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Measurement of the $t\bar{t}$ charge asymmetry in events with highly Lorentz-boosted top quarks in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration *

CERN, Geneva, Switzerland

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ABSTRACT

The measurement of the charge asymmetry in top quark pair events with highly Lorentz-boosted top quarks decaying to a single lepton and jets is presented. The analysis is performed using proton-proton collisions at $\sqrt{s} = 13$ TeV with the CMS detector at the LHC and corresponding to an integrated luminosity of 138 fb^{-1}. The selection is optimized for top quarks produced with large Lorentz boosts, resulting in nonisolated leptons and overlapping jets. The top quark charge asymmetry is measured for events with a $t\bar{t}$ invariant mass larger than 750 GeV and corrected for detector and acceptance effects using a binned maximum likelihood fit. The measured top quark charge asymmetry of $(0.42^{+0.64}_{-0.69})$% is in good agreement with the standard model prediction at next-to-next-to-leading order in quantum chromodynamic perturbation theory with next-to-leading-order electroweak corrections. The result is also presented for two invariant mass ranges, 750–900 and >900 GeV.

1. Introduction

The vast majority of top quarks produced at hadron colliders are from $t\bar{t}$ pairs that originate via the strong interaction. At the LHC proton-proton (pp) collider, the production stems from gluon fusion about 90% of the time, with $q\bar{q}$ annihilation making up the rest [1,2]. At leading order, the standard model (SM) predicts that $t\bar{t}$ production from $q\bar{q}$ annihilation is forward-backward symmetric. However, higher-order SM effects result in a small (≈6.6%) positive forward-backward asymmetry A_{FB}, such that the top quark (antiquark) is preferentially emitted in the direction of the incoming quark (antiquark). The A_{FB} was measured at the Tevatron proton-antiproton collider by the CDF and D0 collaborations [3] and found to be consistent with the theoretical predictions [4]. There is no asymmetry in the gluon fusion $t\bar{t}$ production that dominates at the LHC, but because valence quarks carry, on average, larger momentum than antiquarks (from the sea), the rapidity distribution of top quarks at the LHC is expected to be broader than that of top antiquarks [5,6]. The $t\bar{t}$ charge asymmetry is defined as

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

where $\Delta|y| = |y_t| - |y_{\bar{t}}|$ is the difference between the absolute value of the top quark and antiquark rapidities and N is the number of events. The value of A_C is expected to be about 1% in the SM for LHC [5].

Since the relative contribution of valence quarks increases at high momentum transfer [7], we expect that measuring A_C in a sample of $t\bar{t}$ events with highly Lorentz-boosted top quarks will lead to a more stringent probe of quantum chromodynamic (QCD) predictions and higher sensitivity to beyond-the-SM (BSM) physics processes that might alter the charge asymmetry [8]. Several models predict enhancements with respect to the SM prediction in the presence of new particles, including axigluons [9,10], Z′ bosons [11–13], W′ bosons [10,13,14], scalar isodoublets [15], color triplet scalars [16,17], and color sextet scalars [14,15]. These models introduce new spin-0 and spin-1 particles in the interaction, modifying A_C by exchanging the new particles through interference terms and dedicated loops. The ATLAS and CMS Collaborations have combined their inclusive and differential measurements of A_C [18] at two center-of-mass energies, obtaining $A_C = 0.005 \pm 0.007\,(\text{stat}) \pm 0.006\,(\text{syst})$ and $0.0055 \pm 0.0023\,(\text{stat}) \pm 0.0025\,(\text{syst})$ at 7 and 8 TeV, respectively. These combined measurements show good agreement with the respective SM predictions and uniquely restrict the phase space of possible BSM phenomena that would produce large asymmetries [14]. Along with specific BSM models, deviations from the SM prediction can also be interpreted through an effective field theory (EFT) approach in which new physics contributions are described via a fixed set of dimension-six operators added to the SM Lagrangian [19]. In particular, fits to top quark production and differential distributions, together with Higgs boson, boson pair (diboson), and electroweak precision measure-

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

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ments, are being used in global SM EFT analyses to constrain the operators [20,21].

This Letter presents the first measurement of the $t\bar{t}$ charge asymmetry that uses pp collision data at $\sqrt{s} = 13$ TeV and optimizes the reconstruction of events with $t\bar{t}$ invariant mass ($M_{t\bar{t}}$) above 750 GeV. The kinematic requirements necessarily imply highly boosted top quarks. We target the single-lepton channel, in which both top quarks decay as $t \to bW$, with one W boson decaying leptonically ($W \to \ell\nu$, where ℓ is either a muon or electron), and the other hadronically ($W \to q\bar{q}'$). The charge of the lepton is used to distinguish the top quark from the top antiquark. The highly boosted top quarks yield collimated decay products that appear as partially or fully overlapping energy deposits in our detector. For the top quark decaying to a W boson that decays leptonically (called a top quark leptonic decay), the energy deposits from the lepton overlap with those of the b quark. Dedicated jet and lepton selection requirements at the trigger and offline levels [22] allow us to reconstruct the decay products of the boosted leptonically decaying top quarks by identifying the energy deposits of the leptons without requiring a minimum separation from other signals in the detector. The overwhelming QCD multijet background is controlled with topological requirements. The topology of the top quark decaying to a W boson that decays hadronically (called a top quark hadronic decay) depends on the magnitude of its transverse momentum (p_T). At the high end of the p_T spectrum, the top quark decay products have angular distances between partons that result in overlapping energy deposits. In contrast, at the low end of the p_T spectrum near the kinematic threshold, the energy deposits from each parton appear separated from the others. For intermediate p_T values, the energy deposits of partons originating from the hadronic W boson decay are overlapping, but the b quark is identified separately. All three topologies are considered in this analysis and are referred to as "merged", "semiresolved", and "resolved" for the high, intermediate, and low p_T regions, respectively. Tabulated results are provided in the HEPData record for this analysis [23].

2. The CMS detector and object reconstruction

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 (η) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system [24,25]. 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. [26].

The offline event reconstruction is based on a particle-flow (PF) algorithm [27], which combines information from each subdetector to identify muons, electrons, photons, and charged or neutral hadrons. To avoid inefficiencies observed in the data for very high p_T PF muons, we use muons determined by a different algorithm [28], where muons are reconstructed first in the muon system and then fitted to tracks in the pixel and strip tracker. The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [29]. Charged hadrons associated with other vertices are removed from further consideration. The remaining PF candidates are clustered into jets using the anti-k_T algorithm [30,31] with a distance parameter of 0.4 (called AK4 jets). The same PF candidates are used to build large-radius (AK8) jets using a distance parameter of 0.8, with the effects of additional pp collisions in the same bunch crossing mitigated through the pileup per particle identification algorithm (PUPPI) [32,33]. Any AK4 jet with $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.8$ from the closest AK8 jet, where ϕ is the azimuthal angle, is discarded from the event. The total jet $\vec{p}_T$ is given by the sum of the $\vec{p}_T$ of its constituents. If a lepton is found within $\Delta R < 0.4$ of an AK4 jet or <0.8 of an AK8 jet, its four-momentum is subtracted from that jet [22]. The missing transverse momentum vector $\vec{p}_T^{\,miss}$ is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, and its magnitude is denoted as p_T^{miss} [34]. Corrections are applied to improve the jet energy scale and resolution, and the $\vec{p}_T^{\,miss}$ is modified to account for these corrections [35,36].

Specialized techniques use AK8 jets and jet substructure information [37], including "soft-drop clustering" [38] and "N-subjettiness" [39], to identify the hadronic decay of boosted top quarks, following the techniques detailed in Ref. [22]. Two exclusive categories are considered: hadronically decaying top quarks (t tag) in which the three partons are merged into a single AK8 jet, and hadronically decaying W bosons (W tag) in which the two partons from the W boson are merged into a single AK8 jet, but the bottom quark is reconstructed as a separate AK4 jet. The identification of jets originating from the decay of b hadrons (b tag) employs a deep neural network multi-classification algorithm (DeepJet [40]) that relies on information from the tracker and the calorimeters [41]. The b tagging algorithm is applied to each AK4 jet j with $p_T^j > 50$ GeV and $|\eta^j| < 2.4$. The t and W tagging algorithms are applied to AK8 jets with $p_T^j > 400$ GeV and $|\eta^j| < 2.4$. The algorithms are tuned for misidentification rates smaller than 5% and have efficiencies greater than 80%.

