], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], V. Gori [a,b], P. Lenzi [a,b], M. Meschini [a], S. Paoletti [a], G. Sguazzoni [a], L. Viliani [a,b,15]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera [15]

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli [a,b], F. Ferro [a], M. Lo Vetere [a,b], M.R. Monge [a,b], E. Robutti [a], S. Tosi [a,b]

[a] *INFN Sezione di Genova, Genova, Italy*
[b] *Università di Genova, Genova, Italy*

L. Brianza, M.E. Dinardo [a,b], S. Fiorendi [a,b], S. Gennai [a], R. Gerosa [a,b], A. Ghezzi [a,b], P. Govoni [a,b], S. Malvezzi [a], R.A. Manzoni [a,b,15], B. Marzocchi [a,b], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], S. Pigazzini, S. Ragazzi [a,b], N. Redaelli [a], T. Tabarelli de Fatis [a,b]

[a] *INFN Sezione di Milano-Bicocca, Milano, Italy*
[b] *Università di Milano-Bicocca, Milano, Italy*

S. Buontempo [a], N. Cavallo [a,c], S. Di Guida [a,d,15], M. Esposito [a,b], F. Fabozzi [a,c], A.O.M. Iorio [a,b], G. Lanza [a], L. Lista [a], S. Meola [a,d,15], M. Merola [a], P. Paolucci [a,15], C. Sciacca [a,b], F. Thyssen

[a] *INFN Sezione di Napoli, Napoli, Italy*
[b] *Università di Napoli 'Federico II', Napoli, Italy*
[c] *Università della Basilicata, Potenza, Italy*
[d] *Università G. Marconi, Roma, Italy*

P. Azzi [a,15], N. Bacchetta [a], L. Benato [a,b], D. Bisello [a,b], A. Boletti [a,b], R. Carlin [a,b], P. Checchia [a], M. Dall'Osso [a,b,15], T. Dorigo [a], U. Dosselli [a], F. Gasparini [a,b], U. Gasparini [a,b], F. Gonella [a], A. Gozzelino [a], S. Lacaprara [a], M. Margoni [a,b], A.T. Meneguzzo [a,b], F. Montecassiano [a], M. Passaseo [a], J. Pazzini [a,b,15], N. Pozzobon [a,b], P. Ronchese [a,b], F. Simonetto [a,b], E. Torassa [a], M. Tosi [a,b], M. Zanetti, P. Zotto [a,b], A. Zucchetta [a,b,15], G. Zumerle [a,b]

[a] *INFN Sezione di Padova, Padova, Italy*
[b] *Università di Padova, Padova, Italy*
[c] *Università di Trento, Trento, Italy*

A. Braghieri [a], A. Magnani [a,b], P. Montagna [a,b], S.P. Ratti [a,b], V. Re [a], C. Riccardi [a,b], P. Salvini [a], I. Vai [a,b], P. Vitulo [a,b]

[a] *INFN Sezione di Pavia, Pavia, Italy*
[b] *Università di Pavia, Pavia, Italy*

L. Alunni Solestizi [a,b], G.M. Bilei [a], D. Ciangottini [a,b], L. Fanò [a,b], P. Lariccia [a,b], R. Leonardi [a,b], G. Mantovani [a,b], M. Menichelli [a], A. Saha [a], A. Santocchia [a,b]

[a] *INFN Sezione di Perugia, Perugia, Italy*
[b] *Università di Perugia, Perugia, Italy*

K. Androsov [a,31], P. Azzurri [a,15], G. Bagliesi [a], J. Bernardini [a], T. Boccali [a], R. Castaldi [a], M.A. Ciocci [a,31], R. Dell'Orso [a], S. Donato [a,c], G. Fedi, L. Foà [a,c,†], A. Giassi [a], M.T. Grippo [a,31], F. Ligabue [a,c], T. Lomtadze [a], L. Martini [a,b], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A. Savoy-Navarro [a,32], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a]

[a] *INFN Sezione di Pisa, Pisa, Italy*
[b] *Università di Pisa, Pisa, Italy*
[c] *Scuola Normale Superiore di Pisa, Pisa, Italy*

L. Barone [a,b], F. Cavallari [a], G. D'imperio [a,b,15], D. Del Re [a,b,15], M. Diemoz [a], S. Gelli [a,b], C. Jorda [a], E. Longo [a,b], F. Margaroli [a,b], P. Meridiani [a], G. Organtini [a,b], R. Paramatti [a], F. Preiato [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b]

