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Observation of long-range collective flow in OO and NeNe collisions and implications for nuclear structure studies

The CMS Collaboration*

Abstract

The long-range collective flow of particles produced in oxygen-oxygen (OO) and neon-neon (NeNe) collisions is measured with the CMS detector at the CERN LHC. The data samples were collected at a center-of-mass energy per nucleon pair of 5.36 TeV, with integrated luminosities of 7 nb^{-1} and 0.8 nb^{-1} for OO and NeNe collisions, respectively. Two- and four-particle azimuthal correlations are measured over nearly five units of pseudorapidity. Significant elliptic (v_2) and triangular (v_3) flow harmonics are observed in both systems. The ratios of v_n coefficients between NeNe and OO collisions reveal sensitivity to quadrupole correlations in the nuclear wave functions. Hydrodynamic models with *ab initio* nuclear structure inputs qualitatively reproduce the collision-overlap dependence of both the v_n values and the NeNe to OO ratios. These measurements provide new constraints on hydrodynamic models for small collision systems and offer valuable input on the nuclear structure of ^{16}O and ^{20}Ne .

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Quantum chromodynamics predicts that nuclear matter undergoes a phase transition to a deconfined state of quarks and gluons, known as the quark-gluon plasma (QGP), at extreme temperatures and densities [1, 2]. A key feature of QGP formation is the presence of collective flow, which is characterized by strong correlations in the azimuthal (ϕ) distributions of particles produced over wide pseudorapidity (η) ranges in relativistic nucleus-nucleus collisions. These correlations are quantified through a Fourier decomposition into flow harmonics (v_n , where n is the order of the harmonic), which map the hydrodynamic response of the QGP to the initial collision geometry and its event-by-event fluctuations [3–5]. Experimental v_n results at the BNL RHIC [6–8] and CERN LHC [9–15] can be quantitatively described by hydrodynamic models of a nearly perfect fluid [16–18].

Over the past decade, similar flow-like signals have been observed in high-multiplicity proton-proton (pp) [19–23], proton-nucleus (pA) [15, 24–30], as well as in other collisions involving a light ion with a heavy ion [31–40]. These observations raise the question of whether QGP droplets are produced in small systems [41, 42]. Strong evidence of geometry-driven collective flow has been found in pA collisions [43, 44]. A key challenge in quantitatively describing the collective phenomena in pp and pA collisions is the strong dependence on the proton structure [40, 45]. In addition, pA collisions involve an asymmetric longitudinal geometry, further complicating the theoretical modeling [46, 47]. In contrast, symmetric collisions of light ions provide better control of the initial-state geometry, since it is determined primarily by the spatial distribution of nucleons rather than the partonic structure of the proton [48]. This makes symmetric light ion collisions ideal for the investigation of the final-state collective response in small collision systems.

Ultrarelativistic collisions of ions also offer a unique opportunity to probe nuclear structure. Collective flow measurements are sensitive to spatial correlations in the nuclear ground state, often described in terms of deformation effects [49–56]. Ion collisions provide a probe of the initial matter distribution, and have enabled extraction of the uranium nucleus quadrupole deformation [55]. The study of oxygen-oxygen (OO) and neon-neon (NeNe) collisions is particularly compelling because the two ions have similar mass numbers, leading to expectation of similar hydrodynamic evolution. Differences in their flow properties are therefore expected to primarily reflect differences in their nuclear structure. The ^{16}O and the ^{20}Ne nuclei are predicted to have tetrahedral and “bowling pin”-like intrinsic structures where nucleons may group into α -cluster configurations [57–63], each with two paired neutrons and two paired protons.

Hydrodynamic simulations with *ab initio* nuclear structure inputs, including nuclear lattice effective field theory, variational Monte Carlo, and extended quantum molecular dynamics simulations [64–66], predict that the NeNe to OO elliptic flow (v_2) ratio is directly sensitive to the exotic deformation of ^{20}Ne [48]. Thus, OO and NeNe collisions provide a unique opportunity not only to test to what extent collectivity in small systems is driven by initial geometry, but also to study the nuclear structure of these light ions.

This Letter presents measurements of collective flow in OO and NeNe collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{\text{NN}}} = 5.36$ TeV with the CMS detector at the LHC. The v_2 and v_3 harmonics are extracted from long-range, two-particle correlations over a large pseudorapidity range. The v_2 values are also determined from four-particle correlations with a different response to event-by-event geometry fluctuations than two-particle measurements. The harmonic values, measured for various overlap ranges, are compared to hydrodynamic models incorporating modern understanding of nuclear structure in their initial conditions. Tabulated results are provided in the HEPData record for this analysis [67]. During the final preparation of this Letter, the ATLAS and ALICE Collaborations submitted collective flow results in

OO and NeNe collisions at $\sqrt{s_{\text{NN}}} = 5.36$ TeV, obtained with different analysis techniques and phase-space coverage than used here [68, 69].

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, there are four subdetectors, including a silicon pixel and strip tracker detector, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Iron and quartz-fiber Cherenkov hadron forward (HF) calorimeters, which are subdivided into 0.175×0.175 ($\Delta\eta \times \Delta\phi$) towers, cover the pseudorapidity range $2.9 < |\eta| < 5.2$. The silicon tracker measures charged particles within the range $|\eta| < 3.0$. For charged particles with $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [70]. For the extended pseudorapidity range of charged particles with $|\eta| < 2.4$, the track resolutions are typically 2.5% in p_T and 30–200 (150–950) μm in the transverse (longitudinal) impact parameter. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [71, 72].

The OO and NeNe data were collected in July 2025 and correspond to integrated luminosities of 7 nb^{-1} and 0.8 nb^{-1} , respectively. The events were triggered by requiring one or more energy deposits of at least 7 GeV in either of the HF calorimeters. In the correlation analysis, an additional requirement is imposed that at least two towers have an energy deposit above 4 GeV in each of the HF calorimeters. The events are required to contain a single primary vertex [70] (located along the beam axis at z_{vtx}) that is within 15 cm of the nominal interaction point along the beam axis and 2 cm in the transverse plane. The requirement of only one primary vertex is used to avoid potential effects from multiple interactions in a single bunch crossing, i.e., pileup. The average number of interactions in a single bunch crossing is less than 0.26 (0.13) for OO (NeNe) collisions. Events are classified by collision centrality based on the sum of the total transverse momentum ($E_{\text{T, sum}}^{\text{HF}}$) deposited in the HF calorimeters [73]. The $E_{\text{T, sum}}^{\text{HF}}$ distribution is fitted by a Glauber-model-based calculation [74, 75] to determine the fraction of the total inelastic cross section above a given $E_{\text{T, sum}}^{\text{HF}}$ threshold. The fit starts from a minimum $E_{\text{T, sum}}^{\text{HF}}$ corresponding to 80% centrality, while the contamination due to electromagnetic and diffractive processes from the more peripheral region is studied as a contribution to the systematic uncertainties.

The analysis techniques for two- and multi-particle correlations follow Refs. [9, 10, 21, 24, 43, 76, 77]. The high-purity track selection criteria described in Ref. [70] are used to select primary tracks originating from the primary vertex. Additional requirements are also applied to enhance the purity of primary tracks. The significance of the separation along the beam axis (z) between the track and the primary vertex, $d_z/\sigma(d_z)$, and the significance of the impact parameter relative to the primary vertex transverse to the beam, $d_{xy}/\sigma(d_{xy})$, must be smaller than 3. In the two-particle analysis, for each centrality bin, “trigger” particles are defined as charged particles with $|\eta| < 2.4$ and $0.3 < p_T < 3$ GeV. The number of trigger particles in the event is denoted by N_{trig} . Particle pairs are then formed by associating each trigger particle with the remaining charged particles in the same range of $|\eta| < 2.4$ and $0.3 < p_T < 3$ GeV. The two-dimensional (2D) per-trigger-particle associated yield is defined as

$$\frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta d\Delta\phi} = B(0,0) \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}, \quad (1)$$

where N^{pair} is the number of particle pairs and $\Delta\eta$ ($\Delta\phi$) is the difference in η (ϕ) of the pair. The same-event pair distribution, $S(\Delta\eta, \Delta\phi)$, represents the yield of particle pairs normalized by N_{trig} from the same event. The mixed-event pair distribution, $B(\Delta\eta, \Delta\phi)$, is constructed by pairing the trigger particles in each event with the associated charged particles from 20 different,

randomly selected events in the same 0.5 cm wide z_{vtx} range and from the same centrality class. The ratio $B(0,0)/B(\Delta\eta, \Delta\phi)$ mainly accounts for the pair acceptance effects, with $B(0,0)$ representing the mixed-event associated yield for both particles of the pair going in approximately the same direction and thus having maximum pair acceptance. Each track is weighted by a correction factor derived from the HIJING v1.383 generator [78] with GEANT4 [79] used to simulate the CMS detector response, following the procedure described in Refs. [9, 10, 21, 24, 43, 76, 77]. The track weight accounts for detector effects that include the reconstruction efficiency, the detector acceptance, the fraction of misreconstructed tracks, and the secondary track contamination.

The azimuthal anisotropy harmonics of charged particles can be extracted via a Fourier decomposition of long-range two-particle $\Delta\phi$ correlation functions. These are obtained by averaging the 2D two-particle correlation function over $|\Delta\eta| > 2$ to remove short-range correlations, such as those from jet fragmentation or resonance decays, using

$$\frac{1}{N_{\text{trig}}} \frac{dN^{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi} \left[1 + \sum_n 2V_{n\Delta} \cos(n\Delta\phi) \right], \quad (2)$$

where $V_{n\Delta}$ are the Fourier coefficients and N_{assoc} represents the average number of pairs per trigger particle. The first four Fourier terms are included in the fits to the two-particle correlation functions. Including additional terms has a negligible effect on the results of the Fourier fit. Assuming that the $V_{n\Delta}$ coefficients can be factorized into the product of the single-particle anisotropies [76], the elliptic and triangular anisotropy harmonics, $v_2\{2, |\Delta\eta| > 2\}$ and $v_3\{2, |\Delta\eta| > 2\}$, of trigger particles can be extracted as $v_n = \sqrt{V_{n\Delta}}$.