3. Collider data and simulated samples

We analyze data collected by the CMS detector during Run 2 (2016–2018) and corresponding to a total integrated luminosity of 138 fb^{-1} [42–44]. Events in the muon channel (μ + jets) are selected with a single-muon trigger that requires $p_T^{\mu} > 50$ GeV. Events in the electron channel (e + jets) are selected by either a single-electron trigger with $p_T^{e} > 115$ GeV or a trigger requiring one electron with $p_T^{e} > 50$ GeV and one jet with $p_T^{j} > 165$ GeV [22]. The efficiency of these triggers for events in our signal sample is above 95%. As the e + jets trigger was not available during the early running period in 2017, the integrated luminosity available for the 2017 e + jets channel is reduced by 5 fb^{-1}.

In the offline reconstruction, we select events for the μ + jets (e + jets) channel that contain exactly one muon with $p_T^{\mu} > 55$ GeV and $|\eta^{\mu}| < 2.4$ (one electron with $p_T^{e} > 80$ GeV and $|\eta^{e}| < 2.5$) and at least two AK4 jets, j_1 and j_2, with $p_T^{j_1} > 150$ (185) GeV, $p_T^{j_2} > 50$ GeV, and $|\eta^{j_{1,2}}| < 2.4$. To preserve the identification efficiency of $t\bar{t}$ decay products in the highly boosted topology, no isolation requirement is imposed on the leptons at either the trigger or offline level. To reduce the background from QCD multijet events, we apply a two-dimensional (2D) selection that requires leptons to satisfy either the condition $\Delta R_{min}(\ell, j) > 0.4$ or $p_{T,rel}(\ell, j) > 25$ GeV, where $\Delta R_{min}(\ell, j)$ is the angular separation between the lepton and the closest AK4 jet, and $p_{T,rel}(\ell, j)$ is the transverse momentum of the lepton with respect to the axis of the nearest AK4 jet [22]. Finally, events need to satisfy $p_T^{miss} > 50$ GeV and $p_T^{miss} + p_T^{\mu} > 150$ GeV ($p_T^{miss} > 120$ GeV) in the μ + jets (e + jets) channel. The larger value of the e + jets p_T^{miss} requirement efficiently reduces the larger QCD multijet background in this channel and precludes the need for a separate requirement on $p_T^{miss} + p_T^{e}$. To suppress the contribution from the W + jets background, at least one of the AK4 jets must be b tagged.

A variety of Monte Carlo (MC) simulated samples are used to model the signal and background contributions. A comprehensive description of the generation parameters used, as well as the MC normalization and associated uncertainties, can be found in Ref. [45]. The $t\bar{t}$ and single top quark (ST) processes are produced with the next-to-leading-order (NLO) POWHEG [46,47] generator. Simulated $W+$jets, Drell–Yan (DY) $Z/\gamma+$jets, and QCD multijet processes are generated with MADGRAPH5_aMC@NLO [48] at NLO. The contribution from diboson events is negligible. All samples are interfaced to PYTHIA8 [49] with the CP5 tune [50] for parton showering and hadronization, and processed through a GEANT4-based simulation [51], which models the propagation of the particles through the CMS detector and the corresponding detector response. The NNPDF 3.1 parton distribution functions (PDFs) [52] are used for all samples, and events in all samples include the simulation of additional inelastic pp interactions (pileup) within the same or nearby bunch crossings. Small corrections are applied to all MC samples to improve the agreement with the observed data, derived from data control samples that are independent of the candidate selection. In particular, the transverse momentum of the top quarks at the generator level is multiplied by the function $e^{(0.0615-0.0005 p_{\mathrm{T,top}})}$ to match the distribution measured in data [45].

4. Reconstruction of the top quark pair events

The $t\bar{t}$ system is reconstructed by assigning the four-vectors of the final-state objects to either the leptonic (t_ℓ) or hadronic (t_h) leg of the $t\bar{t}$ decay. The events are separated into the three topologies discussed earlier based on the presence of t- or W-tagged jets: the merged topology contains events with one t tag and no W tag; the semiresolved topology contains events with one W tag and no t tag; and the resolved topology contains the rest of the events that have no t and no W tag. Events with more than one t or W tag are discarded. For events with a t tag, the t-tagged jet is taken as the t_h and only AK4 jets with $\Delta R > 0.8$ from the t_h are considered as candidates for the t_ℓ. For events with a W tag, the W-tagged jet is assigned to the t_h. The AK4 jets with $\Delta R > 0.8$ from the W tag can be assigned to either the t_ℓ or the t_h, and at least one AK4 jet on each side is required. For events with neither a t tag nor a W tag, all possible assignments of AK4 jets are considered for both the t_ℓ and the t_h, and again, at least one AK4 jet on each side is required. There is no upper limit on the number of AK4 jets in any of the topologies. Even though each event includes at least one b-tagged jet, the b tagging information for individual jets is not used. The longitudinal component of the neutrino momentum is inferred by constraining the invariant mass of the lepton plus neutrino system to the W boson mass [53]. Assuming the W boson is on-shell, a quadratic equation for the z component of the momentum of neutrino can be derived:

$$p^{\pm}_{z,\nu} = \frac{\mu p_{z,\ell}}{p^2_{\mathrm{T},\ell}} \pm \sqrt{\frac{\mu^2 p^2_{z,\ell}}{p^4_{\mathrm{T},\ell}} - \frac{E^2_\ell p^2_{\mathrm{T},\nu} - \mu^2}{p^2_{\mathrm{T},\ell}}}\,, \tag{2}$$

where p_ℓ and p_ν are the three momenta of the charged lepton and the neutrino, respectively, with $\vec{p}_{T,\nu} = \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$, and $\mu = \frac{1}{2}M^2_W + \vec{p_{\mathrm{T},\ell}} \cdot \vec{p_{\mathrm{T},\nu}}$. Equation (2) has either 0, 1, or 2 real solutions. In the absence of a real solution, the real part of the complex solutions is used. If there are two real solutions, both cases are tested, effectively doubling the number of hypotheses for that event.

For each event, one $t\bar{t}$ hypothesis is selected based on a two-term χ^2 discriminator used to quantify the compatibility of each hypothesis with a $t\bar{t}$ decay. The discriminator, which was optimized for $t\bar{t}$ invariant masses greater than 750 GeV, is defined as

$$\chi^2 = \left[\frac{M_{\mathrm{lep}} - \langle M_{\mathrm{lep}}\rangle}{\sigma_{M_{\mathrm{lep}}}}\right]^2 + \left[\frac{M_{\mathrm{had}} - \langle M_{\mathrm{had}}\rangle}{\sigma_{M_{\mathrm{had}}}}\right]^2, \tag{3}$$

where M_{lep} and M_{had} are the invariant masses of the reconstructed t_ℓ and t_h decaying top quark, respectively. The quantities $\sigma_{M_{\mathrm{lep}}}$ and $\sigma_{M_{\mathrm{had}}}$ are the resolutions of the leptonic and hadronic top quark reconstruction, respectively, and $\langle M_{\mathrm{lep}}\rangle$ and $\langle M_{\mathrm{had}}\rangle$ are the means of the corresponding mass distributions obtained from simulation for each of the topologies. Because background processes typically result in large values of χ^2, events with $\chi^2 > 30$ are rejected. Finally, only events with $M_{t\bar{t}} > 750$ GeV are retained in our signal candidate sample. Fig. 1 shows comparisons between data and MC simulation for kinematic distributions based on events in the candidate sample. The distributions are shown after the likelihood normalization described in Section 6. The boosted nature of the top quarks in the events becomes evident: the $M_{t\bar{t}}$ range extends to multi-TeV values, events with two and three AK4 jets originating from the collimated top quark decay products are reconstructed, and events with leptons next to the jet axis are retained. Generally good agreement between data and MC is observed.

5. Systematic uncertainties

Systematic uncertainties from numerous sources can affect the normalization and the shape of the distributions of physical observables in both signal and background samples. The systematic uncertainties affecting only the normalization come from the SM theoretical cross section values for each process and the luminosity normalization. All MC samples are normalized according to their respective SM cross section values, as has been done in previous analyses including Ref. [45], and assigned a rate uncertainty of 30% for background processes [54] and 5% for the $t\bar{t}$ signal [55]. Additionally, uncertainties in the integrated luminosity vary from year to year: 2.5, 2.3, and 1.2% for 2018 [44], 2017 [43], and 2016 [42], respectively. These include both correlated and uncorrelated components across the three years, while the overall uncertainty for the 2016–2018 period is 1.6%.

