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The CMS Collaboration*

Abstract

Correlations between azimuthal anisotropy and mean transverse momentum of charged particles in proton-proton (pp), proton-lead (pPb), and peripheral lead-lead (PbPb) collisions are presented as a function of charged particle multiplicity. The pp, pPb and PbPb collision data were collected using the CMS detector at the LHC with a center-of-mass energy per nucleon pair of 13, 8.16 and 5.02 TeV, respectively. The two- and four-particle cumulants for the second- and third-order Fourier anisotropy harmonics are correlated with the mean transverse momentum of charged particles on an event-by-event basis. In pp and pPb systems, the observed correlation coefficients based on two-particle cumulants are found to change from negative to positive values as the charged particle multiplicity decreases. The sign changes disappear when the correlated particles are required to be further apart in pseudorapidity. Additionally, no sign changes in correlation coefficients are observed when employing four-particle cumulants. Models incorporating initial-state gluon saturation and final-state hydrodynamic evolutions are compared to pPb data and the predicted sign changes are not observed.

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*See Appendix B for the list of collaboration members

A hot and dense medium known as the quark-gluon plasma (QGP) has been extensively studied using heavy ion collisions at the BNL RHIC [1–4] and CERN LHC [5–12]. The azimuthal anisotropy of the produced particles in these collisions is a powerful tool to study the collective dynamics and transport properties of the QGP. This anisotropy is characterized by the Fourier coefficients (v_n) of the particle azimuthal angle (ϕ) distribution $\mathrm{d}N/\mathrm{d}\phi \propto 1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]$, where Ψ_n represents the phase of the n^{th}-order azimuthal flow vector (also referred to as the angle of the n^{th}-order symmetry plane). In a hydrodynamic picture, the Fourier anisotropy harmonics are the result of strong partonic rescatterings in the final state, responding to the initial geometry of the colliding system [13–15]. In the past decade, a remarkable similarity in the azimuthal anisotropy signatures has been observed between heavy ion collisions and smaller collision systems, such as proton-proton (pp), proton-lead (pPb), and proton-gold (pAu) [16–26]. The similarity holds even for multiparticle correlations, which can suppress "nonflow" effects that do not result from correlations related to the bulk properties of the medium [23, 27]. These effects can include back-to-back jet correlations and resonance decays, which usually produce particles in localized pseudorapidity (η) regions [28–30]. Apart from the final-state effects, the observed anisotropy in small systems can also originate from initial-state effects, for example, in the color-glass condensate (CGC) effective theory [31–33]. The dominant origin of the azimuthal anisotropy in small systems is still under active discussion [34, 35], because no observable has been found to unambiguously distinguish between the final- and initial-state effects.

In addition to generating the final-state azimuthal anisotropy the hydrodynamic response also results in a radial flow, which contributes to the mean transverse momentum $[p_\mathrm{T}]$ on an event-by-event basis. The correlations between radial and anisotropic flow can be quantified using a modified linear correlator [36, 37],

$$\rho(v_n^2, [p_\mathrm{T}]) = \frac{\mathrm{cov}(v_n^2, [p_\mathrm{T}])}{\sqrt{\mathrm{Var}(v_n^2)_\mathrm{dyn}}\sqrt{\mathrm{Var}([p_\mathrm{T}])_\mathrm{dyn}}}, \tag{1}$$

where $\mathrm{cov}(v_n^2, [p_\mathrm{T}])$ is the covariance between v_n^2 and $[p_\mathrm{T}]$, and $\mathrm{Var}(v_n^2)_\mathrm{dyn}$ and $\mathrm{Var}([p_\mathrm{T}])_\mathrm{dyn}$ are the dynamical variances of the v_n^2 and $[p_\mathrm{T}]$ distributions, respectively. Dynamical variances remove auto-correlation effects, when compared with variances of v_n^2 and $[p_\mathrm{T}]$ distributions, and better capture intrinsic initial-state fluctuations. This correlator defined by Eq. (1) is sensitive to the details of the initial conditions, and its magnitude can be traced back to the initial density profile of the nuclear overlap [38, 39].

Recently it was suggested that this correlator might be able to distinguish between initial- and final-state effects [40]. Specifically, the CGC model predicts a sign change of the $\rho(v_n^2, [p_\mathrm{T}])$ correlator going from high-multiplicity (dominated by final-state effects) to very low-multiplicity (dominated by initial-state effects) events, in small collision systems. A prior ATLAS measurement using two-particle cumulants shows no sign change across the explored multiplicity range in pPb collisions [41]. However, these results do not cover the multiplciity range where the initial-state sign change is expected. It was realized that a sign change could exist due to nonflow effects as shown by the PYTHIA8 event generator with the A2 tune [42, 43]. Measurements of the correlator with proper treatment of nonflow effects, and the searches for correlator sign changes in low-multiplicity pp, pPb, and peripheral PbPb collisions can provide insights into the origin of the azimuthal correlations in small systems.

In this Letter, these correlations are measured to very low multiplicity regions in three collision systems where sign changes are predicted due to the dominance of initial-state effects. Measurements using four-particle cumulants are also presented for the first time to further suppress nonflow effects. The results in pPb collisions are compared directly with CGC predictions. In addition, the correlators for the third Fourier harmonic are also presented as a function of charged particle multiplicity. Tabulated results are provided in the HEPData record for this analysis [44].

The CMS apparatus [45, 46] is a multipurpose, nearly hermetic detector, designed to trigger on and identify electrons, muons, photons, and (charged and neutral) hadrons [47–49]. A global "particle-flow" (PF) algorithm [50] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. Forward hadronic calorimeters (HF), made of steel and quartz fibers, extend the η coverage provided by the barrel and endcap detectors up to $|\eta| \sim 5$. The silicon tracker used in 2016 measured charged particles within the range $|\eta| < 2.5$. For nonisolated particles of $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$ and $|\eta| < 1.4$, the track resolutions were typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [49]. At the start of 2017, a new pixel detector was installed [51]; the upgraded tracker measured particles up to $|\eta| < 3.0$ with typical resolutions of 1.5% in p_{T} and 20–75 μm in the transverse impact parameter [52] for nonisolated particles of $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$. The data sample is collected with a two-level trigger system: at level-1 events are selected by custom hardware processors and the high-level trigger uses fast versions of the offline software [53, 54].