The residual contributions of back-to-back dijet correlations to the measured v_n results are estimated using correlations from peripheral events, following exactly the procedure established in Refs. [22, 76]. The Fourier coefficients, $V_{n\Delta}$, extracted from events with 70–80% centrality are subtracted from those extracted from events with 0–50% centrality after accounting for the jet yield ratio of the selected events, assuming the jet shape does not change from peripheral to central collisions.

The multi-particle analysis is based on correlations among four particles and uses the Q -cumulant method [80], as previously done in proton-lead and lead-lead (PbPb) collisions [43, 76]. By simultaneously correlating four particles, the technique has the advantage of suppressing short-range, two-particle correlations arising from jets and resonance decays. The four-particle correlations also differ in their event-by-event geometry fluctuations response as compared to two-particle measurements. In the Q -cumulant analysis, two- and four-particle azimuthal correlations [80] are evaluated as

$$\begin{aligned} \langle\langle 2 \rangle\rangle &\equiv \langle\langle e^{in(\phi_1 - \phi_2)} \rangle\rangle \quad \text{and} \\ \langle\langle 4 \rangle\rangle &\equiv \langle\langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle\rangle, \end{aligned} \quad (3)$$

where ϕ_i ($i = 1, \dots, 4$) are the azimuthal angles of one unique combination of multiple particles in an event, n is the harmonic number, and $\langle\langle \dots \rangle\rangle$ represents the average over all combinations from all events within a given multiplicity range. The corresponding cumulants, $c_n\{4\}$, are calculated as $c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2$. The Fourier harmonics $v_n\{4\}$ are related to the cumulants using $v_n\{4\} = \sqrt[4]{-c_n\{4\}}$.

The systematic uncertainties in the v_n measurements are estimated by exploring the sensitivity of the results to the primary vertex position, by varying the track quality requirements, by estimating the effects from the centrality definition uncertainties, and by validating the v_n

extraction methods in simulated samples. To evaluate the uncertainties from the vertex dependent detector acceptance, the v_n values are extracted from events with $|z_{\text{vtx}}| < 3$ cm and with $3 < |z_{\text{vtx}}| < 15$ cm. Experimental systematic uncertainties due to track quality requirements are examined by varying the track selection thresholds for $d_z/\sigma(d_z)$ and $d_{xy}/\sigma(d_{xy})$ from 2 to 5. The systematic uncertainties in the centrality definition are studied by repeating the analysis with different higher and lower starting points for the Glauber fit to the HF $E_{T,\text{sum}}^{\text{HF}}$ distribution. The systematic uncertainties from the v_n extraction method are evaluated using the HIJING v1.383 [78] and AMPT [81] event generators to compare the v_n values of generator-level particles with those obtained after simulating the detector response using GEANT4 [79] and then applying the same analysis as done for the experimental data. Potential pileup effects are studied by comparing the reported results to those obtained using events where more than one reconstructed primary vertex is allowed. During the data taking, the O and Ne nuclei in the ion beams can fragment into lighter nuclei accompanied by electromagnetic radiation [82]. This transmutation accumulates as a function of the beam operating time. The effects from beam transmutation are found to be negligible by comparing results at the beginning and the end of collider beam fills [83]. The various sources of systematic uncertainties are added in quadrature to arrive at the final systematic uncertainties. For the $v_2\{2, |\Delta\eta| > 2\}$ results in OO and NeNe collisions, the systematic uncertainties are found to range from 1.1 to 1.5% and from 2.1 to 2.3%, respectively. The corresponding uncertainties for the $v_3\{2, |\Delta\eta| > 2\}$ results range from 1.8 to 4.5% and from 1.7 to 4.2% in OO and NeNe collisions, respectively. For the $v_2\{4\}$ results in OO collisions, a systematic uncertainty of 2.5% is obtained, while the corresponding uncertainties in NeNe collisions range from 2.1 to 2.3%. For the ratios of NeNe to OO v_n values, systematic uncertainties that are correlated between the two systems largely cancel. The systematic uncertainties for the ratios then range from 0.9 to 1.8% for $v_2\{2, |\Delta\eta| > 2\}$, from 1.1 to 1.7% for $v_3\{2, |\Delta\eta| > 2\}$, and from 0.9 to 1.1% for $v_2\{4\}$. The total systematic uncertainties of the measurements are found to decrease from peripheral to central collisions.

The $v_2\{2, |\Delta\eta| > 2\}$, $v_3\{2, |\Delta\eta| > 2\}$, and $v_2\{4\}$ results as functions of centrality in OO and NeNe collisions at $\sqrt{s_{\text{NN}}} = 5.36$ TeV are shown in Fig. 1. Dot-dashed lines indicate the results after correcting for dijet correlations. This correction decreases from peripheral to central collisions, reducing the $v_2\{2, |\Delta\eta| > 2\}$ and $v_3\{2, |\Delta\eta| > 2\}$ values by 4 to 15%.

The $v_2\{2, |\Delta\eta| > 2\}$ values increase from peripheral to mid-central collisions and then decrease in the most central events, similarly to those in PbPb collisions [84], reflecting the initial geometry of the overlapping region and the hydrodynamic response of the system. The $v_3\{2, |\Delta\eta| > 2\}$ values increase toward central collisions. While this trend differs from that observed in PbPb collisions over a wider centrality range, it is consistent with the peripheral PbPb results where the system size is comparable [44]. The rise of v_3 toward more central OO and NeNe collisions is therefore attributed to having a stronger hydrodynamic response as the overlap volume increases, rather than reflecting a fundamentally different pattern of initial-state fluctuations [75]. The $v_2\{4\}$ values are systematically smaller than the $v_2\{2, |\Delta\eta| > 2\}$ values across the shown centrality range. This is expected because of different contributions to $v_2\{2, |\Delta\eta| > 2\}$ and $v_2\{4\}$ from the event-by-event geometry fluctuations [85].

Model calculations are also shown in Fig. 1. The “TRAJECTUM” hydrodynamic framework [86, 87] uses two *ab initio* nuclear structure models, calculated with nuclear lattice effective field theory (NLEFT) [66, 88, 89] and with the projected generator coordinate method (PGCM) [90, 91], to determine the spatial configurations of nucleons within the O and Ne nuclei. The initial energy densities are generated with Trento [92] and evolved with the TRAJECTUM hydrodynamic framework. The NLEFT-based calculations reproduce $v_2\{2, |\Delta\eta| > 2\}$ in central collisions better than PGCM, while both agree with data in more peripheral events. Both models describe

the $v_3\{2, |\Delta\eta| > 2\}$ results across the measured centrality range. The “IP-Glasma” model integrates PGCM into IP-Glasma with JIMWLK evolution [93], followed by MUSIC hydrodynamics [94] and UrQMD hadronic interactions [95]. It tends to overpredict the $v_2\{2, |\Delta\eta| > 2\}$ and $v_3\{2, |\Delta\eta| > 2\}$ values in central collisions, but agrees with data within uncertainties in more peripheral events. These comparisons demonstrate that precise v_n measurements strongly constrain both the initial-state geometry and hydrodynamic response in small systems.

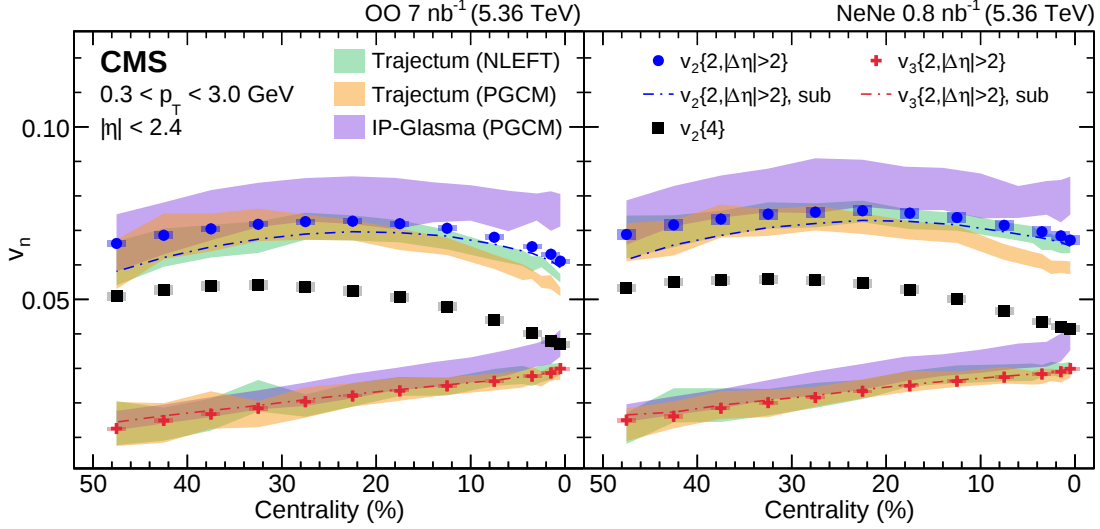


Figure 1: The $v_2\{2, |\Delta\eta| > 2\}$, $v_3\{2, |\Delta\eta| > 2\}$ and $v_2\{4\}$ values for charged particles with $0.3 < p_T < 3.0$ GeV and $|\eta| < 2.4$ are shown as functions of centrality in OO (left) and NeNe (right) collisions at $\sqrt{s_{NN}} = 5.36$ TeV. The $v_2\{2, |\Delta\eta| > 2\}$ and $v_3\{2, |\Delta\eta| > 2\}$ results after subtracting the dijet correlations (denoted as “sub”) are indicated by the dot-dashed lines. Statistical uncertainties are smaller than the markers. The shaded boxes denote systematic uncertainties. Model calculations [48, 93] are shown for comparison to the two-particle correlation results, where the bands represent the combined statistical and systematic uncertainties.