All other systematic uncertainties affect both the normalization and shape of the MC distributions. Uncertainties from experimental sources are applied to both signal and background samples. All MC samples are reweighted to match the pileup distribution in data, which is generated by using the instantaneous luminosity per bunch crossing for each luminosity section, with a total inelastic cross section of 69.2 mb; an uncertainty of 4.6% is applied to this value [56]. All muons and electrons in the simulated samples have uncertainties associated with the high-level trigger (HLT), reconstruction (reco), and identification (ID). The uncertainty associated with the possible misidentification of the sign of the lepton electric charge is negligible. These uncertainties are uncorrelated across lepton flavors but correlated across years and are parameterized as a function of the p_{T} and η of the leptons. There is a uniform uncertainty in the efficiency of the 2D selection that rejects QCD background, and this is uncorrelated across lepton flavors and years. Uncertainties in the jet energy corrections (JEC) and resolution (JER) are parameterized in terms of the jet p_{T} and η and considered correlated across years. The uncertainties in the tagging scale factors are parameterized as a function of the jet p_{T}. The uncertainties in t and W tagging are 100% correlated across years, but the uncertainty in b tagging has both correlated and uncorrelated components [57]. There are different scale factors to account for the cases when the tagging algorithms incorrectly identify (mistag) some jets, so a separate mistagging uncertainty is also assigned.

In addition to the experimental sources, we consider uncertainties affecting the MC simulations. The uncertainty from the choice of PDF is estimated from the Hessian NNPDF3.1 sets according to the procedure described in Ref. [58]. Renormalization (μ_R) and

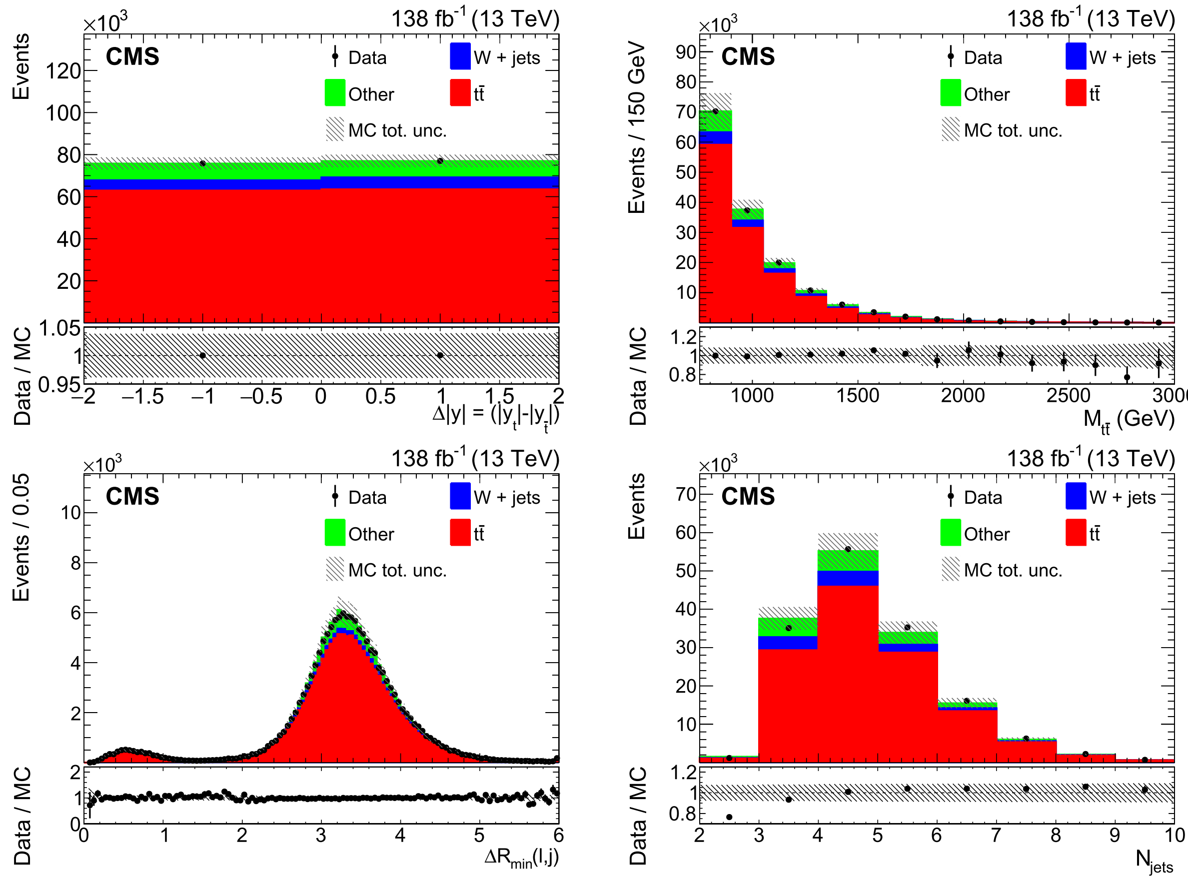

Fig. 1. Comparison between data and MC simulation for kinematic distributions based on events in the candidate sample (described in Section 4): $\Delta|y|$ (upper left), reconstructed $M_{\mathrm{t\bar{t}}}$ (upper right), distance between the lepton and the closest AK4 jet $\Delta R_{\min}(\ell, j)$ (lower left), and the number of AK4 jets (lower right). The vertical bars on the points show the statistical uncertainty in the data. The shaded bands represent the total uncertainty in the MC predictions (described in Section 5). The lower panels give the ratio of the data to the sum of the MC predictions. The distributions are shown after the likelihood normalization described in Section 6.

factorization (μ_F) scales at the matrix element level are varied by a factor of 2 or 0.5 to take into account the effect of higher-order corrections in the $\mathrm{t\bar{t}}$ and W + jets simulations. The matrix element and parton shower matching scale (h_{damp}) regulates the high-p_{T} radiation by damping real emissions from the POWHEG generator; this effect is only taken into account for $\mathrm{t\bar{t}}$ and evaluated using independent simulated samples generated based on parameters derived in Ref. [50]. Uncertainties related to the modeling of initial- and final-state radiation (ISR and FSR) are determined by varying the strong coupling constant α_S at the scale Q^2 for the $\mathrm{t\bar{t}}$ samples. Finally, an uncertainty in the correction to the top quark p_{T} is evaluated as a one-sided variation computed from the difference between the top quark p_{T} distribution with and without the correction [45]. For all these uncertainties, those originating from the same source are considered as 100% correlated between channels and those arising from different sources are considered to be 100% uncorrelated.

6. Unfolded results

The top quark charge asymmetry is obtained by performing a simultaneous binned maximum likelihood fit to data in all bins and categories of the candidate sample as implemented by the LHC Higgs Combination Group [59]. Statistical uncertainties due to the MC sample size are treated separately in each bin with the Barlow–Beeston-lite approach [60]. Each source of systematic uncertainty is included in the likelihood as a unique nuisance parameter. For contributions that apply to multiple analysis channels, the nuisance parameters are fully correlated, allowing better constraints to be placed on the systematic uncertainties. For a given channel k in our analysis, the corresponding likelihood function $\mathcal{L}_k$ is defined as:

$$\mathcal{L}_k = \prod_{j=1}^{N_{\mathrm{reco}}} P\left(n_j; \sum_{i=1}^{N_{\mathrm{gen}}} A_{ji}(\vec{\delta_u})\mu_i(\vec{\delta_u}) + b_j(\vec{\delta_u})\right) N(\vec{\delta_u}), \quad (4)$$

where

- $P(n;\mu)$ represents the Poisson probability of observing n events when μ are expected.
- The indexes i and j run over the number of bins at generator level (N_{gen}) and reconstruction level (N_{reco}), respectively. In this analysis, we use two bins ($N_{\mathrm{reco}} = N_{\mathrm{gen}} = 2$) corresponding to the positive (bin 1) and negative (bin 2) difference between the absolute value of the top quark and antiquark rapidities $\Delta|y|$.
- $\vec{\delta_u}$ are the nuisance parameters.
- A_{ji} is the response matrix, which gives the probability for an event reconstructed in bin j to have been produced in bin i. It is implemented by including the relevant number of reconstructed and generated simulated $\mathrm{t\bar{t}}$ events for each entry, which are subject to the effects of the nuisance parameters. This implementation allows the matrix to account for effects from detector resolution (smearing) as well as detector acceptance and efficiency.
- $\mu_1 = r_{\mathrm{pos}} N_{\mathrm{pos}}^{\mathrm{gen}}$ and $\mu_2 = r_{\mathrm{neg}} N_{\mathrm{neg}}^{\mathrm{gen}}$, where r_{pos} and r_{neg} are the signal strengths multiplying the number of signal events at

Table 1
The event yields for the candidate sample in data and MC simulations after the likelihood fit for each of the 12 channels (μ + jets, e + jets, 3 years; and two mass regions). The uncertainties in the MC predictions include both statistical and systematic components.