The measurements presented in this Letter use pp, pPb and PbPb collisions with center-of-mass energy per nucleon pairs of 13, 8.16 and 5.02 TeV, taken in 2018, 2016, and 2018, and with integrated luminosities of $28.6\,\mathrm{pb}^{-1}$, $186\,\mathrm{nb}^{-1}$ and $0.607\,\mathrm{nb}^{-1}$, respectively [55–58]. When measuring the correlations in pp and pPb collisions, the same beam crossing may contain multiple independent interactions, which constitute a background for the analysis of high-multiplicity events. The average number of collisions per bunch crossing (pileup) in pp (pPb) data varied between 0.1 and 1.3 (0.10 and 0.25). A procedure similar to that described in Ref. [27] is used for identifying and rejecting pileup. Minimum bias (MB) pp and pPb events are triggered by energy deposits in at least one of the two HFs above a threshold of approximately 1 GeV, and the presence of at least one track with $p_{\mathrm{T}} > 0.4\,\mathrm{GeV}$ in the pixel tracker for pPb collisions. Events are also required to contain a primary vertex within 15 cm of the nominal interaction point along the beam axis and 0.2 cm in the transverse direction. The primary vertex is chosen as the reconstructed vertex with the largest number of associated tracks At least two reconstructed tracks were required to be associated with the primary vertex. The MB PbPb events are selected to have signals above readout thresholds in the range of ∼6–12 GeV on both sides of the HF calorimeters. The PbPb events are further filtered to have a primary vertex within 15 cm of the nominal interaction point along the beam axis and 0.2 cm in the transverse direction, and at least two towers with total deposited energy larger or equal to 4 GeV in each of the HF detectors. The trigger, event reconstruction, and selections are described in previous correlation analyses [27–30]. For all data sets analyzed, primary tracks, i.e., tracks that originate from the primary vertex and satisfy the high-purity criteria of Ref. [49], are used to perform the correlation measurements. In addition, the impact parameter significance of the tracks with respect to the primary vertex in the longitudinal and transverse direction is required to be less than 3 standard deviations. The relative p_{T} uncertainty must be less than 10% for the p_{T} range used. To ensure high tracking efficiency and minimal background contamination only tracks with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.5\,\mathrm{GeV}$ are used, as in Ref. [49]. The selected tracks are corrected for tracking inefficiency and acceptance found using simulated Monte Carlo samples from PYTHIA 8.212 [59] tune CP5 [60], HIJING v1.35 [61], and HYDJET 1.9 [62] for pp, pPb, and PbPb, respectively. If not specified otherwise, PYTHIA8 refers to this CP5 tune throughout the paper. The response of the CMS detector to these simulated events is based on GEANT4 [63].

All previous studies [40–43, 64] of the modified linear correlator use v_n^2 from two-particle correlations in Eq. (1). The v_n^2 term can be found from the Q-cumulant method described in Ref. [65]. The two- and four-particle v_n in this method can be written as,

$$v_n\{2\} = \sqrt{c_n\{2\}}, \quad v_n\{4\} = \sqrt[4]{-c_n\{4\}}. \tag{2}$$

The two- and four-particle cumulants $c_n\{2\}$ and $c_n\{4\}$ are

$$c_n\{2\} = \langle\langle 2\rangle\rangle, \quad c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2, \tag{3}$$

where the two- and four-particle correlations $\langle\langle 2\rangle\rangle$ and $\langle\langle 4\rangle\rangle$ are from

$$\langle\langle 2\rangle\rangle = \langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle, \quad \langle\langle 4\rangle\rangle = \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle. \tag{4}$$

Here, ϕ_j (j = 1, …, 4) are the azimuthal angles of four different particles in an event, and the double average symbol $\langle\langle\cdots\rangle\rangle$ indicates that the average is taken over all particles from all events.

To suppress nonflow effects in the $v_n\{2\}$, all previous measurements applied the "subevent method", which separates each event into different subsets in separated η ranges [41, 64]. With two subevents for $c_n\{2\}$, the covariance of the correlator in Eq. (1) is

$$\mathrm{cov}(c_n\{2\}, [p_\mathrm{T}]) = \Re\Big\langle \sum_{a,b} \exp^{in(\phi_a-\phi_b)} \left([p_\mathrm{T}] - \langle[p_\mathrm{T}]\rangle\right)\Big\rangle, \tag{5}$$

where ϕ_a and ϕ_b are the azimuthal angles of particles a and b in subevents A and B, respectively. The $\langle[p_\mathrm{T}]\rangle$ is the average $[p_\mathrm{T}]$ in all the events in a certain multiplicity range. We select tracks with $-2.4 < \eta < -0.75$ to be subevent A, whereas tracks with $0.75 < \eta < 2.4$ belong to subevent B. Tracks from the third subevent in the central region $|\eta| < 0.5$ are used to obtain $[p_\mathrm{T}]$ in each event. These selections ensure that subevents A and B are symmetric in η, and that there is an η gap between each subevent to reduce nonflow effects.

The dynamical variance of $c_n\{2\}$ and $[p_\mathrm{T}]$ are derived in Ref. [37]:

$$\mathrm{Var}(c_n\{2\})_\mathrm{dyn} = \langle\langle 4\rangle\rangle - \langle\langle 2\rangle\rangle^2, \tag{6}$$

$$\mathrm{Var}([p_\mathrm{T}])_\mathrm{dyn} = \Big\langle \left[(p_{\mathrm{T}i} - \langle[p_\mathrm{T}]\rangle)(p_{\mathrm{T}j} - \langle[p_\mathrm{T}]\rangle)\right] \Big\rangle, \tag{7}$$

where the indices $i \neq j$ and both run over all charged particles within $|\eta| < 0.5$.

The correlator $\rho(c_n\{2\}, [p_\mathrm{T}])$ is extracted using particles in the range $0.5 < p_\mathrm{T} < 5.0\,\mathrm{GeV}$. Particles with $p_\mathrm{T} > 5\,\mathrm{GeV}$ are excluded to reduce nonflow effects. The analysis is repeated in different ranges of the number of reconstructed charged particles $N_\mathrm{ch}^\mathrm{rec}$, which is obtained with the same p_T range as the correlator within $|\eta| < 2.4$. The results are presented as a function of N_ch, which is found by applying acceptance and efficiency corrections to $N_\mathrm{ch}^\mathrm{rec}$. For each $N_\mathrm{ch}^\mathrm{rec}$ range used in this analysis, Table 1 of the Appendix reports the mean values of N_ch and also of $N_\mathrm{trk}^\mathrm{offline}$, the number of offline-reconstructed charged particles with $p_\mathrm{T} > 0.4\,\mathrm{GeV}$ and $|\eta| < 2.4$ used in previous CMS measurements [16, 19, 27]. Since we are interested in small collision systems, only peripheral events with $N_\mathrm{ch} < 400$ are presented for PbPb collisions.

Studies using A2 tune of PYTHIA8 [42, 43] show that the remaining nonflow contributions to $c_2\{2\}$ are not negligible when going to very low-multiplicity regions, even with the subevent methods. In these studies, we improve the suppression of nonflow effects with two approaches. In the first approach, we increase the minimum η gap between subevents A and B from 1.5 to 2.0, by changing the $c_2\{2\}$ analysis using particles from $|\eta| > 0.75$ to $|\eta| > 1.00$. Nonflow correlations between particles inside back-to-back jets in the forward η regions still remain with this larger η gap [27].

In the second approach, we extend the current observable by replacing $c_2\{2\}$ with four-particle cumulant $c_2\{4\}$. Although nonflow contributions to multiparticle cumulants are less dominant when compared with two-particle correlations, using the subevent method is important to remove remaining nonflow contributions in multiparticle correlations [66]. Particles with $0.75 < |\eta| < 2.4$ are divided into three equal sized η intervals to obtain $c_2\{4\}$ for each event. These intervals are $-2.4 < \eta < -1.3$, $0.75 < |\eta| < 1.3$, and $1.3 < \eta < 2.4$. The event-by-event $c_2\{4\}$ is then correlated with $[p_T]$ in the same event. When nonflow contributions are not negligible, the method using $c_2\{4\}$ suppresses them much more than the $c_2\{2\}$ method. The correlator using $c_2\{4\}$ is more sensitive to the presence of a sign change in the data. Corrections for tracking efficiency and misreconstructed tracks are done at particle level for both the cumulants and $[p_T]$.