To isolate initial-geometry effects, the ratios of NeNe to OO v_n values are shown in Fig. 2. The results remain consistent, within uncertainties, before and after correcting for dijet correlations. A significant rise of the v_2 ratios from two- and four-particle correlations is observed for the most central collisions, while the v_3 ratios from two-particle correlations exhibit a decreasing trend, which is most pronounced in central events. Unlike the conclusions reached when examining individual v_n values, the Trajectum PGCM calculations reproduce the v_2 ratios more closely, while the NLEFT version tends to overestimate them. Both frameworks qualitatively capture the observed increase towards central events, consistent with the expectations based on a deformed geometry of ^{20}Ne [48]. A quantitative determination of the deformation, however, requires further dedicated studies, since the agreement with data is not uniform across the measured centrality range. None of the three model calculations reproduce the measured v_3 ratios quantitatively, highlighting the need for an improved treatment of initial-state fluctuations in small systems. The IP-Glasma calculations predict a weaker centrality dependence of the v_2 ratio, likely a result of large multiplicity fluctuations that reduce the correlation between centrality and impact parameter [93]. Overall, the precise v_n ratios provide stringent constraints on the modeling of nuclear structure and its implementation in initial-state frameworks, while underscoring the sensitivity of collective flow to the underlying geometry.

In summary, the azimuthal anisotropy of charged-particle emission is measured in oxygen-oxygen (OO) and neon-neon (NeNe) collisions at a center-of-mass energy per nucleon pair of

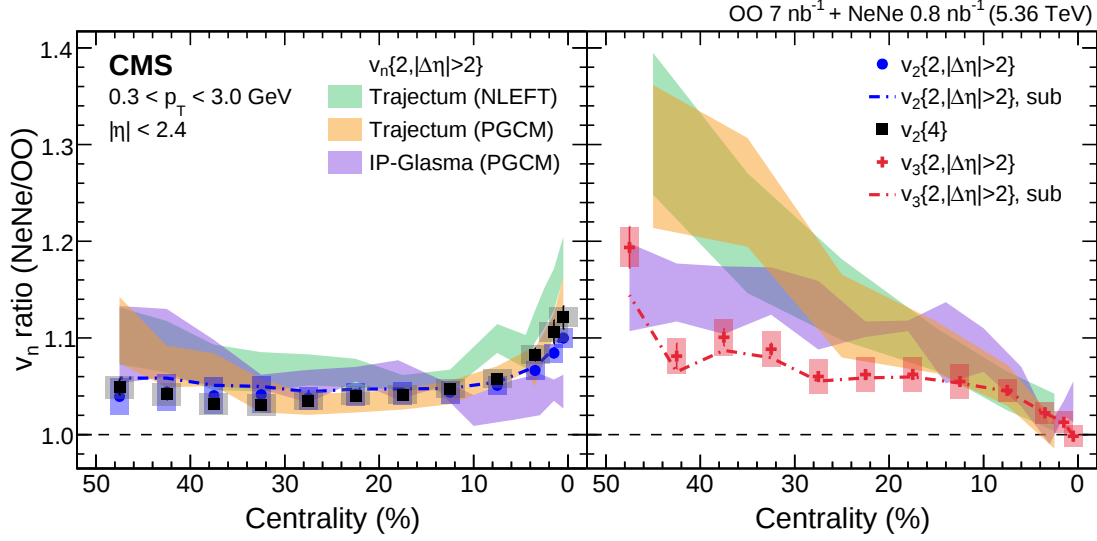


Figure 2: Ratios of $v_2\{2, |\Delta\eta| > 2\}$, $v_2\{4\}$ (left), and $v_3\{2, |\Delta\eta| > 2\}$ (right) of NeNe to OO collisions as functions of centrality. Dot-dashed lines indicate results after subtracting (denoted as “sub”) the dijet correlations. Vertical bars denote statistical uncertainties, and shaded boxes denote systematic uncertainties. Model calculations [48, 93] are shown for comparison to the two-particle correlation results, where the bands represent the combined statistical and systematic uncertainties.

5.36 TeV with the CMS detector. The elliptic (v_2) and triangular (v_3) flow harmonics are extracted from two-particle correlations with a large pseudorapidity gap for multiple centrality ranges, as defined by the fraction of the total inelastic cross section, from 50% (peripheral) to 0% (central) collisions. The v_2 values are also found using four-particle correlations to highlight how event-by-event geometry fluctuations influence the results. The v_2 values rise from peripheral to mid-central events and decrease toward the most central collisions, and the v_3 values increase monotonically, reflecting hydrodynamic response to the initial geometry. The ratios of the NeNe and OO v_n values further isolate initial-geometry effects, with the v_2 ratio increasing strongly toward central collisions, qualitatively consistent with the ^{20}Ne nucleus being deformed. The v_3 ratio is found to decrease from peripheral to the most central collisions. Hydrodynamic models with *ab initio* nuclear structure inputs capture the qualitative trends of both the v_n values and their respective NeNe to OO ratios, although they fail to fully describe the v_n magnitude. These results establish the sensitivity of collective flow in light ion collisions to both the initial geometry and the hydrodynamic medium response. They provide stringent constraints on models of small-system collectivity and offer valuable input to theoretical nuclear structure calculations.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, V. Makarenko , A. Tumasyan¹ 

Institut für Hochenergiephysik, Vienna, Austria

W. Adam , L. Benato , T. Bergauer , M. Dragicevic , C. Giordano, P.S. Hussain , M. Jeitler² , N. Krammer , A. Li , D. Liko , M. Matthewman, J. Schieck² , R. Schöfbeck² , M. Shooshtari , M. Sonawane , W. Waltenberger , C.-E. Wulz² 

Universiteit Antwerpen, Antwerpen, Belgium

T. Janssen , H. Kwon , D. Ocampo Henao , T. Van Laer , P. Van Mechelen 

Vrije Universiteit Brussel, Brussel, Belgium

J. Bierkens , N. Breugelmans, J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , F. Heyen, Y. Hong , P. Kashko , S. Lowette , I. Makarenko , D. Müller , J. Song , S. Tavernier , M. Tytgat³ , G.P. Van Onsem , S. Van Putte , D. Vannerom 

Université Libre de Bruxelles, Bruxelles, Belgium

B. Bilin , B. Clerbaux , A.K. Das, I. De Bruyn , G. De Lentdecker , H. Evard , L. Favart , P. Gianneios , A. Khalilzadeh, F.A. Khan , A. Malara , M.A. Shahzad, A. Sharma , L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer , F. Zhang 

Ghent University, Ghent, Belgium

M. De Coen , D. Dobur , G. Gokbulut , D. Marckx , K. Skovpen , A.M. Tomaru, N. Van Den Bossche , J. van der Linden , J. Vandenbroeck , L. Wezenbeek 

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

H. Aarup Petersen , S. Bein , A. Benecke , A. Bethani , G. Bruno , A. Cappati , J. De Favereau De Jeneret , C. Delaere , F. Gameiro Casalinho , A. Giammanco , A.O. Guzel , V. Lemaitre, J. Lidrych , P. Malek , P. Mastrapasqua , S. Turcpar 

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves , M. Barroso Ferreira Filho , E. Coelho , C. Hensel , D. Matos Figueiredo , T. Menezes De Oliveira , C. Mora Herrera , P. Rebello Teles , M. Soeiro , E.J. Tonelli Manganote⁴ , A. Vilela Pereira 

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

W.L. Aldá Júnior , H. Brandao Malbouisson , W. Carvalho , J. Chinellato⁵ , M. Costa Reis , E.M. Da Costa , G.G. Da Silva⁶ , D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza , S. S. Jesus , T. Laux Kuhn⁶ , M. Macedo , K. Mota Amarilo , L. Mundim , H. Nogima , J.P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel , F. Torres Da Silva De Araujo⁷ 

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

C.A. Bernardes⁶ , L. Calligaris , F. Damas , T.R. Fernandez Perez Tomei , E.M. Gregores , B. Lopes Da Costa , I. Maietto Silverio , P.G. Mercadante , S.F. Novaes , B. Orzari , Sandra S. Padula , V. Scheurer

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

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

University of Sofia, Sofia, BulgariaA. Dimitrov , L. Litov , B. Pavlov , P. Petkov , A. Petrov **Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile**S. Keshri , D. Laroze , S. Thakur **Universidad Tecnica Federico Santa Maria, Valparaiso, Chile**W. Brooks **Beihang University, Beijing, China**T. Cheng , T. Javaid , L. Wang , L. Yuan **Department of Physics, Tsinghua University, Beijing, China**Z. Hu , Z. Liang, J. Liu, X. Wang , H. Yang**Institute of High Energy Physics, Beijing, China**G.M. Chen⁸ , H.S. Chen⁸ , M. Chen⁸ , Y. Chen , Q. Hou , X. Hou, F. Iemmi , C.H. Jiang, H. Liao , G. Liu , Z.-A. Liu⁹ , J.N. Song⁹, S. Song, J. Tao , C. Wang⁸, J. Wang , H. Zhang , J. Zhao **State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**A. Agapitos , Y. Ban , A. Carvalho Antunes De Oliveira , S. Deng , B. Guo, Q. Guo, C. Jiang , A. Levin , C. Li , Q. Li , Y. Mao, S. Qian, S.J. Qian , X. Qin, C. Quaranta , X. Sun , D. Wang , J. Wang, M. Zhang, Y. Zhao, C. Zhou **State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou, China**S. Yang **Sun Yat-Sen University, Guangzhou, China**Z. You **University of Science and Technology of China, Hefei, China**K. Jaffel , N. Lu **Nanjing Normal University, Nanjing, China**G. Bauer^{10,11}, Z. Cui¹¹, B. Li¹², H. Wang , K. Yi¹³ , J. Zhang **Institute of Frontier and Interdisciplinary Science, Shandong University, Qingdao, China**Z. Chen **Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China**Y. Li, J. Peng, Y. Zhou¹⁴**Zhejiang University, Hangzhou, Zhejiang, China**Z. Lin , C. Lu , M. Xiao¹⁵ **Universidad de Los Andes, Bogota, Colombia**C. Avila , D.A. Barbosa Trujillo , A. Cabrera , C. Florez , J. Fraga , J.A. Reyes Vega**Universidad de Antioquia, Medellin, Colombia**C. Rendón , M. Rodriguez , A.A. Ruales Barbosa , J.D. Ruiz Alvarez **University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**N. Godinovic , D. Lelas , A. Sculac 