Process	μ (2018)	μ (2017)	μ (2016)	e (2018)	e (2017)	e (2016)
			$750 < M_{t\bar{t}} < 900$ GeV			
$t\bar{t}$	22 230 ± 1950	16 430 ± 1400	10 370 ± 970	4590 ± 450	2950 ± 260	2560 ± 240
ST	1620 ± 150	2150 ± 190	910 ± 80	410 ± 30	510 ± 40	290 ± 30
W + jets	970 ± 110	1150 ± 120	1250 ± 270	240 ± 30	220 ± 30	320 ± 70
DY	90 ± 20	40 ± 10	50 ± 10	15 ± 3	6 ± 1	10 ± 2
QCD multijet	410 ± 100	270 ± 60	180 ± 40	6 ± 2	2 ± 1	0 ± 0
Total	25 310 ± 1960	20 050 ± 1400	12 770 ± 1000	5270 ± 450	3690 ± 260	3180 ± 250
Data	25 417	20 052	12 735	5219	3674	3127
			$M_{t\bar{t}} > 900$ GeV			
$t\bar{t}$	23 340 ± 2270	17 120 ± 1640	10 700 ± 1060	7140 ± 740	4880 ± 490	4110 ± 430
ST	1650 ± 140	2020 ± 170	920 ± 80	610 ± 60	690 ± 60	420 ± 40
W + jets	1450 ± 170	1330 ± 160	1970 ± 450	520 ± 60	440 ± 50	740 ± 160
DY	110 ± 20	60 ± 10	70 ± 10	30 ± 6	14 ± 3	20 ± 4
QCD multijet	860 ± 120	810 ± 130	470 ± 70	10 ± 3	30 ± 9	40 ± 10
Total	27 400 ± 2280	21 350 ± 1660	14 130 ± 1160	8320 ± 750	6050 ± 500	5330 ± 460
Data	27 298	21 358	14 157	8361	6066	5385

generator level with $M_{t\bar{t}}^{gen} > 750$ GeV in which the value of $\Delta|y|^{gen}$ is positive (N_{pos}^{gen}) or negative (N_{neg}^{gen}), respectively.
- n_j is the number of data events in bin j.
- b_j is the number of background events predicted in bin j.
- $N(\vec{\delta}_u)$ are the priors for the nuisance parameters, with the normalization and shape uncertainties assigned a log-normal and Gaussian distribution, respectively. The shape uncertainty nuisance parameters control the vertical interpolation of histograms that represent the up and down one standard deviation shifts from the nominal distribution [61].

Each analysis channel is defined based on reconstruction-level quantities by a range of $M_{t\bar{t}}$ values and a specific year and lepton flavor. To account for migration of events between mass bins, all simulated events are included, even if the generated mass is outside the reconstructed mass range under consideration. The total likelihood is given by the product of the individual likelihoods from Eq. (4), with the index k running over all 12 channels: two lepton flavors (μ+jets and e+jets), 3 years (2018, 2017, and 2016), and two mass regions ($750 < M_{t\bar{t}} < 900$ GeV and $M_{t\bar{t}} > 900$ GeV). This unfolding approach also has the advantage that the background contributions are constrained by the fit, resulting in smaller systematic uncertainties than those obtained with a direct background subtraction.

The unfolded charge asymmetry at parton level is given by

$$A_C = \frac{r_{pos} N_{pos}^{gen} - r_{neg} N_{neg}^{gen}}{r_{pos} N_{pos}^{gen} + r_{neg} N_{neg}^{gen}}, \quad (5)$$

with r_{pos} and r_{neg} as free parameters in the fit. However, to ensure the uncertainties on A_C are properly estimated, we define r_{pos} in terms of r_{neg} and A_C, and select r_{neg} and A_C as the free parameters. The A_C can also be measured in the two mass regions separately. This is achieved combining subsets of the 12 analysis channels according to the reconstructed $M_{t\bar{t}}$, while redefining N_{pos}^{gen} and N_{neg}^{gen} as the corresponding number of generated signal events with $750 < M_{t\bar{t}}^{gen} < 900$ GeV or $M_{t\bar{t}}^{gen} > 900$ GeV.

Table 1 shows the signal and background yields in our candidate sample after the likelihood fit, separated into the two mass regions. The contributions to our candidate sample from background processes (ST, W + jets, DY, and QCD multijet) are taken from simulation and their normalization allowed to change during the likelihood fit. The higher p_T thresholds on the lepton and leading jet in the electron channel result in significantly reduced signal acceptance compared to the muon channel. Fig. 2 shows $\Delta|y|$ for each of these 12 channels both before and after the likelihood normalization. As can be observed, the likelihood fit reduces the total uncertainty significantly and improves the agreement between data and the MC prediction.

Table 2
Measured unfolded charge asymmetry compared to the theoretical prediction, including NNLO QCD and NLO EW corrections, from Ref. [5]. Results are shown for events with $M_{t\bar{t}} > 750$ GeV and for two invariant mass ranges, 750–900 and >900 GeV. The statistical and systematic uncertainties in the data, the MC statistical uncertainty, and the total uncertainty in the measured values are also shown. All values are in percent.

$M_{t\bar{t}}$(GeV)	A_C	Stat	Syst	MC stat	Total	Prediction
>750	0.42	±0.44	$^{+0.33}_{-0.44}$	± 0.32	$^{+0.64}_{-0.69}$	0.94 $^{+0.05}_{-0.07}$
750–900	0.53	±0.65	$^{+0.37}_{-0.49}$	± 0.45	$^{+0.87}_{-0.93}$	0.87 $^{+0.06}_{-0.08}$
>900	1.23	±0.58	$^{+0.43}_{-0.84}$	± 0.41	$^{+0.82}_{-1.10}$	1.01 $^{+0.06}_{-0.07}$

Table 2 and Fig. 3 show the measured top quark charge asymmetry after unfolding to parton level in the full phase space, compared with the theoretical prediction at next-to-next-to-leading order (NNLO) QCD and NLO EW corrections from Ref. [5]. Good agreement between the data and the MC prediction is observed.

Fig. 4 shows the ±1 standard deviation (σ) impacts of the systematic uncertainties in the A_C measurements for the full signal sample, as well as the effect on the unfolded A_C values for up and down variations of the systematic uncertainty.

7. Summary

A measurement of the charge asymmetry in $t\bar{t}$ events with highly boosted top quarks produced in proton-proton collisions at $\sqrt{s} = 13$ TeV is presented based on 138 fb^{-1} of data collected by the CMS experiment at the LHC. The selection is optimized for top quarks produced with high Lorentz boosts that yield collimated decay products that are partially or fully merged and can result in nonisolated leptons and overlapping jets. The measured top quark charge asymmetry (A_C) is corrected for detector and acceptance effects using a binned maximum likelihood fit.

This is the first CMS measurement to use 13 TeV data and a binned maximum likelihood unfolding technique to measure A_C directly at parton level in the full phase space. In addition, it is the first result that focuses exclusively on the highly Lorentz-boosted regime, using dedicated reconstruction techniques for the hadronically and leptonically decaying top quarks at both the trigger and