The systematic uncertainties in the experimental procedure are evaluated as a function of N_{ch} by using alternative procedures for extracting the correlators. Systematic uncertainties due to tracking inefficiency and misreconstructed track rate are studied by varying the track quality requirements. The selection thresholds on the significances of the transverse and longitudinal track impact parameters divided by their uncertainties are varied from 2 to 5. In addition, the upper limit on the relative p_T uncertainty is varied from 5 to 10%. The resulting systematic uncertainty is from 2×10^{-7} to 5×10^{-6} for the covariances $\mathrm{cov}(c_n\{2\}, [p_T])$ and $\mathrm{cov}(c_n\{4\}, [p_T])$, and from 0.001 to 0.008 for the correlator $\rho(c_n\{2\}, [p_T])$, depending on multiplicity and collision systems. The sensitivity of the results to the primary vertex position along the beam axis (z_{vtx}) is quantified by comparing events with different z_{vtx} locations from -15 to $+15$ cm. The magnitude of this uncertainty is estimated to be from 1×10^{-7} to 2×10^{-5} for the covariances, and from 0.001 to 0.018 for $\rho(c_n\{2\}, [p_T])$, depending on multiplicity and collision system. Systematic effects from event selections are explored by comparing results obtained with and without the requirement of the coincidence of HF calorimeter tower signals above the threshold. The pileup effect is studied by requiring the presence of only a single reconstructed vertex. Systematic uncertainties from event selections and pileup are both found to be less than 6×10^{-6} for the covariances, and less than 0.006 for the correlators in all collision systems. The tracking and vertex position selections are the dominant sources of uncertainty. Systematic uncertainties originating from different sources are added in quadrature to obtain the total systematic uncertainty.

The measurements of covariances from two- and four-particle correlations for the second- and third-order Fourier harmonics in 13 TeV pp, 8.16 TeV pPb, and 5.02 TeV PbPb collisions are presented in Fig. 1. To compare $\mathrm{cov}(c_2\{2\}, [p_T])$ and $\mathrm{cov}(c_2\{4\}, [p_T])$ in the same scale, the values of $\mathrm{cov}(c_2\{4\}, [p_T])$ are multiplied by 4 in all of the panels. In both pp and pPb collisions, $\mathrm{cov}(c_2\{2\}, [p_T])$ for $|\eta| > 0.75$ exhibits a sign change from positive to negative as N_{ch} increases. This trend is qualitatively consistent with the expectation of a sign change from the CGC model. However, no clear sign change is observed in pp and pPb collisions for $\mathrm{cov}(c_2\{4\}, [p_T])$, which mitigates nonflow contributions compared to $\mathrm{cov}(c_2\{2\}, [p_T])$. The $\mathrm{cov}(c_2\{4\}, [p_T])$ values are consistent with 0 in pp collisions with the current statistical precision. As N_{ch} becomes smaller in PbPb collisions, the values of $\mathrm{cov}(c_2\{2\}, [p_T])$ change from positive to negative below $N_{ch} \approx 180$, reach a minimum at $N_{ch} \approx 60$, and then approach zero at the lowest N_{ch} range.

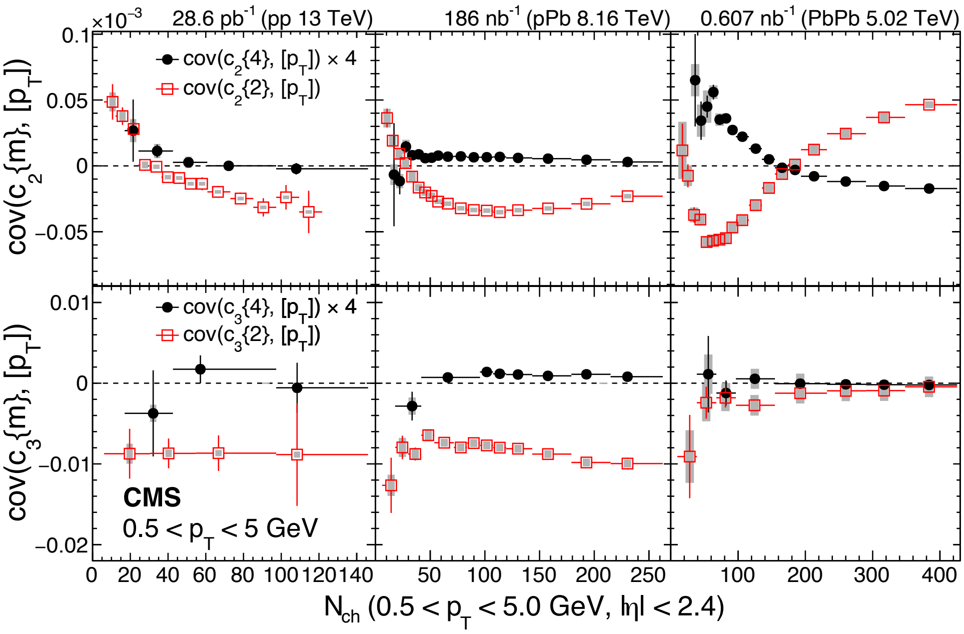

Figure 1: The covariances of cumulants from two- and four-particle correlations and $[p_T]$ as a function of charged particle multiplicity (N_{ch}) in 13 TeV pp (left), 8.16 TeV pPb (middle), and 5.02 TeV PbPb (right) collisions. The two-particle cumulants are obtained with $|\eta| > 0.75$. The upper (lower) panels show the second (third) harmonics. The error bars correspond to statistical uncertainties, while the shaded areas denote the systematic uncertainties.

One feature of the observable with $c_2\{4\}$ is that, when nonflow contributions are not dominant, the variables using $c_2\{4\}$ and $c_2\{2\}$ have opposite signs and trends. This is because the relations between cumulants and v_n are $c_2\{2\} = (v_2\{2\})^2$ and $c_2\{4\} = -(v_2\{4\})^4$ from Eq. (2). As v_n increases, both $v_2\{2\}$ and $v_2\{4\}$ become larger if nonflow and flow fluctuations do not dominate the flow signal. Therefore, the values increase for $c_2\{2\}$ but decrease for $c_2\{4\}$ because of the minus sign. This opposing trends for $\text{cov}(c_2\{2\}, [p_T])$ and $\text{cov}(c_2\{4\}, [p_T])$ are clear for high-multiplicity PbPb results in Fig. 1.

Regarding the third harmonic, $\text{cov}(c_3\{2\}, [p_T])$ is negative for the full N_{ch} range in the three collision systems. The signs of $\text{cov}(c_3\{2\}, [p_T])$ and $\text{cov}(c_3\{4\}, [p_T])$ are opposite in high-multiplicity pPb events, similar to $\text{cov}(c_2\{2\}, [p_T])$ and $\text{cov}(c_2\{4\}, [p_T])$. In both pp and PbPb collisions, the $\text{cov}(c_3\{4\}, [p_T])$ values are consistent with 0 with the current statistical precision.