University of Split, Faculty of Science, Split, Croatia

M. Kovac , A. Petkovic , T. Sculac 

Institute Rudjer Boskovic, Zagreb, Croatia

P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , K. Jakovcic, A. Starodumov ,
T. Susa 

University of Cyprus, Nicosia, Cyprus

A. Attikis , K. Christoforou , S. Konstantinou , C. Leonidou , L. Paizanos ,
F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepenov 

Charles University, Prague, Czech Republic

M. Finger[†] , M. Finger Jr. 

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

Y. Assran^{16,17}, B. El-mahdy¹⁸ 

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

A. Hussein, H. Mohammed 

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

M. Kadastik, T. Lange , C. Nielsen , J. Pata , M. Raidal , N. Seeba , L. Tani 

Department of Physics, University of Helsinki, Helsinki, Finland

E. Brücken , A. Milieva , K. Osterberg , M. Voutilainen 

Helsinki Institute of Physics, Helsinki, Finland

F. Garcia , P. Inkaew , K.T.S. Kallonen , R. Kumar Verma , T. Lampén , K. Lassila-Perini , B. Lehtela , S. Lehti , T. Lindén , N.R. Mancilla Xinto , M. Myllymäki ,
M.m. Rantanen , S. Saariokari , N.T. Toikka , J. Tuominiemi 

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

N. Bin Norjoharuddeen , H. Kirschenmann , P. Luukka , H. Petrow 

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

M. Besancon , F. Couderc , M. Dejardin , D. Denegri, P. Devouge, J.L. Faure , F. Ferri ,
P. Gagne, S. Ganjour , P. Gras , G. Hamel de Monchenault , M. Kumar , V. Lohezic ,
Y. Maidannyk , J. Malcles , F. Orlandi , L. Portales , S. Ronchi , M.Ö. Sahin ,
A. Savoy-Navarro¹⁹ , P. Simkina , M. Titov , M. Tornago 

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

R. Amella Ranz , F. Beaudette , G. Boldrini , P. Busson , C. Charlot , M. Chiusi ,
T.D. Cuisset , O. Davignon , A. De Wit , T. Debnath , I.T. Ehle , S. Ghosh ,
A. Gilbert , R. Granier de Cassagnac , L. Kalipoliti , M. Manoni , M. Nguyen ,
S. Obraztsov , C. Ochando , R. Salerno , J.B. Sauvan , Y. Sirois , G. Sokmen,
L. Urda Gómez , A. Zabi , A. Zghiche 

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

J.-L. Agram²⁰, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, G. Coulon, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, P. Vaucelle

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

A. Di Florio

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

D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourdain, M. Lethuillier, B. Massoteau, L. Mirabito, A. Purohit, M. Vander Donckt, J. Xiao

Georgian Technical University, Tbilisi, Georgia

G. Adamov, I. Lomidze, Z. Tsamalaidze²¹

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

V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, P. Nattland, V. Oppenländer, A. Pauls, D. Pérez Adán, N. Röwert

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

C. Daumann, S. Diekmann, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, N. Kumar, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, A. Pozdnyakov, W. Redjeb, H. Reithler, U. Sarkar, V. Sarkisovi, A. Schmidt, C. Seth, A. Sharma, J.L. Spah, V. Vaulin, S. Zaleski

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

M.R. Beckers, C. Dziwok, G. Flügge, N. Hoeflich, T. Kress, A. Nowack, O. Pooth, A. Stahl, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany

A. Abel, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, I. Andreev, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman²², K. Borras²³, A. Campbell, S. Chatterjee, L.X. Coll Saravia, G. Eckerlin, D. Eckstein, E. Gallo²², A. Geiser, M. Guthoff, A. Hinzmann, L. Jeppe, M. Kase-mann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Per-nia, K.-Y. Lin, K. Lipka²⁴, W. Lohmann²⁵, J. Malvaso, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, A.B. Meyer, G. Milella, K. Moral Figueroa, A. Mussgiller, L.P. Nair, J. Niedziela, A. Nürnberg, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, L. Rygaard, M. Scham^{26,23}, S. Schnake²³, P. Schütze, C. Schwanenberger²², D. Schwarz, D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, M. Torkian, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, K. Wich-mann, L. Wiens²³, C. Wissing, Y. Yang, S. Zakharov, A. Zimmermann Castro Santos

University of Hamburg, Hamburg, Germany

A.R. Alves Andrade, M. Antonello, S. Bollweg, M. Bonanomi, L. Ebeling, K. El Morabit, Y. Fischer, M. Frahm, E. Garutti, A. Grohsjean, A.A. Guvenli, J. Haller, D. Hundhausen, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, F. Labe, J. Lange, A. Lobanov, J. Matthiesen, L. Moureaux, K. Nikolopoulos, A. Paasch, K.J. Pena Rodriguez, N. Prouvost, B. Raciti, M. Rieger, D. Savoia, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie

G. Steinbrück , R. Ward , B. Wiederspan, M. Wolf , C. Yede 

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , A. Brusamolino , E. Butz , Y.M. Chen , T. Chwalek , A. Dierlamm , G.G. Dincer , D. Druzhkin , U. Elicabuk, N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann²⁷ , M. Horzela , F. Hummer , U. Husemann , J. Kieseler , M. Klute , J. Knolle , R. Kunnilan Muhammed Rafeek, O. Lavoryk , J.M. Lawhorn , A. Lintuluoto , S. Maier , A.A. Monsch , M. Mormile , Th. Müller , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , R. Schmieder, N. Shadskiy , I. Shvetsov , H.J. Simonis , L. Sowa , L. Stockmeier, K. Tauqeer, M. Toms , B. Topko , N. Trevisani , C. Verstege , T. Voigtländer , R.F. Von Cube , J. Von Den Driesch, M. Wassmer , C. Winter, R. Wolf , W.D. Zeuner , X. Zuo 

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

G. Anagnostou , G. Daskalakis , A. Kyriakis 

National and Kapodistrian University of Athens, Athens, Greece

G. Melachroinos, Z. Painesis , I. Paraskevas , N. Saoulidou , K. Theofilatos , E. Tziaferi , E. Tzovara , K. Vellidis , I. Zisopoulos 

National Technical University of Athens, Athens, Greece

T. Chatzistavrou , G. Karapostoli , K. Kousouris , E. Siamarkou, G. Tsipolitis 

University of Ioánnina, Ioánnina, Greece

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

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

C. Hajdu , D. Horvath^{28,29} , K. Márton, A.J. Rádl³⁰ , F. Sikler , V. Veszpremi 

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

M. Csanád , K. Farkas , A. Fehérkuti³¹ , M.M.A. Gadallah³² , Á. Kadlecik , M. León Coello , G. Pásztor , G.I. Veres 

Faculty of Informatics, University of Debrecen, Debrecen, Hungary

B. Ujvari , G. Zilizi 

HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

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

T. Csorgo³¹ , F. Nemes³¹ , T. Novak , I. Szanyi³³ 

IIT Bhubaneswar, Bhubaneswar, India

S. Bahinipati , S. Nayak, R. Raturi

Panjab University, Chandigarh, India

S. Bansal , S.B. Beri, V. Bhatnagar , S. Chauhan , N. Dhingra³⁴ , A. Kaur , H. Kaur , M. Kaur , S. Kumar , T. Sheokand, J.B. Singh , A. Singla 

University of Delhi, Delhi, India

A. Bhardwaj , A. Chhetri , B.C. Choudhary , A. Kumar , A. Kumar , M. Naimuddin , S. Phor , K. Ranjan , M.K. Saini

Indian Institute of Technology Mandi (IIT-Mandi), Himachal Pradesh, IndiaP. Palni **University of Hyderabad, Hyderabad, India**S. Acharya³⁵ , B. Gomber **Indian Institute of Technology Kanpur, Kanpur, India**S. Mukherjee **Saha Institute of Nuclear Physics, HBNI, Kolkata, India**S. Bhattacharya , S. Das Gupta, S. Dutta , S. Dutta, S. Sarkar**Indian Institute of Technology Madras, Madras, India**M.M. Ameen , P.K. Behera , S. Chatterjee , G. Dash , A. Dattamunsi, P. Jana , P. Kalbhor , S. Kamble , J.R. Komaragiri³⁶ , T. Mishra , P.R. Pujahari , A.K. Sikdar , R.K. Singh , P. Verma , S. Verma , A. Vijay **IISER Mohali, India, Mohali, India**