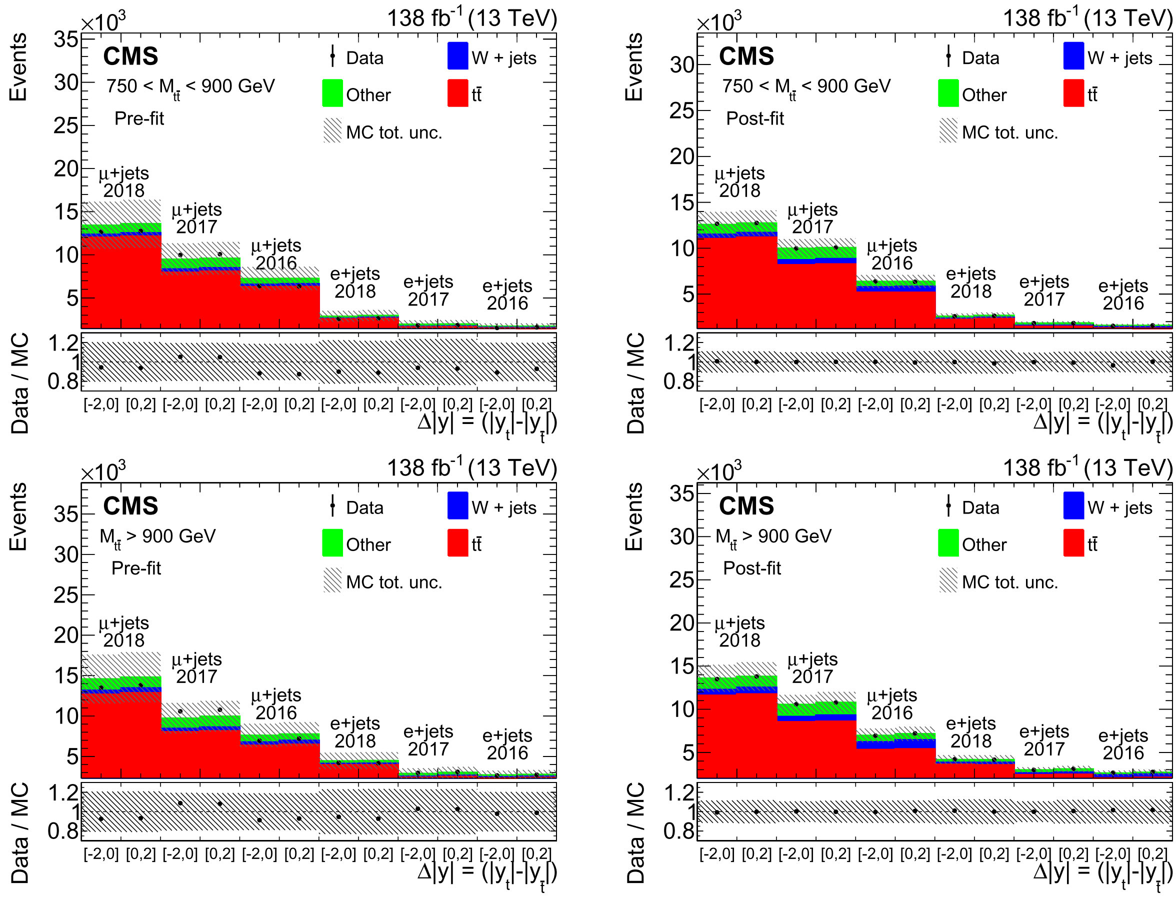

Fig. 2. Comparison between data and MC simulation for $\Delta|y|$ for each of the 12 analysis channels, both before (left) and after (right) the likelihood normalization. The plots in the upper row correspond to $750 < M_{t\bar{t}} < 900$ GeV, and the plots in the lower row to $M_{t\bar{t}} > 900$ GeV. The vertical bars on the points represent the statistical uncertainties in the data and the shaded bands give the combined MC statistical and systematic uncertainties. The lower panels display the ratio of the data yields to the sum of the MC predictions.

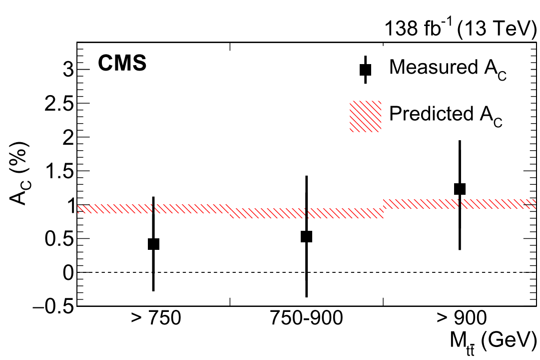

Fig. 3. Unfolded A_C in the full phase space presented in different mass regions after combining the $\mu+$jets and e + jets channels. The vertical bars represent the total uncertainties. The measured values are compared to the theoretical prediction, including NNLO QCD and NLO EW corrections, from Ref. [5].

offline stages. Since the relative contribution of valence quarks increases at high momentum transfer, A_C is especially sensitive to beyond the standard model processes in this highly boosted phase space.

The resulting unfolded charge asymmetry for $t\bar{t}$ events with invariant masses satisfying $M_{t\bar{t}} > 750$ GeV is $(0.42^{+0.64}_{-0.69})\%$, where the uncertainty includes both statistical and systematic components. The corresponding theoretical prediction at next-to-next-to-leading order in QCD perturbation theory with next-to-leading-order electroweak corrections from Ref. [5] is $(0.94^{+0.05}_{-0.07})\%$. Good agreement between the measurement and the most precise standard model

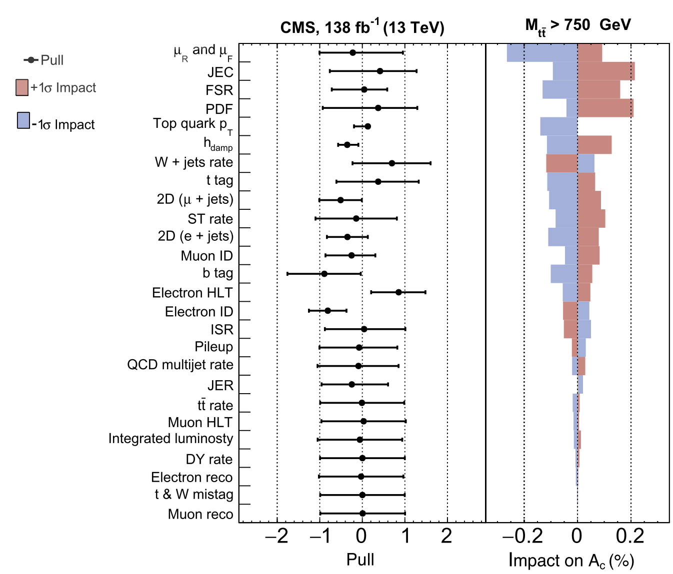

Fig. 4. Summary of the dominant systematic uncertainties affecting the A_C measurement. The left column lists the sources of systematic uncertainty, treated as nuisance parameters in the fit, in order of importance. In the middle column (Pull), the black points with their ±1 standard deviation horizontal bars show for each uncertainty the difference between the observed best fit value and the nominal value, divided by the expected standard deviation. The right column (Impact on A_C (%)), shows the change in the measured A_C if a nuisance is varied by one standard deviation (σ) up, in red, and down, in blue.

prediction is thus observed. The result demonstrates that top quark properties can be precisely measured in the highly boosted topology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS policy as stated in "CMS data preservation, re-use and open access policy".

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The CMS Collaboration

A. Tumasyan [1]

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, P.S. Hussain, M. Jeitler[2], N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck[2], R. Schöfbeck, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz[2]

Institut für Hochenergiephysik, Vienna, Austria

M.R. Darwish[3], T. Janssen, T. Kello[4], H. Rejeb Sfar, P. Van Mechelen

Universiteit Antwerpen, Antwerpen, Belgium

E.S. Bols, J. D'Hondt, A. De Moor, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, D. Vannerom

Vrije Universiteit Brussel, Brussel, Belgium

B. Clerbaux, G. De Lentdecker, L. Favart, D. Hohov, J. Jaramillo, K. Lee, M. Mahdavikhorrami, I. Makarenko, A. Malara, S. Paredes, L. Pétré, N. Postiau, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Université Libre de Bruxelles, Bruxelles, Belgium

D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Rendón, C. Roskas, A. Samalan, K. Skovpen, M. Tytgat, N. Van Den Bossche, B. Vermassen, L. Wezenbeek

Ghent University, Ghent, Belgium

A. Benecke, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, K. Mondal, A. Taliercio, T.T. Tran, P. Vischia, S. Wertz

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

G.A. Alves, E. Coelho, C. Hensel, A. Moraes, P. Rebello Teles

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, V. Dos Santos Sousa, S. Fonseca De Souza, J. Martins[7], C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo[8], A. Vilela Pereira

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

C.A. Bernardes[6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

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

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

A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

University of Sofia, Sofia, Bulgaria

S. Thakur

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile

T. Cheng, T. Javaid [9], M. Mittal, L. Yuan

Beihang University, Beijing, China

M. Ahmad, G. Bauer [10], Z. Hu, S. Lezki, K. Yi [10,11]

Department of Physics, Tsinghua University, Beijing, China

G.M. Chen [9], H.S. Chen [9], M. Chen [9], F. Iemmi, C.H. Jiang, A. Kapoor, H. Kou, H. Liao, Z.-A. Liu [12], V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. An, Y. Ban, C. Chen, A. Levin, C. Li, Q. Li, X. Lyu, Y. Mao, S.J. Qian, X. Sun, D. Wang, J. Xiao, H. Yang

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

M. Lu, Z. You

Sun Yat-Sen University, Guangzhou, China

X. Gao [4], D. Leggat, H. Okawa, Y. Zhang

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

Z. Lin, C. Lu, M. Xiao

Zhejiang University, Hangzhou, Zhejiang, China

C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao, F. Ramirez, M. Rodriguez, J.D. Ruiz Alvarez

Universidad de Antioquia, Medellin, Colombia

D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak

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

Z. Antunovic, M. Kovac, T. Sculac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, B.K. Chitroda, D. Ferencek, S. Mishra, M. Roguljic, A. Starodumov [13], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, K. Christoforou, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

University of Cyprus, Nicosia, Cyprus

M. Finger [13], M. Finger Jr. [13], A. Kveton

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A.A. Abdelalim [14,15], E. Salama [16,17]

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

M.A. Mahmoud, Y. Mohammed

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

S. Bhowmik, R.K. Dewanjee, K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, J. Ott, M.m. Rantanen, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, H. Petrow, T. Tuuva

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, P. Jarry, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro [18], P. Simkina, M. Titov