The correlator with a larger η gap ($|\eta| > 1.0$ corresponding to a minimum η gap of 2.0) for the cumulants is shown in Fig. 2. In both pp and pPb collisions, the sign change at low N_{ch} disappears with the larger η gap between the two subevents, which is also observed in calculations using PYTHIA8. The predictions in pPb collisions at 5.02 TeV from the IP-Glasma+MUSIC+UrQMD model [40] with $0.5 < p_T < 5.0$ GeV are compared with the data in Fig. 2. This model includes gluon saturation in the initial state followed by hydrodynamic evolution and hadronic interactions. The characteristic sign change of the correlator predicted by this model is observed in data at the same N_{ch} location for $|\eta| > 0.75$, but it disappears when using $|\eta| > 1.0$, which leads to less nonflow effects. The results indicate that after removing more nonflow effects, the CGC signal is not observed in the data. More nonflow studies incorporated in the CGC model are needed to understand the origin of azimuthal anisotropy in small systems. Results from the ATLAS Collaboration in pPb (PbPb) collisions at 5.02 TeV with $0.3 < p_T < 2.0$ GeV ($0.5 < p_T < 5.0$ GeV) [41] are also compared and found to be consistent with results obtained from this analysis.

The $n = 3$ correlators measured with the larger η gap are negative in all three collison systems. The results are compared with predictions from a hydrodynamic simulation of pPb collisions [67] using $p_T > 0.5$ GeV and having an average root-mean-square (RMS) transverse radius of the initial fireball of either 0.9 or 1.5 fm. These sizes correspond to two versions of the Glauber model for the initial state [68]: the smaller fireball with 0.9 fm deposits entropy in the nucleon overlap region between the participant nucleons, while the larger fireball with 1.5 fm deposits entropy at both positions of the participant nucleons. Qualitatively, the data are better described by the smaller initial fireball, suggesting that entropy deposition should occur in the nucleon overlap region rather than at the center of both nucleons. The predictions from IP-Glasma+MUSIC+UrQMD for $n = 3$ also indicate a sign change, although it is not observed in data.

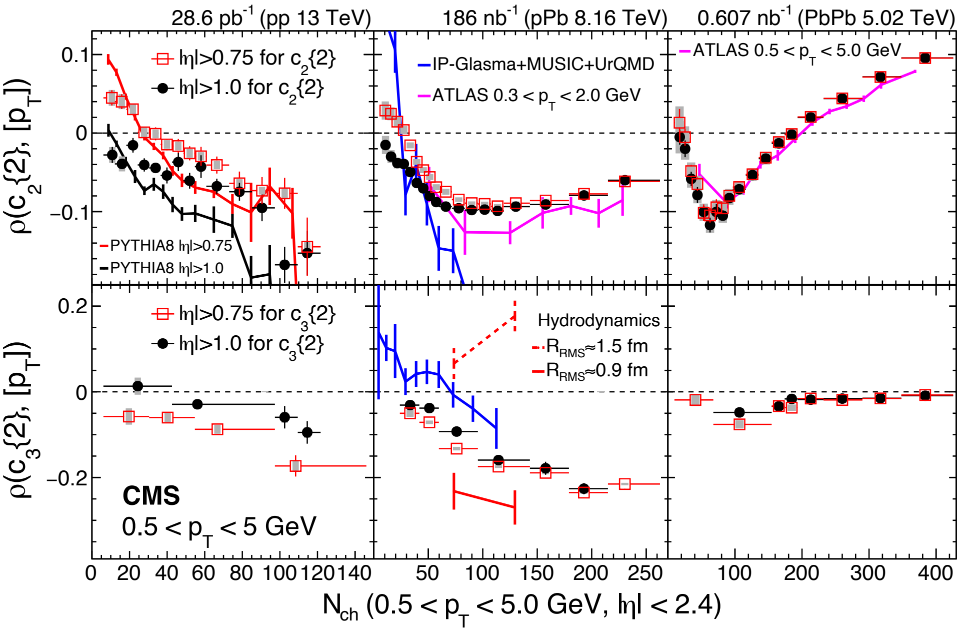

Figure 2: The correlator using two-particle cumulant from $|\eta| > 0.75$ and $|\eta| > 1.0$ as a function of N_{ch} in 13 TeV pp (left), 8.16 TeV pPb (middle), and 5.02 TeV PbPb (right) collisions. The upper (lower) panels show the second (third) harmonics. The error bars correspond to the statistical uncertainties, and the shaded areas denote the systematic uncertainties. Calculations from PYTHIA8 (upper left panel, red and black lines) and IP-Glasma+MUSIC+UrQMD (middle panels, blue lines) [40] are compared with the data. Hydrodynamic predictions (lower middle panel, red lines) [67] with an average RMS transverse radius of the initial fireball of either 0.9 or 1.5 fm are also included in the comparison. The magenta lines in the middle and right upper panels represent the ATLAS results [41] in pPb and PbPb collisions at 5.02 TeV using $|\eta| > 0.75$ with the error bars denoting the statistical and systematic uncertainties added in quadrature.

In summary, correlations between mean transverse momentum $[p_T]$ and multiparticle cumulants from two- and four-particle correlations for Fourier harmonics $n = 2$ and $n = 3$ are presented in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV, proton-lead (pPb) collisions at $\sqrt{s_{NN}} = 8.16$ TeV and peripheral lead-lead (PbPb) collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Sign changes in the modified linear correlators are observed as a function of charged particle multiplicity when using two-particle cumulants with a minimum η gap of 1.5, in the pp and pPb systems. These sign changes disappear when nonflow effects are suppressed using a minimum η gap of 2.0. To further reduce nonflow contribution, four-particle cumulants $c_2\{4\}$ are also correlated with $[p_T]$ which shows no sign change in pp and pPb collisions, similar to the two-particle correlation results with a larger η gap. This indicates that after removing nonflow effects, the sign change predicted at low multiplicity by initial-state saturation is not observed.

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References

[1] PHOBOS Collaboration, "System size dependence of cluster properties from two-particle angular correlations in CuCu and AuAu collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 200\,\mathrm{GeV}$", *Phys. Rev. C* **81** (2010) 024904, doi:10.1103/PhysRevC.81.024904, arXiv:0812.1172.

[2] STAR Collaboration, "Distributions of charged hadrons associated with high transverse momentum particles in pp and AuAu collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 200\,\mathrm{GeV}$", *Phys. Rev. Lett.* **95** (2005) 152301, doi:10.1103/PhysRevLett.95.152301, arXiv:nucl-ex/0501016.

[3] STAR Collaboration, "Long-range rapidity correlations and jet production in high energy nuclear collisions", *Phys. Rev. C* **80** (2009) 064912, doi:10.1103/PhysRevC.80.064912, arXiv:0909.0191.

[4] PHOBOS Collaboration, "High transverse momentum triggered correlations over a large pseudorapidity acceptance in AuAu collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 200\,\mathrm{GeV}$", *Phys. Rev. Lett.* **104** (2010) 062301, doi:10.1103/PhysRevLett.104.062301, arXiv:0903.2811.