[a] *INFN Sezione di Roma, Roma, Italy*
[b] *Università di Roma, Roma, Italy*

N. Amapane [a,b], R. Arcidiacono [a,c,15], S. Argiro [a,b], M. Arneodo [a,c], R. Bellan [a,b], C. Biino [a], N. Cartiglia [a], M. Costa [a,b], R. Covarelli [a,b], A. Degano [a,b], N. Demaria [a], L. Finco [a,b], B. Kiani [a,b], C. Mariotti [a], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], E. Monteil [a,b], M.M. Obertino [a,b], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], G.L. Pinna Angioni [a,b], F. Ravera [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], A. Solano [a,b], A. Staiano [a]

[a] *INFN Sezione di Torino, Torino, Italy*
[b] *Università di Torino, Torino, Italy*
[c] *Università del Piemonte Orientale, Novara, Italy*

S. Belforte [a], V. Candelise [a,b], M. Casarsa [a], F. Cossutti [a], G. Della Ricca [a,b], B. Gobbo [a], C. La Licata [a,b], A. Schizzi [a,b], A. Zanetti [a]

[a] *INFN Sezione di Trieste, Trieste, Italy*
[b] *Università di Trieste, Trieste, Italy*

S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, S.W. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Kyungpook National University, Daegu, Republic of Korea

J.A. Brochero Cifuentes, H. Kim, T.J. Kim [33]

Chonbuk National University, Jeonju, Republic of Korea

S. Song

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

S. Cho, S. Choi, Y. Go, D. Gyun, B. Hong, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

H.D. Yoo

Seoul National University, Seoul, Republic of Korea

M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu, M.S. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali [34], F. Mohamad Idris [35], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz [36], A. Hernandez-Almada, R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

I. Pedraza, H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib, M. Waqas

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

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

National Centre for Nuclear Research, Swierk, Poland

G. Brona, K. Bunkowski, A. Byszuk [37], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia

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

I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev [38,39], V.V. Mitsyn, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, E. Tikhonenko, N. Voytishin, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim [40], E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

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

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

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

M. Chadeeva, R. Chistov, M. Danilov, O. Markin, E. Tarkovskii

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

V. Andreev, M. Azarkin [39], I. Dremin [39], M. Kirakosyan, A. Leonidov [39], G. Mesyats, S.V. Rusakov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin [41], L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, N. Korneeva, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, V. Savrin

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

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic [42], P. Cirkovic, D. Devetak, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

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

J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon [15], J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, E. Curras, P. De Castro Manzano, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, L. Benhabib, G.M. Berruti, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio,

A. De Roeck, E. Di Marco [43], M. Dobson, M. Dordevic, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, V. Knünz, M.J. Kortelainen, K. Kousouris, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli [44], L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, A. Racz, T. Reis, G. Rolandi [45], M. Rovere, M. Ruan, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas [46], J. Steggemann, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns [47], G.I. Veres [22], N. Wardle, H.K. Wöhri, A. Zagozdzinska [37], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte [†], W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov [48], M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler [49], L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang

Universität Zürich, Zurich, Switzerland

K.H. Chen, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

Arun Kumar, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.f. Tsai, Y.M. Tzeng

National Taiwan University (NTU), Taipei, Taiwan

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

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

A. Adiguzel, M.N. Bakirci [50], S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal [51], G. Onengut [52], K. Ozdemir [53], A. Polatoz, D. Sunar Cerci [54], B. Tali [54], C. Zorbilmez

Cukurova University, Adana, Turkey

B. Bilin, S. Bilmis, B. Isildak [55], G. Karapinar [56], M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya [57], O. Kaya [58], E.A. Yetkin [59], T. Yetkin [60]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen [61], F.I. Vardarlı

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold [62], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev [63], C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, S.D. Worm

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, R. Lane, R. Lucas [62], L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko [48], J. Pela, B. Penning, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta [64], T. Virdee [15], S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

J. Alimena, G. Benelli, E. Berry, D. Cutts, A. Ferapontov, A. Garabedian, J. Hakala, U. Heintz, O. Jesus, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, R. Syarif

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Davis, Davis, USA

R. Cousins, P. Everaerts, A. Florent, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Los Angeles, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova PANEVA, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Malberti, M. Olmedo Negrete, A. Shrinivas, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, M. Derdzinski, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech [65], C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, J. Incandela, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, I. Suarez, C. West, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

D. Anderson, A. Apresyan, J. Bendavid, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, USA

J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Lewis, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, C. Newman-Holmes [†], V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, 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

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, P. Milenovic [66], G. Mitselmakher, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

University of Florida, Gainesville, USA

S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

A. Ackert, J.R. Adams, T. Adams, A. Askew, S. Bein, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi [67], M. Hohlmann, H. Kalakhety, D. Noonan, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, P. Turner, N. Varelas, Z. Wu, M. Zakaria, J. Zhang