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

C. Baldenegro Barrera, F. Beaudette, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, F. Damas, O. Davignon, B. Diab, G. Falmagne, B.A. Fontana Santos Alves, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, G. Liu, J. Motta, M. Nguyen, C. Ochando, L. Portales, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, E. Vernazza, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

J.-L. Agram [19], J. Andrea, D. Apparu, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

S. Beauceron, B. Blancon, G. Boudoul, A. Carle, N. Chanon, J. Choi, D. Contardo, P. Depasse, C. Dozen [20], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, L. Torterotot, M. Vander Donckt, P. Verdier, S. Viret

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

D. Chokheli, I. Lomidze, Z. Tsamalaidze[13]

Georgian Technical University, Tbilisi, Georgia

V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, M. Teroerde

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

S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, M. Erdmann, P. Fackeldey, D. Fasanella, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, M.y. Lee, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, S. Mondal, S. Mukherjee, D. Noll, A. Novak, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, H. Reithler, A. Schmidt, S.C. Schuler, A. Sharma, A. Stein, L. Vigilante, S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, W. Haj Ahmad[21], O. Hlushchenko, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

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

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar, F. Blekman[22], K. Borras[23], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[22], A. Geiser, A. Giraldi, G. Greau, A. Grohsjean, V. Guglielmi, M. Guthoff, A. Jafari[24], N.Z. Jomhari, B. Kaech, M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[25], W. Lohmann[26], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, G. Milella, M. Mormile, A. Mussgiller, A. Nürnberg, Y. Otarid, D. Pérez Adán, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham[27,23], V. Scheurer, S. Schnake[23], P. Schütze, C. Schwanenberger[22], M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, N. Tonon[†], M. Van De Klundert, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Walter, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[23], C. Wissing, S. Wuchterl, Y. Yang, A. Zimermmane Castro Santos

Deutsches Elektronen-Synchrotron, Hamburg, Germany

A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, M. Bonanomi, P. Connor, K. De Leo, M. Eich, K. El Morabit, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, M. Hajheidari, J. Haller, A. Hinzmann, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, A. Mehta, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, M. Rieger, O. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

University of Hamburg, Hamburg, Germany

S. Brommer, M. Burkart, E. Butz, R. Caspart, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, J.O. Gosewisch, A. Gottmann, F. Hartmann[28], M. Horzela,

U. Husemann, M. Klute, R. Koppenhöfer, A. Lintuluoto, S. Maier, S. Mitra, Th. Müller, M. Neukum, M. Oh, G. Quast, K. Rabbertz, J. Rauser, M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, N. Trevisani, R. Ulrich, J. van der Linden, R.F. Von Cube, M. Wassmer, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch, X. Zuo

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, P. Assiouras, G. Daskalakis, A. Kyriakis, A. Stakia

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

M. Diamantopoulou, D. Karasavvas, P. Kontaxakis, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National and Kapodistrian University of Athens, Athens, Greece

G. Bakas, T. Chatzistavrou, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

National Technical University of Athens, Athens, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Gianneios, C. Kamtsikis, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

University of Ioánnina, Ioánnina, Greece

M. Csanád, K. Farkas, M.M.A. Gadallah[29], S. Lökös[30], P. Major, K. Mandal, G. Pásztor, A.J. Rádl[31], O. Surányi, G.I. Veres

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

M. Bartók[32], G. Bencze, C. Hajdu, D. Horvath[33,34], F. Sikler, V. Veszpremi

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi[32], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, B. Ujvari[35]

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo[31], F. Nemes[31], T. Novak

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[36], R. Gupta, A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, P. Kumari, M. Meena, K. Sandeep, T. Sheokand, J.B. Singh[37], A. Singla, A.K. Virdi

Panjab University, Chandigarh, India

A. Ahmed, A. Bhardwaj, B.C. Choudhary, A. Kumar, M. Naimuddin, K. Ranjan, S. Saumya

University of Delhi, Delhi, India

S. Baradia, S. Barman[38], S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber[39], M. Maity[38], P. Palit, G. Saha, B. Sahu, S. Sarkar

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, S.C. Behera, P. Kalbhor, J.R. Komaragiri[40], D. Kumar[40], A. Muhammad, L. Panwar[40], R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar, P.C. Tiwari[40], S. Verma

Indian Institute of Technology Madras, Madras, India

K. Naskar[41]

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, I. Das, S. Dugad, M. Kumar, G.B. Mohanty, P. Suryadevara

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, A. Thachayath

Tata Institute of Fundamental Research-B, Mumbai, India

S. Bahinipati[42], A.K. Das, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[43], A. Nayak[43], P. Saha, S.K. Swain, D. Vats[43]

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

A. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rastogi, S. Sharma

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

H. Bakhshiansohi[44,45], E. Khazaie[45], M. Zeinali[46]

Isfahan University of Technology, Isfahan, Iran

S. Chenarani[47], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

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

M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia[a,b], R. Aly[a,b,14], C. Aruta[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], W. Elmetenawee[a,b], F. Errico[a,b], L. Fiore[a], G. Iaselli[a,c], M. Ince[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], D. Ramos[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], Ü. Sözbilir[a], A. Stamerra[a], R. Venditti[a], P. Verwilligen[a]

[a] INFN Sezione di Bari, Bari, Italy
[b] Università di Bari, Bari, Italy
[c] Politecnico di Bari, Bari, Italy

G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], L. Brigliadori[a], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,48], L. Lunerti[a,b], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

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

S. Costa[a,b,49], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,49], C. Tuve[a,b]

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

G. Barbagli[a], G. Bardelli[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a,b], M. Meschini[a], S. Paoletti[a], R. Seidita[a,b], G. Sguazzoni[a], L. Viliani[a]

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

L. Benussi, S. Bianco, S. Meola[28], D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Bozzo[a,b], P. Chatagnon[a], F. Ferro[a], R. Mulargia[a], E. Robutti[a], S. Tosi[a,b]

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

A. Benaglia[a], G. Boldrini[a], F. Brivio[a,b], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], B.S. Pinolini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b], D. Zuolo[a,b]

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

S. Buontempo[a], F. Carnevali[a,b], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,50], P. Paolucci[a,28], B. Rossi[a], C. Sciacca[a,b]

[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], N. Bacchetta[a,51], D. Bisello[a,b], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], G. Grosso[a], M. Gulmini[a,52], L. Layer[a,53], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], G. Strong[a], M. Tosi[a,b], H. Yarar[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

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

S. Abu Zeid[a,17], C. Aimè[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

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

P. Asenov[a,54], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,54], A. Piccinelli[a,b], M. Presilla[a,b], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

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

P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a,b], D. Bruschini[a,c], R. Castaldi[a], M.A. Ciocci[a,b], V. D'Amante[a,d], R. Dell'Orso[a], M.R. Di Domenico [a,d], S. Donato [a], A. Giassi [a], F. Ligabue [a,c], G. Mandorli [a,c], D. Matos Figueiredo [a], A. Messineo [a,b], M. Musich [a,b], F. Palla [a], S. Parolia [a,b], G. Ramirez-Sanchez [a,c], A. Rizzi [a,b], G. Rolandi [a,c], S. Roy Chowdhury [a], T. Sarkar [a], A. Scribano [a], N. Shafiei [a,b], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], N. Turini [a,d], 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
[d] Università di Siena, Siena, Italy

P. Barria [a], M. Campana [a,b], F. Cavallari [a], D. Del Re [a,b], E. Di Marco [a], M. Diemoz [a], E. Longo [a,b], P. Meridiani [a], G. Organtini [a,b], F. Pandolfi [a], R. Paramatti [a,b], C. Quaranta [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b], L. Soffi [a], R. Tramontano [a,b]

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

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], A. Bellora [a,b], C. Biino [a], N. Cartiglia [a], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a], M. Grippo [a,b], B. Kiani [a,b], F. Legger [a], C. Mariotti [a], S. Maselli [a], A. Mecca [a,b], E. Migliore [a,b], E. Monteil [a,b], M. Monteno [a], M.M. Obertino [a,b], G. Ortona [a], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], M. Ruspa [a,c], K. Shchelina [a], F. Siviero [a,b], V. Sola [a], A. Solano [a,b], D. Soldi [a,b], A. Staiano [a], M. Tornago [a,b], D. Trocino [a], G. Umoret [a,b], A. Vagnerini [a,b]

[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], A. Da Rold [a,b], G. Della Ricca [a,b], G. Sorrentino [a,b]

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

S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, M.S. Ryu, S. Sekmen, Y.C. Yang

Kyungpook National University, Daegu, Korea

H. Kim, D.H. Moon

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

E. Asilar, T.J. Kim, J. Park

Hanyang University, Seoul, Korea

S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Korea University, Seoul, Korea

J. Goh

Kyung Hee University, Department of Physics, Seoul, Korea

H.S. Kim, Y. Kim, S. Lee

Sejong University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, S. Lee, B.H. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