[5] CMS Collaboration, "Long-range and short-range dihadron angular correlations in central PbPb collisions at a nucleon-nucleon center of mass energy of 2.76 TeV", *JHEP* **07** (2011) 076, doi:10.1007/JHEP07(2011)076, arXiv:1105.2438.

[6] ALICE Collaboration, "Higher harmonic anisotropic flow measurements of charged particles in PbPb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV", *Phys. Rev. Lett.* **107** (2011) 032301, doi:10.1103/PhysRevLett.107.032301, arXiv:1105.3865.

[7] ALICE Collaboration, "Harmonic decomposition of two-particle angular correlations in PbPb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV", *Phys. Lett. B* **708** (2012) 249, doi:10.1016/j.physletb.2012.01.060, arXiv:1109.2501.

[8] CMS Collaboration, "Centrality dependence of dihadron correlations and azimuthal anisotropy harmonics in PbPb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV", *Eur. Phys. J. C* **72** (2012) 2012, doi:10.1140/epjc/s10052-012-2012-3, arXiv:1201.3158.

[9] ALICE Collaboration, "Elliptic flow of charged particles in PbPb collisions at 2.76 TeV", *Phys. Rev. Lett.* **105** (2010) 252302, doi:10.1103/PhysRevLett.105.252302, arXiv:1011.3914.

[10] ATLAS Collaboration, "Measurement of the azimuthal anisotropy for charged particle production in $\sqrt{s_{_{NN}}} = 2.76$ TeV lead-lead collisions with the ATLAS detector", *Phys. Rev. C* **86** (2012) 014907, doi:10.1103/PhysRevC.86.014907, arXiv:1203.3087.

[11] CMS Collaboration, "Measurement of the elliptic anisotropy of charged particles produced in PbPb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV", *Phys. Rev. C* **87** (2013) 014902, doi:10.1103/PhysRevC.87.014902, arXiv:1204.1409.

[12] CMS Collaboration, "Overview of high-density QCD studies with the CMS experiment at the LHC", 2024. arXiv:2405.10785. Submitted to Physics Reports.

[13] B. H. Alver, C. Gombeaud, M. Luzum, and J.-Y. Ollitrault, "Triangular flow in hydrodynamics and transport theory", *Phys. Rev. C* **82** (2010) 034913, doi:10.1103/PhysRevC.82.034913, arXiv:1007.5469.

[14] B. Schenke, S. Jeon, and C. Gale, "Elliptic and triangular flow in event-by-event (3+1)d viscous hydrodynamics", *Phys. Rev. Lett.* **106** (2011) 042301, doi:10.1103/PhysRevLett.106.042301, arXiv:1009.3244.

[15] Z. Qiu, C. Shen, and U. Heinz, "Hydrodynamic elliptic and triangular flow in PbPb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV", *Phys. Lett. B* **707** (2012) 151, doi:10.1016/j.physletb.2011.12.041, arXiv:1110.3033.

[16] CMS Collaboration, "Observation of long-range near-side angular correlations in proton-proton collisions at the LHC", *JHEP* **09** (2010) 091, doi:10.1007/JHEP09(2010)091, arXiv:1009.4122.

[17] ATLAS Collaboration, "Observation of long-range elliptic azimuthal anisotropies in $\sqrt{s_{_{NN}}} = 13$ and 2.76 TeV pp collisions with the ATLAS detector", *Phys. Rev. Lett.* **116** (2016) 172301, doi:10.1103/PhysRevLett.116.172301, arXiv:1509.04776.

[18] CMS Collaboration, "Measurement of long-range near-side two-particle angular correlations in pp collisions at $\sqrt{s} = 13$ TeV", *Phys. Rev. Lett.* **116** (2016) 172302, doi:10.1103/PhysRevLett.116.172302, arXiv:1510.03068.

[19] CMS Collaboration, "Observation of long-range near-side angular correlations in proton-lead collisions at the LHC", *Phys. Lett. B* **718** (2013) 795, doi:10.1016/j.physletb.2012.11.025, arXiv:1210.5482.

[20] ALICE Collaboration, "Long-range angular correlations on the near and away side in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *Phys. Lett. B* **719** (2013) 29, doi:10.1016/j.physletb.2013.01.012, arXiv:1212.2001.

[21] ATLAS Collaboration, "Observation of associated near-side and away-side long-range correlations in $\sqrt{s_{NN}} = 5.02$ TeV proton-lead collisions with the ATLAS detector", *Phys. Rev. Lett.* **110** (2013) 182302, doi:10.1103/PhysRevLett.110.182302, arXiv:1212.5198.

[22] LHCb Collaboration, "Measurements of long-range near-side angular correlations in $\sqrt{s_{NN}} = 5$ TeV proton-lead collisions in the forward region", *Phys. Lett. B* **762** (2016) 473, doi:10.1016/j.physletb.2016.09.064, arXiv:1512.00439.

[23] PHENIX Collaboration, "Measurements of multiparticle correlations in dAu collisions at 200, 62.4, 39, and 19.6 GeV and pAu collisions at 200 GeV and implications for collective behavior", *Phys. Rev. Lett.* **120** (2018) 062302, doi:10.1103/PhysRevLett.120.062302, arXiv:1707.06108.

[24] PHENIX Collaboration, "Measurement of long-range angular correlations and azimuthal anisotropies in high-multiplicity pAu collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev. C* **95** (2017) 034910, doi:10.1103/PhysRevC.95.034910, arXiv:1609.02894.

[25] PHENIX Collaboration, "Measurements of elliptic and triangular flow in high-multiplicity ^{3}He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev. Lett.* **115** (2015) 142301, doi:10.1103/PhysRevLett.115.142301, arXiv:1507.06273.

[26] PHENIX Collaboration, "Creation of quark-gluon plasma droplets with three distinct geometries", *Nature Phys.* **15** (2019) 214, doi:10.1038/s41567-018-0360-0, arXiv:1805.02973.

[27] CMS Collaboration, "Multiplicity and transverse momentum dependence of two- and four-particle correlations in pPb and PbPb collisions", *Phys. Lett. B* **724** (2013) 213, doi:10.1016/j.physletb.2013.06.028, arXiv:1305.0609.

[28] CMS Collaboration, "Evidence for collective multiparticle correlations in pPb collisions", *Phys. Rev. Lett.* **115** (2015) 012301, doi:10.1103/PhysRevLett.115.012301, arXiv:1502.05382.

[29] CMS Collaboration, "Evidence for collectivity in pp collisions at the LHC", *Phys. Lett. B* **765** (2017) 193, doi:10.1016/j.physletb.2016.12.009, arXiv:1606.06198.

[30] CMS Collaboration, "Multiparticle correlation studies in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV", *Phys. Rev. C* **101** (2020) 014912, doi:10.1103/PhysRevC.101.014912, arXiv:1904.11519.

[31] K. Dusling and R. Venugopalan, "Evidence for BFKL and saturation dynamics from dihadron spectra at the LHC", *Phys. Rev. D* **87** (2013) 051502, doi:10.1103/PhysRevD.87.051502, arXiv:1210.3890.