B.K. Sirasva

Tata Institute of Fundamental Research-A, Mumbai, IndiaL. Bhatt, S. Dugad , G.B. Mohanty , M. Shelake , P. Suryadevara**Tata Institute of Fundamental Research-B, Mumbai, India**A. Bala , S. Banerjee , S. Barman³⁷ , R.M. Chatterjee, M. Guchait , Sh. Jain , A. Jaiswal, S. Kumar , M. Maity³⁷, G. Majumder , K. Mazumdar , S. Parolia , R. Saxena , A. Thachayath **National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India**D. Maity³⁸ , P. Mal , K. Naskar³⁸ , A. Nayak³⁸ , K. Pal , P. Sadangi, S.K. Swain , S. Varghese³⁸ , D. Vats³⁸ **Indian Institute of Science Education and Research (IISER), Pune, India**S. Dube , P. Hazarika , B. Kansal , A. Laha , R. Sharma , S. Sharma , K.Y. Vaish **Indian Institute of Technology Hyderabad, Telangana, India**S. Ghosh **Isfahan University of Technology, Isfahan, Iran**H. Bakhshiansohi³⁹ , A. Jafari⁴⁰ , V. Sedighzadeh Dalavi , M. Zeinali⁴¹ **Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**S. Bashiri , S. Chenarani⁴² , S.M. Etesami , Y. Hosseini , M. Khakzad , E. Khazaie , M. Mohammadi Najafabadi , S. Tizchang⁴³ **University College Dublin, Dublin, Ireland**M. Felcini , M. Grunewald **INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy**M. Abbrescia^{a,b} , M. Barbieri^{a,b}, M. Buonsante^{a,b} , A. Colaleo^{a,b} , D. Creanza^{a,c} , N. De Filippis^{a,c} , M. De Palma^{a,b} , W. Elmetenawee^{a,b,44} , N. Ferrara^{a,c} , L. Fiore^a , L. Generoso^{a,b}, L. Longo^a , M. Louka^{a,b} , G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^a , V. Mastrapasqua^{a,b} , S. My^{a,b} , F. Nenna^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b} , A. Pompili^{a,b} , G. Pugliese^{a,c} , R. Radogna^{a,b} , D. Ramos^a , A. Ranieri^a , L. Silvestris^a , F.M. Simone^{a,c} , Ü. Sözbilir^a , A. Stamerra^{a,b} , D. Troiano^{a,b} 

R. Venditti^{a,b} , P. Verwilligen^a , A. Zaza^{a,b} 

INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy

G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , P. Capiluppi^{a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} , G.M. Dallavalle^a , T. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , R. Farinelli^a , P. Giacomelli^a , C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,45} , M. Lorusso^{a,b} , L. Lunerti^a , S. Marcellini^a , F.L. Navarria^{a,b} , G. Paggi^{a,b} , A. Perrotta^a , A.M. Rossi^{a,b} , S. Rossi Tisbeni^{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,46} , A. Di Mattia^a , A. Lapertosa^a , R. Potenza^{a,b} , A. Tricomi^{a,b,46} 

INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

J. Altork^{a,b} , P. Assiouras^a , G. Barbagli^a , G. Bardelli^a , M. Bartolini^{a,b} , A. Calandri^{a,b} , B. Camaiani^{a,b} , A. Cassese^a , R. Ceccarelli^a , V. Ciulli^{a,b} , C. Civinini^a , R. D'Alessandro^{a,b} , L. Damenti^{a,b} , E. Focardi^{a,b} , T. Kello^a , G. Latino^{a,b} , P. Lenzi^{a,b} , M. Lizzo^a , M. Meschini^a , S. Paoletti^a , A. Papanastassiou^{a,b} , G. Sguazzoni^a , L. Viliani^a 

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , S. Meola⁴⁷ , D. Piccolo 

INFN Sezione di Genova^a, Università di Genova^b, Genova, Italy

M. Alves Gallo Pereira^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 , F. Brivio^a , V. Camagni^{a,b} , F. Cetorelli^{a,b} , F. De Guio^{a,b} , M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , R. Gerosa^{a,b} , A. Ghezzi^{a,b} , P. Govoni^{a,b} , L. Guzzi^a , M.R. Kim^a , G. Lavizzari^{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} , S. Palluotto^{a,b} , D. Pedrini^a , A. Perego^{a,b} , G. Pizzati^{a,b} , T. Tabarelli de Fatis^{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 , C. Di Fraia^{a,b} , F. Fabozzi^{a,c} , L. Favilla^{a,d} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,48} , P. Paolucci^{a,27} , B. Rossi^a 

INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy; Università degli Studi di Cagliari^c, Cagliari, Italy

P. Azzi^a , N. Bacchetta^{a,49} , D. Bisello^{a,b} , L. Borella^a , P. Bortignon^{a,c} , G. Bortolato^{a,b} , A.C.M. Bulla^{a,c} , P. Checchia^a , T. Dorigo^{a,50} , F. Fanzago^a , F. Gasparini^{a,b} , U. Gasparini^{a,b} , S. Giorgetti^a , E. Lusiani^a , M. Margoni^{a,b} , A.T. Meneguzzo^{a,b} , J. Pazzini^{a,b} , F. Primavera^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , F. Simonetto^{a,b} , M. Tosi^{a,b} , A. Triossi^{a,b} , S. Ventura^a , M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b} 

INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

A. Braghieri^a , S. Calzaferri^{a,b} , P. Montagna^{a,b} , M. Pelliccioni^{a,b} , V. Re^a , C. Riccardi^{a,b} , P. Salvini^a , I. Vai^{a,b} , P. Vitulo^{a,b} 

INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy

S. Ajmal^{a,b} , M.E. Ascoti^{a,b} , G.M. Bilei^a , C. Carrivale^{a,b} , D. Ciangottini^{a,b} , L. Della Penna^{a,b} , L. Fanò^{a,b} , V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,51} , 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

C. Aimè^{a,b} , C.A. Alexe^{a,c} , P. Asenov^{a,b} , P. Azzurri^a , G. Bagliesi^a , L. Bianchini^{a,b} , T. Boccali^a , E. Bossini^a , D. Bruschini^{a,c} , R. Castaldi^a , F. Cattafesta^{a,c} , M.A. Ciocci^{a,d} , M. Cipriani^{a,b} , R. Dell'Orso^a , S. Donato^{a,b} , R. Forti^{a,b} , A. Giassi^a , F. Ligabue^{a,c} , A.C. Marini^{a,b} , A. Messineo^{a,b} , S. Mishra^a , V.K. Muraleedharan Nair Bindhu^{a,b} , S. Nandan^a , F. Palla^a , M. Riggirello^{a,c} , A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^{a,52} , T. Sarkar^a , A. Scribano^a , P. Solanki^{a,b} , P. Spagnolo^a , F. Tenchini^{a,b} , R. Tenchini^a , G. Tonelli^{a,b} , N. Turini^{a,d} , F. Vaselli^{a,c} , A. Venturi^a , P.G. Verdini^a 

INFN Sezione di Roma^a, Sapienza Università di Roma^b, Roma, Italy

P. Akrap^{a,b} , C. Basile^{a,b} , S.C. Behera^a , F. Cavallari^a , L. Cunqueiro Mendez^{a,b} , F. De Ruggi^{a,b} , D. Del Re^{a,b} , E. Di Marco^a , M. Diemoz^a , F. Errico^a , L. Frosina^{a,b} , R. Gargiulo^{a,b} , B. Harikrishnan^{a,b} , F. Lombardi^{a,b} , E. Longo^{a,b} , L. Martikainen^{a,b} , J. Mijuskovic^{a,b} , G. Organtini^{a,b} , N. Palmeri^{a,b} , R. Paramatti^{a,b} , S. Rahatlou^{a,b} , C. Rovelli^a , F. Santanastasio^{a,b} , L. Soffi^a , V. Vladimirov^{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,c} , R. Bellan^{a,b} , A. Bellora^{a,b} , C. Biino^a , C. Borca^{a,b} , N. Cartiglia^a , M. Costa^{a,b} , R. Covarelli^{a,b} , N. Demaria^a , L. Finco^a , M. Grippio^{a,b} , B. Kiani^{a,b} , L. Lanteri^{a,b} , F. Legger^a , F. Luongo^{a,b} , C. Mariotti^a , S. Maselli^a , A. Mecca^{a,b} , L. Menzio^{a,b} , P. Meridiani^a , E. Migliore^{a,b} , M. Monteno^a , M.M. Obertino^{a,b} , G. Ortona^a , L. Pacher^{a,b} , N. Pastrone^a , M. Ruspà^{a,c} , F. Siviero^{a,b} , V. Sola^{a,b} , A. Solano^{a,b} , A. Staiano^a , C. Tarricone^{a,b} , D. Trocino^a , G. Umoret^{a,b} , E. Vlasov^{a,b} , R. White^{a,b} 

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

J. Babbar^{a,b,52} , S. Belforte^a , V. Candelise^{a,b} , M. Casarsa^a , F. Cossutti^a , K. De Leo^a , G. Della Ricca^{a,b} , R. Delli Gatti^{a,b} 

Kyungpook National University, Daegu, Korea

S. Dogra , J. Hong , J. Kim, T. Kim , D. Lee, H. Lee , J. Lee, S.W. Lee , C.S. Moon , Y.D. Oh , S. Sekmen , B. Tae, Y.C. Yang 

Department of Mathematics and Physics - GWNu, Gangneung, Korea

M.S. Kim 

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

G. Bak , P. Gwak , H. Kim , D.H. Moon , J. Seo 

Hanyang University, Seoul, Korea

E. Asilar , F. Carnevali , J. Choi⁵³ , T.J. Kim , Y. Ryou 

Korea University, Seoul, Korea

S. Ha , S. Han, B. Hong , J. Kim , K. Lee, K.S. Lee , S. Lee , J. Yoo 

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh , J. Shin , S. Yang 

Sejong University, Seoul, Korea

Y. Kang , H. S. Kim , Y. Kim , B. Ko, S. Lee

Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi , J. Choi, W. Jun , H. Kim , J. Kim , T. Kim, Y. Kim, Y.W. Kim , S. Ko , H. Lee , J. Lee , J. Lee , B.H. Oh , J. Shin , U.K. Yang, I. Yoon 