Seoul National University, Seoul, Korea

W. Jang, D.Y. Kang, Y. Kang, D. Kim, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, J.A. Merlin, I.C. Park, Y. Roh, D. Song, I.J. Watson, S. Yang

University of Seoul, Seoul, Korea

S. Ha, H.D. Yoo

Yonsei University, Department of Physics, Seoul, Korea

M. Choi, M.R. Kim, H. Lee, Y. Lee, Y. Lee, I. Yu

Sungkyunkwan University, Suwon, Korea

T. Beyrouthy, Y. Maghrbi

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait

K. Dreimanis, G. Pikurs, M. Seidel, V. Veckalns

Riga Technical University, Riga, Latvia

M. Ambrozas, A. Carvalho Antunes De Oliveira, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

Vilnius University, Vilnius, Lithuania

N. Bin Norjoharuddeen, S.Y. Hoh[55], I. Yusuff[55], Z. Zolkapli

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

J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala, H. Castilla-Valdez, I. Heredia-De La Cruz[56], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández

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

C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bubanja, J. Mijuskovic[57], N. Raicevic

University of Montenegro, Podgorica, Montenegro

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, M. Gul, H.R. Hoorani, W.A. Khan, M. Shoaib, M. Waqas

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

V. Avati, L. Grzanka, M. Malawski

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

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

M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, J. Varela

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

P. Adzic[58], M. Dordevic, P. Milenovic, J. Milosevic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, D.D. Redondo Ferrero, L. Romero, S. Sánchez Navas, J. Sastre, L. Urda Gómez, J. Vazquez Escobar, C. Willmott

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

J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, A. García Alonso, G. Gomez, C. Lasaosa García, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, J. Piedra Gomez, C. Prieels, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

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

M.K. Jayananda, B. Kailasapathy[59], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

University of Ruhuna, Department of Physics, Matara, Sri Lanka

D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†], D. Barney, J. Bendavid, M. Bianco, B. Bilin, A. Bocci, E. Brondolin, C. Caillol, T. Camporesi, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, S. Choudhury, M. Cipriani, L. Cristella,

D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, F. Fallavollita[60], A. Florent, L. Forthomme, G. Franzoni, W. Funk, S. Ghosh, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, E. Govorkova, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, N. Kratochwil, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, B. Maier, L. Malgeri, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[61], A.G. Stahl Leiton, S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, J. Wanczyk[62], K.A. Wozniak, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada[63], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[63], L. Noehte[63], T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

T.K. Aarrestad, K. Androsov[62], M. Backhaus, P. Berger, A. Calandri, K. Datta, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, A. Mascellani[62], F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, D. Ruini, D.A. Sanz Becerra, J. Steggemann[62], D. Valsecchi[28], R. Wallny

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

C. Amsler[64], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

Universität Zürich, Zurich, Switzerland

C. Adloff[65], C.M. Kuo, W. Lin, P.K. Rout, S.S. Yu

National Central University, Chung-Li, Taiwan

L. Ceard, Y. Chao, K.F. Chen, P.s. Chen, H. Cheng, W.-S. Hou, R. Khurana, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, H.y. Wu, E. Yazgan, P.r. Yu

National Taiwan University (NTU), Taipei, Taiwan

C. Asawatangtrakuldee, N. Srimanobhas

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

D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu[66], E. Eskut, Y. Guler[67], E. Gurpinar Guler[67], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[68], A. Polatoz, A.E. Simsek, B. Tali[69], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

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

G. Karapinar[70], K. Ocalan[71], M. Yalvac[72]

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[73], O. Kaya[74], S. Tekten[75]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak[66], Y. Komurcu, S. Sen[66]

Istanbul Technical University, Istanbul, Turkey

O. Aydilek, S. Cerci[69], B. Hacisahinoglu, I. Hos[76], B. Isildak[77], B. Kaynak, S. Ozkorucuklu, C. Simsek, D. Sunar Cerci[69]

Istanbul University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

D. Anthony, E. Bhal, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[78], K. Walkingshaw Pass, R. White

University of Bristol, Bristol, United Kingdom

A.H. Ball, K.W. Bell, A. Belyaev[79], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg[80], Sh. Jain, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, C.E. Brown, O. Buchmuller, V. Cacchio, V. Cepaitis, G.S. Chahal[81], D. Colling, J.S. Dancu, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, M. Mieskolainen, D.G. Monk, J. Nash[82], M. Pesaresi, B.C. Radburn-Smith, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[28], M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

Imperial College, London, United Kingdom

K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Brunel University, Uxbridge, United Kingdom

S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, B. McMaster, M. Saunders, S. Sawant, C. Sutantawibul, J. Wilson

Baylor University, Waco, TX, USA

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

Catholic University of America, Washington, DC, USA

S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio[83], C. West

The University of Alabama, Tuscaloosa, AL, USA

A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, C. Erice, E. Fontanesi, D. Gastler, S. May, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan

Boston University, Boston, MA, USA

G. Benelli, B. Burkle, X. Coubez[23], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[84], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, M. Narain, N. Pervan, S. Sagir[85], F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

Brown University, Providence, RI, USA

J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, D. Pellett, B. Regnery, Y. Yao, F. Zhang

University of California, Davis, Davis, CA, USA

M. Bachtis, R. Cousins, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, W.A. Nash, S. Regnard, D. Saltzberg, B. Stone, V. Valuev

University of California, Los Angeles, CA, USA

R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, W. Si, S. Wimpenny

University of California, Riverside, Riverside, CA, USA

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, R. Gerosa, L. Giannini, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, M. Pieri, B.V. Sathia Narayanan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, Y. Xiang, A. Yagil

University of California, San Diego, La Jolla, CA, USA

N. Amin, C. Campagnari, M. Citron, G. Collura, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim, A.J. Li, P. Masterson, H. Mei, M. Oshiro, M. Quinnan, J. Richman, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, P. Siddireddy, D. Stuart, S. Wang

University of California, Santa Barbara - Department of Physics, Santa Barbara, CA, USA

A. Bornheim, O. Cerri, I. Dutta, A. Latorre, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, CA, USA

J. Alison, S. An, M.B. Andrews, P. Bryant, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, S. Murthy, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

Carnegie Mellon University, Pittsburgh, PA, USA

J.P. Cumalat, W.T. Ford, A. Hassani, G. Karathanasis, E. MacDonald, F. Marini, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper

University of Colorado Boulder, Boulder, CO, USA

J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, D. Gadkari, S. Hogan, J. Monroy, J.R. Patterson, D. Quach, J. Reichert, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Cornell University, Ithaca, NY, USA

M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, K.F. Di Petrillo, J. Dickinson, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[86], F. Ravera, A. Reinsvold Hall[87], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

Fermi National Accelerator Laboratory, Batavia, IL, USA

P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, R.D. Field, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, E. Kuznetsova, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang, Z. Wu

University of Florida, Gainesville, FL, USA

T. Adams, A. Askew, R. Habibullah, V. Hagopian, T. Kolberg, G. Martinez, H. Prosper, O. Viazlo, M. Wulansatiti, R. Yohay, J. Zhang

Florida State University, Tallahassee, FL, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy[17], M. Hohlmann, R. Kumar Verma, M. Rahmani, F. Yumiceva

Florida Institute of Technology, Melbourne, FL, USA

M.R. Adams, H. Becerril Gonzalez, R. Cavanaugh, S. Dittmer, O. Evdokimov, C.E. Gerber, D.J. Hofman, D.S. Lemos, A.H. Merrit, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, X. Wang, Z. Ye, J. Yoo

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

M. Alhusseini, K. Dilsiz[88], L. Emediato, R.P. Gandrajula, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[89], J. Nachtman, O. Neogi, H. Ogul[90], Y. Onel, A. Penzo, C. Snyder, E. Tiras[91]

The University of Iowa, Iowa City, IA, USA

O. Amram, B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, S. Kyriacou, P. Maksimovic, J. Roskes, S. Sekhar, M. Swartz, T.Á. Vámi

Johns Hopkins University, Baltimore, MD, USA

A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, P. Baringer, A. Bean, Z. Flowers, T. Isidori, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, Q. Wang, J. Williams, G. Wilson

The University of Kansas, Lawrence, KS, USA

B. Allmond, S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam, D. Roy

Kansas State University, Manhattan, KS, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, CA, USA

E. Adams, A. Baden, O. Baron, A. Belloni, A. Bethani, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, L. Wang, K. Wong

University of Maryland, College Park, MD, USA

D. Abercrombie, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, P. Harris, M. Hu, D. Kovalskyi, J. Krupa, Y.-J. Lee, K. Long, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, J. Wang, Z. Wang, B. Wyslouch, T.J. Yang