[32] A. Dumitru and V. Skokov, "Anisotropy of the semiclassical gluon field of a large nucleus at high energy", *Phys. Rev. D* **91** (2015) 074006, doi:10.1103/PhysRevD.91.074006, arXiv:1411.6630.

[33] B. Schenke, S. Schlichting, and R. Venugopalan, "Azimuthal anisotropies in pPb collisions from classical Yang–Mills dynamics", *Phys. Lett. B* **747** (2015) 76, doi:10.1016/j.physletb.2015.05.051, arXiv:1502.01331.

[34] J. L. Nagle and W. A. Zajc, "Small-system collectivity in relativistic hadronic and nuclear collisions", *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 211, doi:10.1146/annurev-nucl-101916-123209, arXiv:1801.03477.

[35] W. Busza, K. Rajagopal, and W. van der Schee, "Heavy ion collisions: the big picture, and the big questions", *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 339, doi:10.1146/annurev-nucl-101917-020852, arXiv:1802.04801.

[36] A. Mazeliauskas and D. Teaney, "Fluctuations of harmonic and radial flow in heavy ion collisions with principal components", *Phys. Rev. C* **93** (2016) 024913, doi:10.1103/PhysRevC.93.024913, arXiv:1509.07492.

[37] P. Bozek, "Transverse-momentum–flow correlations in relativistic heavy ion collisions", *Phys. Rev. C* **93** (2016) 044908, doi:10.1103/PhysRevC.93.044908, arXiv:1601.04513.

[38] B. Schenke, C. Shen, and D. Teaney, "Transverse momentum fluctuations and their correlation with elliptic flow in nuclear collisions", *Phys. Rev. C* **102** (2020) 034905, doi:10.1103/PhysRevC.102.034905, arXiv:2004.00690.

[39] G. Giacalone, F. G. Gardim, J. Noronha-Hostler, and J.-Y. Ollitrault, "Correlation between mean transverse momentum and anisotropic flow in heavy ion collisions", *Phys. Rev. C* **103** (2021) 024909, doi:10.1103/PhysRevC.103.024909, arXiv:2004.01765.

[40] G. Giacalone, B. Schenke, and C. Shen, "Observable signatures of initial-state momentum anisotropies in nuclear collisions", *Phys. Rev. Lett.* **125** (2020) 192301, doi:10.1103/PhysRevLett.125.192301, arXiv:2006.15721.

[41] ATLAS Collaboration, "Measurement of flow harmonics correlations with mean transverse momentum in lead-lead and proton-lead collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ with the ATLAS detector", *Eur. Phys. J. C* **79** (2019) 985, doi:10.1140/epjc/s10052-019-7489-6, arXiv:1907.05176.

[42] C. Zhang, A. Behera, S. Bhatta, and J. Jia, "Nonflow effects in correlation between harmonic flow and transverse momentum in nuclear collisions", *Phys. Lett. B* **822** (2021) 136702, doi:10.1016/j.physletb.2021.136702, arXiv:2102.05200.

[43] S. H. Lim and J. L. Nagle, "Exploring origins for correlations between flow harmonics and transverse momentum in small collision systems", *Phys. Rev. C* **103** (2021) 064906, doi:10.1103/PhysRevC.103.064906, arXiv:2103.01348.

[44] "HEPData record for this analysis", 2024. doi:10.17182/hepdata.132364.

[45] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[46] CMS Collaboration, "Development of the CMS detector for the CERN LHC Run 3", 9, 2023. arXiv:2309.05466.

[47] CMS Collaboration, "Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC", *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.

[48] CMS Collaboration, "Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$", *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.

[49] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[50] CMS Collaboration, "Particle-flow reconstruction and global event description with the CMS detector", *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[51] Tracker Group of the CMS Collaboration, "The CMS phase-1 pixel detector upgrade", *JINST* **16** (2021) P02027, doi:10.1088/1748-0221/16/02/P02027, arXiv:2012.14304.

[52] CMS Collaboration, "Track impact parameter resolution for the full pseudo rapidity coverage in the 2017 dataset with the CMS phase-1 pixel detector", CMS Detector Performance Note CMS-DP-2020-049, 2020.

[53] CMS Collaboration, "Performance of the CMS level-1 trigger in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$", *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.

[54] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[55] CMS Collaboration, "CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13\,\text{TeV}$", CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.

[56] CMS Collaboration, "CMS luminosity measurement using 2016 proton-nucleus collisions at $\sqrt{s_{_{\text{NN}}}} = 8.16\,\text{TeV}$", CMS Physics Analysis Summary CMS-PAS-LUM-17-002, 2018.

[57] CMS Collaboration, "CMS luminosity measurement using nucleus-nucleus collisions at $\sqrt{s_{_{\text{NN}}}} = 5.02\,\text{TeV}$ in 2018", CMS Physics Analysis Summary CMS-PAS-LUM-18-001, 2022.

[58] CMS Collaboration, "Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ in 2015 and 2016 at CMS", *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.

[59] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[60] CMS Collaboration, "Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements", *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

[61] M. Gyulassy and X.-N. Wang, "HIJING 1.0: A Monte Carlo program for parton and particle production in high-energy hadronic and nuclear collisions", *Comput. Phys. Commun.* **83** (1994) 307, doi:10.1016/0010-4655(94)90057-4, arXiv:nucl-th/9502021.

[62] I. P. Lokhtin and A. M. Snigirev, “A model of jet quenching in ultrarelativistic heavy ion collisions and high-p_{T} hadron spectra at RHIC”, *Eur. Phys. J. C* **45** (2006) 211, doi:10.1140/epjc/s2005-02426-3, arXiv:hep-ph/0506189.

[63] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. and Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[64] ALICE Collaboration, “Characterizing the initial conditions of heavy-ion collisions at the LHC with mean transverse momentum and anisotropic flow correlations”, *Phys. Lett. B* **834** (2022) 137393, doi:10.1016/j.physletb.2022.137393, arXiv:2111.06106.

[65] A. Bilandzic, R. Snellings, and S. Voloshin, “Flow analysis with cumulants: Direct calculations”, *Phys. Rev. C* **83** (2011) 044913, doi:10.1103/PhysRevC.83.044913, arXiv:1010.0233.

[66] J. Jia, M. Zhou, and A. Trzupek, “Revealing long-range multiparticle collectivity in small collision systems via subevent cumulants”, *Phys. Rev. C* **96** (2017) 034906, doi:10.1103/PhysRevC.96.034906, arXiv:1701.03830.

[67] P. Bozek and H. Mehrabpour, “Correlation coefficient between harmonic flow and transverse momentum in heavy ion collisions”, *Phys. Rev. C* **101** (2020) 064902, doi:10.1103/PhysRevC.101.064902, arXiv:2002.08832.

[68] A. Bzdak, B. Schenke, P. Tribedy, and R. Venugopalan, “Initial state geometry and the role of hydrodynamics in proton-proton, proton-nucleus and deuteron-nucleus collisions”, *Phys. Rev. C* **87** (2013) 064906, doi:10.1103/PhysRevC.87.064906, arXiv:1304.3403.