University of Seoul, Seoul, Korea

W. Jang , D.Y. Kang, D. Kim , S. Kim , J.S.H. Lee , Y. Lee , I.C. Park , Y. Roh, I.J. Watson 

Yonsei University, Department of Physics, Seoul, Korea

G. Cho, K. Hwang , B. Kim , S. Kim, K. Lee , H.D. Yoo 

Sungkyunkwan University, Suwon, Korea

Y. Lee , I. Yu 

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

T. Beyrouthy , Y. Gharbia 

Kuwait University - College of Science - Department of Physics, Safat, Kuwait

F. Alazemi 

Riga Technical University, Riga, Latvia

K. Dreimanis , O.M. Eberlins , A. Gaile , C. Munoz Diaz , D. Osite , G. Pikurs , R. Plese , A. Potrebko , M. Seidel , D. Sidiropoulos Kontos 

University of Latvia (LU), Riga, Latvia

N.R. Strautnieks 

Vilnius University, Vilnius, Lithuania

M. Ambrozias , A. Juodagalvis , S. Nargelas , A. Rinkevicius , G. Tamulaitis 

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

I. Yusuff⁵⁴ , Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez , A. Castaneda Hernandez , A. Cota Rodriguez , L.E. Cuevas Picos, H.A. Encinas Acosta, L.G. Gallegos Maríñez, J.A. Murillo Quijada , L. Valencia Palomo 

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

G. Ayala , H. Castilla-Valdez , H. Crotte Ledesma , R. Lopez-Fernandez , J. Mejia Guisao , R. Reyes-Almanza , A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera , D.L. Ramirez Guadarrama, M. Ramírez García 

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bautista , F.E. Neri Huerta , I. Pedraza , H.A. Salazar Ibarguen , C. Uribe Estrada 

University of Montenegro, Podgorica, Montenegro

I. Bujanja , N. Raicevic 

University of Canterbury, Christchurch, New Zealand

P.H. Butler 

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

A. Ahmad , M.I. Asghar , A. Awais , M.I.M. Awan, W.A. Khan 

AGH University of Krakow, Krakow, Poland

V. Avati, L. Forthomme , L. Grzanka , M. Malawski , K. Piotrkowski 

National Centre for Nuclear Research, Swierk, Poland

M. Bluj , 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 , A. Muhammad 

Warsaw University of Technology, Warsaw, Poland

P. Fokow , K. Pozniak , W. Zabolotny 

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

M. Araujo , D. Bastos , C. Beirão Da Cruz E Silva , A. Boletti , M. Bozzo , T. Camporesi , G. Da Molin , M. Gallinaro , J. Hollar , N. Leonardo , G.B. Marozzo , A. Petrilli , M. Pisano , J. Seixas , J. Varela , J.W. Wulff 

Faculty of Physics, University of Belgrade, Belgrade, Serbia

P. Adzic , L. Markovic , P. Milenovic , V. Milosevic 

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

D. Devetak , M. Dordevic , J. Milosevic , L. Nadderd , V. Rekovic , M. Stojanovic 

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

M. Alcalde Martinez , J. Alcaraz Maestre , Cristina F. Bedoya , J.A. Brochero Cifuentes , Oliver M. Carretero , M. Cepeda , M. Cerrada , N. Colino , B. De La Cruz , A. Delgado Peris , A. Escalante Del Valle , D. Fernández Del Val , J.P. Fernández Ramos , J. Flix , M.C. Fouz , M. Gonzalez Hernandez , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , J. Llorente Merino , C. Martin Perez , E. Martin Viscasilas , D. Moran , C. M. Morcillo Perez , Á. Navarro Tobar , R. Paz Herrera , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , J. Vazquez Escobar 

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. Ayllon Torresano , A. Cardini , J. Cuevas , J. Del Riego Badas , D. Estrada Acevedo , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , P. Leguina , M. Obeso Menendez , E. Palencia Cortezon , J. Prado Pico , A. Soto Rodríguez , P. Vischia 

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

S. Blanco Fernández , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez , G. Gomez , C. Lasasoa García , R. Lopez Ruiz , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , E. Navarrete Ramos , J. Piedra Gomez , C. Quintana San Emeterio , L. Scodellaro , I. Vila , R. Vilar Cortabitarte , J.M. Vizán García 

University of Colombo, Colombo, Sri Lanka

B. Kailasapathy⁵⁵ , D.D.C. Wickramarathna 

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

W.G.D. Dharmaratna⁵⁶ , K. Liyanage , N. Perera 

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , C. Amendola , R. Ardino , E. Auffray , J. Baechler, D. Barney , J. Bendavid , M. Bianco , A. Bocci , L. Borgonovi , C. Botta , A. Bragagnolo , C.E. Brown , C. Caillol , G. Cerminara , P. Connor , K. Cormier , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , P.J. Fernández Manteca , B.A. Fontana Santos Alves , E. Fontanesi , W. Funk , A. Gaddi, S. Giani, D. Gigi, K. Gill , F. Glege , M. Glowacki, A. Gruber , J. Hegeman , J.K. Heikkilä , R. Hofsaess , B. Huber , T. James , P. Janot , O. Kaluzinska , O. Karacheban²⁵ , G. Karathanasis , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , A.-M. Lyon , M. Magherini , L. Malgeri , M. Mannelli , A. Mehta , F. Meijers , J.A. Merlin, S. Mersi , E. Meschi , M. Migliorini , F. Monti , F. Moortgat , M. Mulders , M. Musich , I. Neutelings , S. Orfanelli, F. Pantaleo , M. Pari , G. Petrucciani , A. Pfeiffer , M. Pierini , M. Pitt , H. Qu , D. Rabady , A. Reimers , B. Ribeiro Lopes , F. Riti , P. Rosado , M. Rovere , H. Sakulin , R. Salvatico , S. Sanchez Cruz , S. Scarfi , M. Selvaggi , K. Shchelina , P. Silva , P. Sphicas⁵⁷ , A.G. Stahl Leiton , A. Steen , S. Summers , D. Treille , P. Tropea , E. Vernazza , J. Wanczyk⁵⁸ , S. Wuchterl , M. Zarucki , P. Zehetner , P. Zejdl , G. Zevi Della Porta 

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland

T. Bevilacqua⁵⁹ , L. Caminada⁵⁹ , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , U. Langenegger , A. Nigamova , L. Noehte⁵⁹ , T. Rohe , A. Samalan 

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

T.K. Aarrestad , M. Backhaus , G. Bonomelli , C. Cazzaniga , K. Datta , P. De Bryas Dexmiers D'Archiacchiac⁵⁸ , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Glessgen , C. Grab , N. Härringer , T.G. Harte , W. Lustermann , M. Malucchi , R.A. Manzoni , L. Marchese , A. Mascellani⁵⁸ , F. Nessi-Tedaldi , F. Pauss , B. Ristic , R. Seidita , J. Steggemann⁵⁸ , A. Tarabini , D. Valsecchi , R. Wallny 

Universität Zürich, Zurich, Switzerland

C. Amsler⁶⁰ , P. Bäertschi , F. Bilandzija , M.F. Canelli , G. Celotto , V. Guglielmi , A. Jofrehei , B. Kilminster , T.H. Kwok , S. Leontsinis , V. Lukashenko , A. Macchiolo , F. Meng , M. Missiroli , J. Motta , P. Robmann, E. Shokr , F. Stäger , R. Tramontano , P. Viscone 

National Central University, Chung-Li, Taiwan

D. Bhowmik, C.M. Kuo, P.K. Rout , S. Taj , P.C. Tiwari³⁶ 

National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, K.F. Chen , Z.g. Chen, A. De Iorio , W.-S. Hou , T.h. Hsu, Y.w. Kao, S. Karmakar , G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , X.f. Su , J. Thomas-Wilsker , L.s. Tsai, D. Tsionou, H.y. Wu , E. Yazgan 

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

C. Asawatrangkuldee , N. Srimanobhas 

Tunis El Manar University, Tunis, Tunisia

Y. Maghrbi 

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

D. Agyel , F. Dolek , I. Dumanoglu⁶¹ , Y. Guler⁶² , E. Gurbinar Guler⁶² , C. Isik 

O. Kara⁶³ , A. Kayis Topaksu , Y. Komurcu , G. Onengut , K. Ozdemir⁶⁴ , B. Tali⁶⁵ ,
U.G. Tok , E. Uslan , I.S. Zorbakir 

Hacettepe University, Ankara, Turkey

S. Sen 

Middle East Technical University, Physics Department, Ankara, Turkey

M. Yalvac⁶⁶ 

Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi⁶⁷ , E. Gülmez , M. Kaya⁶⁸ , O. Kaya⁶⁹ , M.A. Sarkisla⁷⁰,
S. Tekten⁷¹ 

Istanbul Technical University, Istanbul, Turkey

D. Boncukcu , A. Cakir , K. Cankocak^{61,72} 

Istanbul University, Istanbul, Turkey

B. Haciosahinoglu , I. Hos⁷³ , B. Kaynak , S. Ozkorucuklu , O. Potok , H. Sert ,
C. Simsek , C. Zorbilmez 

Yildiz Technical University, Istanbul, Turkey

S. Cerci , C. Dozen⁷⁴ , B. Isildak , E. Simsek , D. Sunar Cerci , T. Yetkin⁷⁴ 

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

A. Boyaryntsev , O. Dadazhanova, B. Grynyov 

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

L. Levchuk 

University of Bristol, Bristol, United Kingdom

J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , D. Dharmender,
H. Flacher , J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Parames-
varan , L. Robertshaw, M.S. Sanjrani³⁹, J. Segal, V.J. Smith 

Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell , A. Belyaev⁷⁵ , C. Brew , R.M. Brown , D.J.A. Cockerill ,
A. Elliot , K.V. Ellis, J. Gajownik , K. Harder , S. Harper , J. Linacre , K. Manolopoulos,
M. Moallemi , D.M. Newbold , E. Olaiya , D. Petyt , T. Reis , A.R. Sahasransu ,
G. Salvi , T. Schuh, C.H. Shepherd-Themistocleous , I.R. Tomalin , K.C. Whalen ,
T. Williams 