Massachusetts Institute of Technology, Cambridge, MA, USA

R.M. Chatterjee, B. Crossman, A. Evans, J. Hiltbrand, B.M. Joshi, C. Kapsiak, M. Krohn, Y. Kubota, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Minnesota, Minneapolis, MN, USA

L.M. Cremaldi

University of Mississippi, Oxford, MS, USA

K. Bloom, M. Bryson, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, C. Joo, R. Kamalieddin, I. Kravchenko, I. Reed, J.E. Siado, G.R. Snow[†], W. Tabb, A. Wightman, F. Yan, A.G. Zecchinelli

University of Nebraska-Lincoln, Lincoln, NE, USA

G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, M. Morris, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

State University of New York at Buffalo, Buffalo, NY, USA

G. Alverson, E. Barberis, Y. Haddad, Y. Han, A. Krishna, J. Li, J. Lidrych, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, MA, USA

S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, K.A. Hahn, Y. Liu, N. Odell, M.H. Schmitt, M. Velasco

Northwestern University, Evanston, IL, USA

R. Band, R. Bucci, M. Cremonesi, A. Das, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko[13], R. Ruchti, A. Townsend, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

University of Notre Dame, Notre Dame, IN, USA

B. Bylsma, M. Carrigan, L.S. Durkin, B. Francis, C. Hill, M. Joyce, A. Lesauvage, M. Nunez Ornelas, K. Wei, B.L. Winer, B.R. Yates

The Ohio State University, Columbus, OH, USA

F.M. Addesa, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

Princeton University, Princeton, NJ, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, PR, USA

A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic, J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, IN, USA

J. Dolen, N. Parashar

Purdue University Northwest, Hammond, IN, USA

D. Acosta, A. Baty, T. Carnahan, M. Decaro, S. Dildick, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Rotter, W. Shi, S. Yang, E. Yigitbasi, L. Zhang[92], Y. Zhang

Rice University, Houston, TX, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus, G.P. Van Onsem

University of Rochester, Rochester, NY, USA

K. Goulianos

The Rockefeller University, New York, NY, USA

B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, D. Jaroslawski, O. Karacheban[26], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Routray, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

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

H. Acharya, A.G. Delannoy, S. Fiorendi, T. Holmes, E. Nibigira, S. Spanier

University of Tennessee, Knoxville, TN, USA

O. Bouhali[93], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[94], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas A&M University, College Station, TX, USA

N. Akchurin, J. Damgov, V. Hegde, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, A. Whitbeck

Texas Tech University, Lubbock, TX, USA

E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

Vanderbilt University, Nashville, TN, USA

B. Cardwell, B. Cox, G. Cummings, J. Hakala, R. Hirosky, A. Ledovskoy, A. Li, C. Neu, C.E. Perez Lara, B. Tannenwald

University of Virginia, Charlottesville, VA, USA

P.E. Karchin, N. Poudyal

Wayne State University, Detroit, MI, USA

S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens

University of Wisconsin - Madison, Madison, WI, USA

S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov[95], E. Boos, V. Borshch, D. Budkouski, V. Bunichev, V. Chekhovsky, R. Chistov[95], A. Dermenev, T. Dimova[95], I. Dremin, M. Dubinin[86], L. Dudko, V. Epshteyn, A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, A. Gribushin, V. Ivanchenko, Y. Ivanov, V. Kachanov, L. Kardapoltsev[95], V. Karjavine, A. Karneyeu, V. Kim[95], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, V. Klyukhin, D. Konstantinov, V. Korenkov, A. Kozyrev[95], N. Krasnikov, A. Lanev, P. Levchenko, A. Litomin, N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev[95], V. Murzin, A. Nikitenko[96], S. Obraztsov, A. Oskin, I. Ovtin[95], V. Palichik, P. Parygin, V. Perelygin, M. Perfilov, S. Polikarpov[95], V. Popov, E. Popova, O. Radchenko[95], M. Savina, V. Savrin, D. Selivanova, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[95], S. Slabospitskii, V. Smirnov, D. Sosnov, V. Sulimov, E. Tcherniaev, A. Terkulov, O. Teryaev, I. Tlisova,

M. Toms, A. Toropin, L. Uvarov, A. Uzunian, E. Vlasov, P. Volkov, A. Vorobyev, N. Voytishin, B.S. Yuldashev[97], A. Zarubin, I. Zhizhin, A. Zhokin

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

† Deceased.
[1] Also at Yerevan State University, Yerevan, Armenia.
[2] Also at TU Wien, Vienna, Austria.
[3] Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.
[4] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[5] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[6] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[7] Also at UFMS, Nova Andradina, Brazil.
[8] Also at The University of the State of Amazonas, Manaus, Brazil.
[9] Also at University of Chinese Academy of Sciences, Beijing, China.
[10] Also at Nanjing Normal University Department of Physics, Nanjing, China.
[11] Now at The University of Iowa, Iowa City, Iowa, USA.
[12] Also at University of Chinese Academy of Sciences, Beijing, China.
[13] Also at an institute or an international laboratory covered by a cooperation agreement with CERN.
[14] Also at Helwan University, Cairo, Egypt.
[15] Now at Zewail City of Science and Technology, Zewail, Egypt.
[16] Also at British University in Egypt, Cairo, Egypt.
[17] Now at Ain Shams University, Cairo, Egypt.
[18] Also at Purdue University, West Lafayette, Indiana, USA.
[19] Also at Université de Haute Alsace, Mulhouse, France.
[20] Also at Department of Physics, Tsinghua University, Beijing, China.
[21] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[22] Also at University of Hamburg, Hamburg, Germany.
[23] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[24] Also at Isfahan University of Technology, Isfahan, Iran.
[25] Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[26] Also at Brandenburg University of Technology, Cottbus, Germany.
[27] Also at Forschungszentrum Jülich, Juelich, Germany.
[28] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[29] Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[30] Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary.
[31] Also at Wigner Research Centre for Physics, Budapest, Hungary.
[32] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[33] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[34] Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania.
[35] Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary.
[36] Also at Punjab Agricultural University, Ludhiana, India.
[37] Also at UPES - University of Petroleum and Energy Studies, Dehradun, India.
[38] Also at University of Visva-Bharati, Santiniketan, India.
[39] Also at University of Hyderabad, Hyderabad, India.
[40] Also at Indian Institute of Science (IISc), Bangalore, India.
[41] Also at Indian Institute of Technology (IIT), Mumbai, India.
[42] Also at IIT Bhubaneswar, Bhubaneswar, India.
[43] Also at Institute of Physics, Bhubaneswar, India.
[44] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[45] Now at Department of Physics, Isfahan University of Technology, Isfahan, Iran.
[46] Also at Sharif University of Technology, Tehran, Iran.
[47] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[48] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[49] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[50] Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
[51] Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
[52] Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
[53] Also at Università di Napoli 'Federico II', Napoli, Italy.
[54] Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy.
[55] Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
[56] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[57] Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
[58] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[59] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[60] Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
[61] Also at National and Kapodistrian University of Athens, Athens, Greece.
[62] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[63] Also at Universität Zürich, Zurich, Switzerland.

[64] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[65] Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[66] Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[67] Also at Konya Technical University, Konya, Turkey.
[68] Also at Izmir Bakircay University, Izmir, Turkey.
[69] Also at Adiyaman University, Adiyaman, Turkey.
[70] Also at Istanbul Gedik University, Istanbul, Turkey.
[71] Also at Necmettin Erbakan University, Konya, Turkey.
[72] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[73] Also at Marmara University, Istanbul, Turkey.
[74] Also at Milli Savunma University, Istanbul, Turkey.
[75] Also at Kafkas University, Kars, Turkey.
[76] Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[77] Also at Yildiz Technical University, Istanbul, Turkey.
[78] Also at Vrije Universiteit Brussel, Brussel, Belgium.
[79] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[80] Also at University of Bristol, Bristol, United Kingdom.
[81] Also at IPPP Durham University, Durham, United Kingdom.
[82] Also at Monash University, Faculty of Science, Clayton, Australia.
[83] Also at Università di Torino, Torino, Italy.
[84] Also at Bethel University, St. Paul, Minnesota, USA.
[85] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[86] Also at California Institute of Technology, Pasadena, California, USA.
[87] Also at United States Naval Academy, Annapolis, Maryland, USA.
[88] Also at Bingol University, Bingol, Turkey.
[89] Also at Georgian Technical University, Tbilisi, Georgia.
[90] Also at Sinop University, Sinop, Turkey.
[91] Also at Erciyes University, Kayseri, Turkey.
[92] Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China.
[93] Also at Texas A&M University at Qatar, Doha, Qatar.
[94] Also at Kyungpook National University, Daegu, Korea.
[95] Also at another institute or international laboratory covered by a cooperation agreement with CERN.
[96] Also at Imperial College, London, United Kingdom.
[97] Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.