University of Illinois at Chicago (UIC), Chicago, USA

B. Bilki [68], W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya [69], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok [70], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

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

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, C. Bruner, J. Castle, R.P. Kenny III, A. Kropivnitskaya, D. Majumder, M. Malek, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, Q. Wang

The University of Kansas, Lawrence, USA

A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Kansas State University, Manhattan, USA

D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

University of Maryland, College Park, USA

A. Apyan, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, 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, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti, B. Dahmes, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, K. Klapoetke, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, R. Bartek, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, D. Knowlton, I. Kravchenko, F. Meier, J. Monroy, F. Ratnikov, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska–Lincoln, Lincoln, USA

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

Northeastern University, Boston, USA

S. Bhattacharya, K.A. Hahn, A. Kubik, J.F. Low, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko [38], M. Planer, A. Reinsvold, R. Ruchti, N. Rupprecht, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, W. Ji, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully, A. Zuranski

Princeton University, Princeton, USA

S. Malik

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, K. Jung, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University, West Lafayette, USA

N. Parashar, J. Stupak

Purdue University Calumet, Hammond, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

J.P. Chou, E. Contreras-Campana, D. Ferencek, Y. Gershtein, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, K. Nash, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

Rutgers, The State University of New Jersey, Piscataway, USA

M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

University of Tennessee, Knoxville, USA

O. Bouhali [71], A. Castaneda Hernandez [71], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon [72], V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, J. Wood, F. Xia

University of Virginia, Charlottesville, USA

C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

Wayne State University, Detroit, USA

D.A. Belknap, D. Carlsmith, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, P. Verwilligen, N. Woods

University of Wisconsin–Madison, Madison, WI, USA

[†] Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
[3] Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
[4] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[5] Also at Centre National de la Recherche Scientifique (CNRS) – IN2P3, Paris, France.
[6] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[7] Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.
[8] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[9] Also at Suez University, Suez, Egypt.
[10] Now at British University in Egypt, Cairo, Egypt.
[11] Also at Cairo University, Cairo, Egypt.
[12] Now at Helwan University, Cairo, Egypt.
[13] Now at Ain Shams University, Cairo, Egypt.
[14] Also at Université de Haute Alsace, Mulhouse, France.
[15] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[16] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[17] Also at Tbilisi State University, Tbilisi, Georgia.
[18] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[19] Also at University of Hamburg, Hamburg, Germany.
[20] Also at Brandenburg University of Technology, Cottbus, Germany.
[21] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[22] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[23] Also at University of Debrecen, Debrecen, Hungary.
[24] Also at Indian Institute of Science Education and Research, Bhopal, India.
[25] Also at University of Visva-Bharati, Santiniketan, India.
[26] Now at King Abdulaziz University, Jeddah, Saudi Arabia.
[27] Also at University of Ruhuna, Matara, Sri Lanka.
[28] Also at Isfahan University of Technology, Isfahan, Iran.
[29] Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
[30] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[31] Also at Università degli Studi di Siena, Siena, Italy.
[32] Also at Purdue University, West Lafayette, USA.
[33] Now at Hanyang University, Seoul, Republic of Korea.

[34] Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.

[35] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.

[36] Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.

[37] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

[38] Also at Institute for Nuclear Research, Moscow, Russia.

[39] Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.

[40] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

[41] Also at California Institute of Technology, Pasadena, USA.

[42] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.

[43] Also at INFN Sezione di Roma; Università di Roma, Roma, Italy.

[44] Also at National Technical University of Athens, Athens, Greece.

[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 Institute for Theoretical and Experimental Physics, Moscow, Russia.

[49] Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.

[50] Also at Gaziosmanpasa University, Tokat, Turkey.

[51] Also at Mersin University, Mersin, Turkey.

[52] Also at Cag University, Mersin, Turkey.

[53] Also at Piri Reis University, Istanbul, Turkey.

[54] Also at Adiyaman University, Adiyaman, Turkey.

[55] Also at Ozyegin University, Istanbul, Turkey.

[56] Also at Izmir Institute of Technology, Izmir, 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 Yildiz Technical University, Istanbul, Turkey.

[61] Also at Hacettepe University, Ankara, Turkey.

[62] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

[63] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

[64] Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.

[65] Also at Utah Valley University, Orem, USA.

[66] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

[67] Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.

[68] Also at Argonne National Laboratory, Argonne, USA.

[69] Also at Erzincan University, Erzincan, Turkey.

[70] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

[71] Also at Texas A&M University at Qatar, Doha, Qatar.

[72] Also at Kyungpook National University, Daegu, Republic of Korea.