A Mapping between N_{ch} and $N_{trk}^{offline}$ in pp, pPb, and PbPb collisions

Table 1: Average multiplicity of reconstructed tracks per N_{ch}^{rec} bin for N_{ch} in this analysis and $N_{trk}^{offline}$ in previous CMS measurements [16, 19, 27] in pp, pPb, and peripheral PbPb collisions. Uncertainties in the tracking efficiency corrected N_{ch} are included.

	pp		pPb		PbPb	
N_{ch}^{rec} range	$\langle N_{ch}\rangle$	$\langle N_{trk}^{offline}\rangle$	$\langle N_{ch}\rangle$	$\langle N_{trk}^{offline}\rangle$	$\langle N_{ch}\rangle$	$\langle N_{trk}^{offline}\rangle$
$[0, 20)$	8±0	9	11±0	12	16±1	14
$[20, 40)$	34±1	34	36±1	36	57±2	48
$[40, 60)$	58±2	56	60±2	60	96±4	80
$[60, 80)$	82±3	78	83±3	82	135±5	112
$[80, 100)$	106±4	101	107±4	105	175±7	144
$[100, 150)$	132±5	125	140±6	137	240±10	197
$[150, 200)$			198±8	191	335±13	276
$[200, 250)$			256±10	246	434±17	353

B The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Tumasyan

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, P.S. Hussain, M. Jeitler[1], N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck[1], R. Schöfbeck, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz[1]

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[2], T. Janssen, T. Kello[3], H. Rejeb Sfar, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, 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

Université Libre de Bruxelles, Bruxelles, 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

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

Université Catholique de Louvain, Louvain-la-Neuve, 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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, E. Coelho, C. Hensel, A. Moraes, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[4], E.M. Da Costa, G.G. Da Silveira[5], D. De Jesus Damiao, V. Dos Santos Sousa, S. Fonseca De Souza, J. Martins[6], C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, A. Vilela Pereira

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[5], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

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

S. Thakur

Beihang University, Beijing, China
T. Cheng, T. Javaid[7], M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, G. Bauer[8], Z. Hu, S. Lezki, K. Yi[8,9]

Institute of High Energy Physics, Beijing, China
G.M. Chen[7], H.S. Chen[7], M. Chen[7], F. Iemmi, C.H. Jiang, A. Kapoor, H. Liao, Z.-A. Liu[10], V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. An, Y. Ban, A. Levin, C. Li, Q. Li, X. Lyu, Y. Mao, S.J. Qian, X. Sun, D. Wang, J. Xiao, H. Yang

Sun Yat-Sen University, Guangzhou, China
M. Lu, Z. You

University of Science and Technology of China, Hefei, China
N. Lu

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao[3], D. Leggat, H. Okawa, Y. Zhang

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, F. Ramirez, M. Rodriguez, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, B.K. Chitroda, D. Ferencek, S. Mishra, M. Roguljic, A. Starodumov[11], T. Susa

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

Charles University, Prague, Czech Republic
M. Finger[11], M. Finger Jr.[11], A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim[12,13], E. Salama[14,15]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M.A. Mahmoud, Y. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, R.K. Dewanjee, K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, 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

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[16], P. Simkina, M. Titov

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

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[17], 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

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
S. Beauceron, B. Blancon, G. Boudoul, A. Carle, N. Chanon, J. Choi, D. Contardo, P. Depasse, C. Dozen[18], 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

Georgian Technical University, Tbilisi, Georgia
I. Bagaturia[19], I. Lomidze, Z. Tsamalaidze[11]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, 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, F. Torres Da Silva De Araujo[20], L. Vigilante, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[21], O. Hlushchenko, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, 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. Velyka, 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

University of Hamburg, 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

Karlsruher Institut fuer Technologie, Karlsruhe, 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, M. Link, A. Lintuluoto, S. Maier, S. Mitra, Th. Müller, M. Neukum, M. Oh, G. Quast, K. Rabbertz, J. Rauser, M. Schnepf, 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

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, P. Assiouras, G. Daskalakis, A. Kyriakis, A. Stakia

National and Kapodistrian University of Athens, Athens, 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 Technical University of Athens, Athens, Greece
G. Bakas, T. Chatzistavrou, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, 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

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók[29], G. Bencze, C. Hajdu, D. Horvath[30,31], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, M.M.A. Gadallah[32], S. Lökös[33], P. Major, K. Mandal, G. Pásztor, A.J. Rádl[34], O. Surányi, G.I. Veres

HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[29], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, B. Ujvari[35]

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[34], F. Nemes[34], T. Novak

Panjab University, Chandigarh, India
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

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, M. Naimuddin, K. Ranjan, S. Saumya

Saha Institute of Nuclear Physics, HBNI, Kolkata, 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

Indian Institute of Technology Madras, Madras, 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, R.K. Singh, P.C. Tiwari[40], S. Verma

Bhabha Atomic Research Centre, Mumbai, India
K. Naskar[41]

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, I. Das, S. Dugad, M. Kumar, G.B. Mohanty, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India

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

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

Indian Institute of Science Education and Research (IISER), Pune, India
A. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rastogi, S. Sharma

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[44,45], E. Khazaie[45], M. Zeinali[46]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[47], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,b,12], 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], 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]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], C. Ciocca[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]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,49], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,49], C. Tuve[a,b]

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Meola[50], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
M. Bozzo[a,b], P. Chatagnon[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

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

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, 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,51], P. Paolucci[a,28], B. Rossi[a], C. Sciacca[a,b]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy
P. Azzi[a], N. Bacchetta[a,52], D. Bisello[a,b], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], S. Fantinel[a], F. Fanzago[a], F. Gasparini[a,b], U. Gasparini[a,b], G. Grosso[a], 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], G. Strong[a], M. Tosi[a,b], H. Yarar[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
S. Abu Zeid[a,15], 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]

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

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, 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], 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]

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

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, 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], R. Mulargia[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]

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

Kyungpook National University, Daegu, Korea
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

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon

Hanyang University, Seoul, Korea
E. Asilar, T.J. Kim, J. Park

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

Kyung Hee University, Department of Physics, Seoul, Korea
J. Goh

Sejong University, Seoul, Korea
H. S. Kim, Y. Kim, S. Lee

Seoul National 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

University of Seoul, 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

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, H. Lee, Y. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia
K. Dreimanis, G. Pikurs, A. Potrebko, M. Seidel, V. Veckalns[55]

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

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, S.Y. Hoh[56], I. Yusuff[56], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
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

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, I. Heredia-De La Cruz[57], R. Lopez-Fernandez,

C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
I. Bubanja, J. Mijuskovic[58], N. Raicevic

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, M. Gul, H.R. Hoorani, W.A. Khan, M. Shoaib, M. Waqas

AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, J. Varela

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
P. Adzic[59], M. Dordevic, P. Milenovic, J. Milosevic

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

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz

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

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

University of Colombo, Colombo, Sri Lanka
M.K. Jayananda, B. Kailasapathy[60], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
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[61], 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[62], A.G. Stahl Leiton, S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, J. Wanczyk[63], K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[64], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[64], L. Noehte[64], T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, K. Androsov[63], 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[63], 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[63], D. Valsecchi[28], R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[65], 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