Imperial College, London, United Kingdom

I. Andreou , R. Bainbridge , P. Bloch , O. Buchmuller, C.A. Carrillo Montoya ,
D. Colling , I. Das , P. Dauncey , G. Davies , M. Della Negra , S. Fayer, G. Fedi ,
G. Hall , H.R. Hoorani , A. Howard, G. Iles , C.R. Knight , P. Krueper , J. Langford ,
K.H. Law , J. León Holgado , L. Lyons , A.-M. Magnan , B. Maier , S. Mallios,
A. Mastronikolis , M. Mieskolainen , J. Nash⁷⁶ , M. Pesaresi , P.B. Pradeep ,
B.C. Radburn-Smith , A. Richards, A. Rose , L. Russell , K. Savva , C. Seez ,
R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , T. Virdee²⁷ , M. Vojinovic ,
N. Wardle , D. Winterbottom 

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, Texas, USA

S. Abdullin , A. Brinkerhoff , E. Collins , M.R. Darwish , J. Dittmann , K. Hatakeyama , V. Hegde , J. Hiltbrand , B. McMaster , J. Samudio , S. Sawant , C. Sutantawibul , J. Wilson 

Bethel University, St. Paul, Minnesota, USA

J.M. Hogan 

Catholic University of America, Washington, DC, USA

R. Bartek , A. Dominguez , S. Raj , B. Sahu³⁵ , A.E. Simsek , S.S. Yu 

The University of Alabama, Tuscaloosa, Alabama, USA

B. Bam , A. Buchot Perraguin , S. Campbell, R. Chudasama , S.I. Cooper , C. Crovella , G. Fidalgo , S.V. Gleyzer , A. Khukhunaishvili , K. Matchev , E. Pearson, P. Rumerio⁷⁷ , E. Usai , R. Yi 

Boston University, Boston, Massachusetts, USA

S. Cholak , G. De Castro, Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , J. Fulcher , F. Golf , S. Jeon , J. O'Cain, I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , E. Wurtz, A.G. Zecchinelli 

Brown University, Providence, Rhode Island, USA

G. Barone , G. Benelli , D. Cutts , S. Ellis , L. Gouskos , M. Hadley , U. Heintz , K.W. Ho , T. Kwon , L. Lambrecht , G. Landsberg , K.T. Lau , J. Luo , S. Mondal , J. Roloff, T. Russell , S. Sagir⁷⁸ , X. Shen , M. Stamenkovic , N. Venkatasubramanian 

University of California, Davis, Davis, California, USA

S. Abbott , S. Baradia , B. Barton , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez , E. Cannaert, M. Chertok , M. Citron , J. Conway , P.T. Cox , F. Eble , R. Erbacher , O. Kukral , G. Mocellin , S. Ostrom , I. Salazar Segovia, J.S. Tafoya Vargas , W. Wei , S. Yoo 

University of California, Los Angeles, California, USA

K. Adamidis, M. Bachtis , D. Campos, R. Cousins , S. Crossley , G. Flores Avila , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , Y.f. Lo , E. Manca , A. Nunez Del Prado , D. Saltzberg , V. Valuev 

University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , G. Hanson 

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

A. Aportela , A. Arora , J.G. Branson , S. Cittolin , S. Cooperstein , B. D'Anzi , D. Diaz , J. Duarte , L. Giannini , Y. Gu, J. Guiang , V. Krutelyov , R. Lee , J. Letts , H. Li, M. Masciovecchio , F. Mokhtar , S. Mukherjee , M. Pieri , D. Primosch, M. Quinnan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , A. Yagil , Z. Zhao

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

A. Barzdukas , L. Brennan , C. Campagnari , S. Carron Montero⁷⁹ , K. Downham , C. Grieco , M.M. Hussain, J. Incandela , M.W.K. Lai, A.J. Li , P. Masterson , J. Richman , S.N. Santpur , R. Schmitz , D. Stuart , T.Á. Vámi , X. Yan , D. Zhang 

California Institute of Technology, Pasadena, California, USA

A. Albert , S. Bhattacharya , A. Bornheim , O. Cerri, R. Kansal , J. Mao , H.B. Newman , G. Reales Gutiérrez, T. Sievert, M. Spiropulu , J.R. Vlimant , R.A. Wynne , S. Xie 

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison , S. An , M. Cremonesi , V. Dutta , E.Y. Ertorer , T. Ferguson , T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil , M. Kanemura , C. Liu , M. Marchegiani , P. Meiring , S. Murthy , P. Palit , K. Park , M. Paulini , A. Roberts , A. Sanchez , W. Terrill 

University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat , W.T. Ford , A. Hart , S. Kwan , J. Pearkes , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper , D. Zuolo 

Cornell University, Ithaca, New York, USA

J. Alexander , X. Chen , J. Dickinson , A. Duquette , J. Fan , X. Fan , J. Grassi , S. Hogan , P. Kotamnives , J. Monroy , G. Niendorf , M. Oshiro , J.R. Patterson , A. Ryd , J. Thom , P. Wittich , R. Zou , L. Zygala 

Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , O. Amram , 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 , C. Cosby , G. Cummings , I. Dutta , V.D. Elvira , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green , A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , J. Hirschauer , V. Innocente , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , B. Klima , S. Lammel , C. Lee , D. Lincoln , R. Lipton , T. Liu , K. Maeshima , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁰ , C.E. Perez Lara , V. Perovic , F. Ravera , A. Reinsvold Hall⁸¹ , L. Ristori , M. Safdari , E. Sexton-Kennedy , E. Smith , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , C. Wang , I. Zoi 

University of Florida, Gainesville, Florida, USA

C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field , C. Huh , E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , V. Sulimov , Y. Takahashi , J. Wang 

Florida State University, Tallahassee, Florida, USA

T. Adams , A. Al Kadhimi , A. Askew , S. Bower , R. Goff , R. Hashmi , A. Hassani , R.S. Kim , T. Kolberg , G. Martinez , M. Mazza , H. Prosper , P.R. Prova , R. Yohay 

Florida Institute of Technology, Melbourne, Florida, USA

B. Alsufyani , S. Butalla , S. Das , M. Hohlmann , M. Lavinsky , E. Yanes 

University of Illinois Chicago, Chicago, Illinois, USA

M.R. Adams , N. Barnett , A. Baty , C. Bennett , R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , H. Gupta , M. Hawksworth , A. Hingrajiya , D.J. Hofman , Z. Huang , J.h. Lee , C. Mills , S. Nanda , G. Nigmatkulov , B. Ozek , T. Phan , D. Pilipovic , R. Pradhan , E. Prifti , P. Roy , T. Roy , D. Shekar , N. Singh , A. Thielen , M.B. Tonjes , N. Varelas , M.A. Wadud , J. Yoo 

The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini , D. Blend , K. Dilsiz⁸² , O.K. Köseyan , A. Mestvirishvili⁸³ , O. Neogi , H. Ogul⁸⁴ , Y. Onel , A. Penzo , C. Snyder , E. Tiras⁸⁵ 

Johns Hopkins University, Baltimore, Maryland, USA

B. Blumenfeld , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , S. Sekhar , M.V. Srivastav , M. Swartz 

The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , R. Bhattacharya , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , S. Popescu⁸⁶ , C. Rogan , C. Royon , S. Rudrabhatla , S. Sanders , C. Smith , G. Wilson 

Kansas State University, Manhattan, Kansas, USA

B. Allmond , N. Islam , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , G.G. Reddy , D. Roy , G. Sorrentino 

University of Maryland, College Park, Maryland, USA

A. Baden , A. Belloni , J. Bistany-riebman , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim , S. Lascio , P. Major , A.C. Mignerey , C. Palmer , C. Papageorgakis , M.M. Paranjpe , E. Popova⁸⁷ , A. Shevelev , L. Zhang 

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

C. Baldenegro Barrera , H. Bossi , S. Bright-Thonney , I.A. Cali , Y.c. Chen , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov , G. Grosso , P. Harris , D. Hoang , G.M. Innocenti , K. Ivanov , D. Kovalskiy , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long , C. McGinn , A. Novak , M.I. Park , C. Paus , C. Reissel , C. Roland , G. Roland , S. Rothman , T.a. Sheng , G.S.F. Stephans , D. Walter , J. Wang , Z. Wang , B. Wyslouch , T. J. Yang 

University of Minnesota, Minneapolis, Minnesota, USA

A. Alpina , B. Crossman , W.J. Jackson , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi , R. Rusack , O. Sancar , R. Saradhy , N. Strobbe 

University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , K.H.M. Kwok , A. Rohilla , J.E. Siado , W. Tabb , A. Vagnerini , A. Wightman , F. Yan 

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

H. Bandyopadhyay , L. Hay , H.w. Hsia , I. Iashvili , A. Kalogeropoulos , A. Kharchilava , A. Mandal , M. Morris , D. Nguyen , S. Rappoccio , H. Rejeb Sfar , A. Williams , D. Yu 

Northeastern University, Boston, Massachusetts, USA

A. Aarif , G. Alverson , E. Barberis , J. Bonilla , B. Bylsma , M. Campana , J. Dervan , Y. Haddad , Y. Han , I. Israr , A. Krishna , M. Lu , N. Manganelli , R. McCarthy , D.M. Morse , T. Orimoto , L. Skinnari , C.S. Thoreson , E. Tsai , D. Wood 

Northwestern University, Evanston, Illinois, USA

S. Dittmer , K.A. Hahn , M. McGinnis , Y. Miao , D.G. Monk , M.H. Schmitt , A. Taliercio , M. Velasco , J. Wang 

University of Notre Dame, Notre Dame, Indiana, USA

G. Agarwal , R. Band , R. Bucci , S. Castells , A. Das , A. Datta , A. Ehnis , R. Goldouzian , M. Hildreth , K. Hurtado Anampa , T. Ivanov , C. Jessop , A. Karneyeu , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano , N. Marinelli , T. McCauley , C. Mcgrady , C. Moore , Y. Musienko²¹ , H. Nelson 