National Central University, Chung-Li, Taiwan
C. Adloff[66], C.M. Kuo, W. Lin, P.K. Rout, S.S. Yu

National Taiwan University (NTU), Taipei, 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

High Energy Physics Research Unit, Department of Physics, Faculty of Science,

Chulalongkorn University, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu[67], E. Eskut, Y. Guler[68], E. Gurpinar Guler[68], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[69], A. Polatoz, A.E. Simsek, B. Tali[70], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
G. Karapinar[71], K. Ocalan[72], M. Yalvac[73]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[74], O. Kaya[75], S. Tekten[76]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[67], Y. Komurcu, S. Sen[67]

Istanbul University, Istanbul, Turkey
O. Aydilek, S. Cerci[70], B. Hacisahinoglu, I. Hos[77], B. Isildak[78], B. Kaynak, S. Ozkorucuklu, C. Simsek, D. Sunar Cerci[70]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
D. Anthony, E. Bhal, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[79], K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[80], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg[81], 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

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, C.E. Brown, O. Buchmuller, V. Cacchio, V. Cepaitis, G.S. Chahal[82], 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[83], 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

Brunel University, Uxbridge, United Kingdom
K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanu-

ganti, B. McMaster, M. Saunders, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA
S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio[84], C. West

Boston University, Boston, Massachusetts, 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

Brown University, Providence, Rhode Island, USA
G. Benelli, B. Burkle, X. Coubez[23], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[85], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, M. Narain, N. Pervan, S. Sagir[86], F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, California, 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, Los Angeles, California, 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, Riverside, Riverside, California, USA
R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, W. Si, S. Wimpenny

University of California, San Diego, La Jolla, California, 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, Santa Barbara - Department of Physics, Santa Barbara, California, 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

California Institute of Technology, Pasadena, California, USA
A. Bornheim, O. Cerri, I. Dutta, A. Latorre, J.M. Lawhorn, J. Mao, H.B. Newman, T. Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, 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

University of Colorado Boulder, Boulder, Colorado, 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

Cornell University, Ithaca, New York, 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

Fermi National Accelerator Laboratory, Batavia, Illinois, 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[87], F. Ravera, A. Reinsvold Hall[88], 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

University of Florida, Gainesville, Florida, USA
P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, R.D. Field, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, E. Kuznetsova[89], K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang, Z. Wu

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Askew, N. Bower, R. Habibullah, V. Hagopian, T. Kolberg, G. Martinez, H. Prosper, O. Viazlo, M. Wulansatiti, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA
M.M. Baarmand, S. Butalla, T. Elkafrawy[15], M. Hohlmann, R. Kumar Verma, M. Rahmani, F. Yumiceva

University of Illinois Chicago, Chicago, Illinois, 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

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, K. Dilsiz[90], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[91], J. Nachtman, O. Neogi, H. Ogul[92], Y. Onel, A. Penzo, C. Snyder, E. Tiras[93]

Johns Hopkins University, Baltimore, Maryland, 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

The University of Kansas, Lawrence, Kansas, 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, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, S. Duric, A. Ivanov, K. Kaadze, A. Kalogeropoulos, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam, D. Roy

Lawrence Livermore National Laboratory, Livermore, California, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, Maryland, 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

Massachusetts Institute of Technology, Cambridge, Massachusetts, 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

University of Minnesota, Minneapolis, Minnesota, 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 Mississippi, Oxford, Mississippi, USA
L.M. Cremaldi

University of Nebraska-Lincoln, Lincoln, Nebraska, 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

State University of New York at Buffalo, Buffalo, New York, USA
G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, M. Morris, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

Northeastern University, Boston, Massachusetts, 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

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

University of Notre Dame, Notre Dame, Indiana, 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[11], R. Ruchti, A. Townsend, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, 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

Princeton University, Princeton, New Jersey, USA
F.M. Addesa, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, G. Kopp, S. Kwan, D. Lange, D. Marlow, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, Indiana, 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[16], J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, Indiana, USA
J. Dolen, N. Parashar

Rice University, Houston, Texas, USA
D. Acosta, A. Baty, T. Carnahan, 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, S. Yang, E. Yigitbasi, L. Zhang[94], Y. Zhang

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, P. Parygin, E. Popova, E. Ranken, R. Taus, G.P. Van Onsem

The Rockefeller University, New York, New York, USA
K. Goulianos

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

University of Tennessee, Knoxville, Tennessee, USA
H. Acharya, A.G. Delannoy, S. Fiorendi, T. Holmes, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, USA
O. Bouhali[95], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[96], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

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

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

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

Wayne State University, Detroit, Michigan, USA
P.E. Karchin, N. Poudyal

University of Wisconsin - Madison, Madison, Wisconsin, 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

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, D. Budkouski, I. Golutvin, I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[97,98], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev[99], A. Zarubin, I. Zhizhin, G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[97], P. Levchenko, V. Murzin, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev, Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, I. Tlisova, A. Toropin, T. Aushev, V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[100], V. Popov, M. Toms, E. Vlasov, A. Zhokin, R. Chistov[97], M. Danilov[97], S. Polikarpov[97], D. Selivanova, V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov, A. Belyaev, E. Boos, A. Ershov, A. Gribushin, A. Kaminskiy, L. Khein, O. Kodolova, V. Korotkikh, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan, V. Blinov[97], T. Dimova[97], L. Kardapoltsev[97], A. Kozyrev[97], I. Ovtin[97], O. Radchenko[97], Y. Skovpen[97], V. Kachanov, D. Konstantinov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Borshch, E. Tcherniaev

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN
V. Chekhovsky, A. Litomin, V. Makarenko

†: Deceased
[1]Also at TU Wien, Vienna, Austria
[2]Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
[3]Also at Université Libre de Bruxelles, Bruxelles, Belgium
[4]Also at Universidade Estadual de Campinas, Campinas, Brazil
[5]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
[6]Also at UFMS, Nova Andradina, Brazil
[7]Also at University of Chinese Academy of Sciences, Beijing, China
[8]Also at Nanjing Normal University, Nanjing, China
[9]Now at The University of Iowa, Iowa City, Iowa, USA
[10]Also at University of Chinese Academy of Sciences, Beijing, China
[11]Also at an institute or an international laboratory covered by a cooperation agreement with CERN
[12]Also at Helwan University, Cairo, Egypt
[13]Now at Zewail City of Science and Technology, Zewail, Egypt
[14]Also at British University in Egypt, Cairo, Egypt

[15]Now at Ain Shams University, Cairo, Egypt
[16]Also at Purdue University, West Lafayette, Indiana, USA
[17]Also at Université de Haute Alsace, Mulhouse, France
[18]Also at Istinye University, Istanbul, Turkey
[19]Also at Ilia State University, Tbilisi, Georgia
[20]Also at The University of the State of Amazonas, Manaus, Brazil
[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 Institute of Physics, University of Debrecen, Debrecen, Hungary
[30]Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
[31]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[32]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[33]Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
[34]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[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 Università degli Studi Guglielmo Marconi, Roma, Italy
[51]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[52]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[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 Riga Technical University, Riga, Latvia
[56]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[57]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[58]Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[59]Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
[60]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka

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