M. Osherson , A. Piccinelli , R. Ruchti , A. Townsend , Y. Wan, M. Wayne , H. Yockey

The Ohio State University, Columbus, Ohio, USA

M. Carrigan , R. De Los Santos , L.S. Durkin , C. Hill , M. Joyce , D.A. Wenzl, B.L. Winer , B. R. Yates 

Princeton University, Princeton, New Jersey, USA

H. Bouchamaoui , G. Dezoort , P. Elmer , A. Frankenthal , M. Galli , B. Greenberg , N. Haubrich , K. Kennedy, G. Kopp , Y. Lai , D. Lange , A. Loeliger , D. Marlow , I. Ojalvo , J. Olsen , F. Simpson , D. Stickland , C. Tully 

University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik , R. Sharma 

Purdue University, West Lafayette, Indiana, USA

S. Chandra , A. Gu , L. Gutay, M. Huwiler , M. Jones , A.W. Jung , D. Kondratyev , J. Li , M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov , N.R. Saha , J.F. Schulte , F. Wang , A. Wildridge , W. Xie , Y. Yao , Y. Zhong 

Purdue University Northwest, Hammond, Indiana, USA

N. Parashar , A. Pathak , E. Shumka 

Rice University, Houston, Texas, USA

D. Acosta , A. Agrawal , C. Arbour , T. Carnahan , P. Das , K.M. Ecklund , F.J.M. Geurts , T. Huang , I. Krommydas , N. Lewis, W. Li , J. Lin , C. Loizides , O. Miguel Colin , B.P. Padley , R. Redjimi , J. Rotter , C. Vico Villalba , M. Wulansatiti , E. Yigitbasi , Y. Zhang 

University of Rochester, Rochester, New York, USA

O. Bessidskaia Bylund, A. Bodek , P. de Barbaro[†] , R. Demina , A. Garcia-Bellido , H.S. Hare , O. Hindrichs , N. Parmar , P. Parygin⁸⁷ , H. Seo , R. Taus 

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

B. Chiarito, J.P. Chou , S.V. Clark , S. Donnelly, D. Gadkari , Y. Gershtein , E. Halkiadakis , C. Houghton , D. Jaroslawski , A. Kobert , I. Laflotte , A. Lath , J. Martins , M. Perez Prada , B. Rand , J. Reichert , P. Saha , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora 

University of Tennessee, Knoxville, Tennessee, USA

D. Ally , A.G. Delannoy , S. Fiorendi , J. Harris, T. Holmes , A.R. Kanuganti , N. Karunarathna , J. Lawless, L. Lee , E. Nibigira , B. Skipworth, S. Spanier 

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

D. Aebi , M. Ahmad , T. Akhter , K. Androsov , A. Basnet , A. Bolshov, O. Bouhali⁸⁸ , A. Cagnotta , V. D'Amante , R. Eusebi , P. Flanagan , J. Gilmore , Y. Guo, T. Kamon , S. Luo , R. Mueller , A. Safonov 

Texas Tech University, Lubbock, Texas, USA

N. Akchurin , J. Damgov , Y. Feng , N. Gogate , W. Jin , Y. Kazhykarim, K. Lamichhane , S.W. Lee , C. Madrid , A. Mankel , T. Peltola , I. Volobouev 

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt , Y. Chen , S. Greene, A. Gurrola , W. Johns , R. Kunnawalkam Elayavalli , A. Melo , D. Rathjens , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen , J. Zhang

University of Virginia, Charlottesville, Virginia, USA

B. Cardwell , H. Chung , B. Cox , J. Hakala , G. Hamilton Ilha Machado, R. Hirosky , M. Jose, A. Ledovsky , C. Mantilla , C. Neu , C. Ramón Álvarez , Z. Wu

Wayne State University, Detroit, Michigan, USA

S. Bhattacharya , P.E. Karchin 

University of Wisconsin - Madison, Madison, Wisconsin, USA

A. Aravind , S. Banerjee , K. Black , T. Bose , E. Chavez , S. Dasu , P. Everaerts , C. Galloni, H. He , M. Herndon , A. Herve , C.K. Koraka , S. Lomte , R. Loveless , A. Mallampalli , A. Mohammadi , S. Mondal, T. Nelson, G. Parida , L. Pétré , D. Pinna , A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi , W. Vetens , A. Warden 

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

S. Afanasiev , V. Alexakhin , Yu. Andreev , T. Aushev , D. Budkouski , R. Chistov , M. Danilov , T. Dimova , A. Ershov , S. Gninenko , I. Gorbunov , A. Gribushin , A. Kamenev , V. Karjavine , M. Kirsanov , V. Klyukhin , O. Kodolova⁸⁹ , V. Koronkov , I. Korsakov, A. Kozyrev , N. Krasnikov , A. Lanev , A. Malakhov , V. Matveev , A. Nikitenko^{90,89} , V. Palichik , V. Pereygin , S. Petrushanko , O. Radchenko , M. Savina , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen , K. Slizhevskiy, V. Smirnov , O. Teryaev , I. Tlisoa , A. Toropin , N. Voytishin , A. Zarubin , I. Zhizhin 

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN

E. Boos , V. Bunichev , M. Dubinin⁸⁰ , V. Savrin , A. Snigirev , L. Dudko , V. Kim²¹ , V. Murzin , V. Oreshkin , D. Sosnov 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

³Also at Ghent University, Ghent, Belgium

⁴Also at FACAMP - Faculdades de Campinas, Sao Paulo, Brazil

⁵Also at Universidade Estadual de Campinas, Campinas, Brazil

⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁷Also at The University of the State of Amazonas, Manaus, Brazil

⁸Also at University of Chinese Academy of Sciences, Beijing, China

⁹Also at University of Chinese Academy of Sciences, Beijing, China

¹⁰Also at School of Physics, Zhengzhou University, Zhengzhou, China

¹¹Now at Henan Normal University, Xinxiang, China

¹²Also at University of Shanghai for Science and Technology, Shanghai, China

¹³Also at The University of Iowa, Iowa City, Iowa, USA

¹⁴Also at Nanjing Normal University, Nanjing, China

¹⁵Also at Center for High Energy Physics, Peking University, Beijing, China

¹⁶Also at Suez University, Suez, Egypt

¹⁷Now at British University in Egypt, Cairo, Egypt

¹⁸Also at Cairo University, Cairo, Egypt

¹⁹Also at Purdue University, West Lafayette, Indiana, USA

²⁰Also at Université de Haute Alsace, Mulhouse, France

²¹Also at an institute formerly covered by a cooperation agreement with CERN

²²Also at University of Hamburg, Hamburg, Germany

- ²³Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ²⁴Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- ²⁵Also at Brandenburg University of Technology, Cottbus, Germany
- ²⁶Also at Forschungszentrum Jülich, Jülich, Germany
- ²⁷Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ²⁸Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
- ²⁹Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- ³⁰Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- ³¹Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
- ³²Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ³³Also at The University of Kansas, Lawrence, Kansas, USA
- ³⁴Also at Punjab Agricultural University, Ludhiana, India
- ³⁵Also at University of Hyderabad, Hyderabad, India
- ³⁶Also at Indian Institute of Science (IISc), Bangalore, India
- ³⁷Also at University of Visva-Bharati, Santiniketan, India
- ³⁸Also at Institute of Physics, Bhubaneswar, India
- ³⁹Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴⁰Also at Isfahan University of Technology, Isfahan, Iran
- ⁴¹Also at Sharif University of Technology, Tehran, Iran
- ⁴²Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴³Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
- ⁴⁴Also at Helwan University, Cairo, Egypt
- ⁴⁵Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴⁶Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁴⁷Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁴⁸Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁴⁹Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵⁰Also at Lulea University of Technology, Lulea, Sweden
- ⁵¹Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵²Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
- ⁵³Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
- ⁵⁴Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁵Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁶Also at Saegis Campus, Nugegoda, Sri Lanka
- ⁵⁷Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁵⁸Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁵⁹Also at Universität Zürich, Zurich, Switzerland
- ⁶⁰Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶¹Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶²Also at Konya Technical University, Konya, Turkey
- ⁶³Also at Istanbul Topkapi University, Istanbul, Turkey
- ⁶⁴Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁵Also at Adiyaman University, Adiyaman, Turkey
- ⁶⁶Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey

-
- ⁶⁷Also at Istanbul Sabahattin Zaim University, Istanbul, Turkey
- ⁶⁸Also at Marmara University, Istanbul, Turkey
- ⁶⁹Also at Milli Savunma University, Istanbul, Turkey
- ⁷⁰Also at Informatics and Information Security Research Center, Gebze/Kocaeli, Turkey
- ⁷¹Also at Kafkas University, Kars, Turkey
- ⁷²Now at Istanbul Okan University, Istanbul, Turkey
- ⁷³Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁴Also at Istinye University, Istanbul, Turkey
- ⁷⁵Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁷⁶Also at Monash University, Faculty of Science, Clayton, Australia
- ⁷⁷Also at Università di Torino, Torino, Italy
- ⁷⁸Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- ⁷⁹Also at California Lutheran University,, Thousand Oaks, California, USA
- ⁸⁰Also at California Institute of Technology, Pasadena, California, USA
- ⁸¹Also at United States Naval Academy, Annapolis, Maryland, USA
- ⁸²Also at Bingol University, Bingol, Turkey
- ⁸³Also at Georgian Technical University, Tbilisi, Georgia
- ⁸⁴Also at Sinop University, Sinop, Turkey
- ⁸⁵Also at Erciyes University, Kayseri, Turkey
- ⁸⁶Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
- ⁸⁷Now at another institute formerly covered by a cooperation agreement with CERN
- ⁸⁸Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar
- ⁸⁹Also at Yerevan Physics Institute, Yerevan, Armenia
- ⁹⁰Also at Imperial College, London, United Kingdom