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Multiparticle correlation studies in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$

The CMS Collaboration*

Abstract

The second- and third-order azimuthal anisotropy Fourier harmonics of charged particles produced in pPb collisions, at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$, are studied over a wide range of event multiplicities. Multiparticle correlations are used to isolate global properties stemming from the collision overlap geometry. The second-order “elliptic” harmonic moment is obtained with high precision through four-, six-, and eight-particle correlations and, for the first time, the third-order “triangular” harmonic moment is studied using four-particle correlations. A sample of peripheral PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ that covers a similar range of event multiplicities as the pPb results is also analyzed. Model calculations of initial-state fluctuations in pPb and PbPb collisions can be directly compared to the high precision experimental results. This work provides new insight into the fluctuation-driven origin of the v_3 coefficients in pPb and PbPb collisions, and into the dominating overall collision geometry in PbPb collisions at the earliest stages of heavy ion interactions.

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1 Introduction

In collisions of ultra relativistic heavy ions, two-particle azimuthal correlations between the large number of particles created over a broad range in pseudorapidity, were first observed in gold–gold and copper–copper collisions at the BNL RHIC [1–4], and have subsequently been studied in lead–lead (PbPb) collisions at the CERN LHC [5–11]. These correlations are thought to reflect the collective motion of a strongly interacting and expanding medium with quark and gluon degrees of freedom, namely, the quark-gluon plasma [12]. The observed azimuthal correlation structure can be characterized by Fourier harmonics, with the second (v_2) and third (v_3) harmonics referred to as “elliptic” and “triangular” flow, respectively. Within a hydrodynamic picture, the Fourier harmonics are related to the initial geometry of the colliding system and provide insight into the transport properties of the produced medium [13–15]. Fluctuations can also arise from the discrete substructure of the interaction region at the parton level [16, 17] and can have a significant effect on the observed higher-order harmonic coefficients.

Two-particle azimuthal correlations, which are long-range in pseudorapidity, are also found in small systems for collisions leading to high final-state particle densities. At the LHC, long-range correlations have been observed in proton–proton (pp) [18–20] and proton–lead (pPb) [21–24] collisions. Similar results have been obtained at RHIC in studies of deuteron–gold, proton–gold, and helium-3–gold collisions [25–28]. The origin of the long-range correlations in systems involving only a small number of participating nucleons is still under active discussion [29]. One possibility is that fluctuation-driven asymmetries in the initial-state nucleon locations within the overlap region are transferred to the final-state particle distributions through the hydrodynamic evolution of an expanding plasma [30–32]. Alternatively, it has been proposed that the observed behavior arises from the transfer of initial-state gluon correlations to the produced particles [33–35].

Studies of azimuthal correlations in small systems using two or more particles, as achieved through the use of a multiparticle cumulant expansion [36], show that the pp [37] and pPb [38] systems develop similar collective behavior to that found in heavier systems [39]. The cumulants quantify an n th order contribution of the azimuthal correlation that is irreducible to lower-order correlations. By requiring correlations among multiple particles, correlations that are not related to a bulk property of the medium, such as back-to-back jet correlations and resonance decays, are strongly suppressed [40]. The v_n harmonics based on different orders of the multiparticle expansion provide information on the event-by-event fluctuation of the observed anisotropy [41]. Previous v_2 multiparticle cumulant results for pPb collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\text{NN}}} = 5.02$ TeV suggest a direct correlation of the final-state asymmetry with the initial-state eccentricity of the participating nucleons [38, 42]. The v_3 harmonic is expected to be dominated by fluctuations in the initial-state geometry. The multiparticle correlations of the v_3 harmonic are then expected to reflect these fluctuations. An earlier multiparticle correlation measurement by the ATLAS Collaboration has found evidence for a finite v_3 harmonic amplitude in the pPb system [43]. With precise measurements of the v_2 and v_3 multiparticle cumulants, it becomes possible to make direct comparison of calculations based on eccentricity fluctuations in the initial-state geometry to the higher-order moments of the fluctuation distributions. The measurements provide key input for models that explore the hydrodynamic expansion of the medium [44, 45], as well as for models that propose that final-state asymmetries in light systems arise from partons scattering off localized domains of color charge in the initial state [34]. In the hydrodynamic picture, the v_2 and v_3 values are dominated by fluctuations in pPb collisions. In PbPb collisions, the v_2 value is dominated by the lenticular shape of the overlap geometry, while the v_3 value is dominated by initial-state fluctuations of the nucleon locations [16].

In this work, the results from pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV are studied with a significant improvement in the precision of the v_2 results compared to the earlier measurements at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. For the first time, the v_3 harmonic is determined by multiparticle correlations. The pPb results are also compared to those found for PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV to explore the dependence on the overlap geometry. The ratios between the four-particle and two-particle v_n values provide information on the relative importance of the global geometry and the fluctuation-driven asymmetries [46]. These ratios are explored for both the v_2 and v_3 harmonics and are compared between the pPb and PbPb systems.

2 Experimental setup and data sample

The CMS detector comprises a number of subsystems [47]. The results in this paper are mainly based on the silicon tracker information. The silicon tracker, located in the 3.8 T field of a superconducting solenoid, consists of 1 440 silicon pixel and 15 148 silicon strip detector modules. The silicon tracker measures charged particles within the laboratory pseudorapidity range $|\eta| < 2.5$, and provides an impact parameter resolution of $\approx 15 \mu\text{m}$ and a transverse momentum (p_{T}) resolution better than 1.5% up to 100 GeV/c [47]. The electromagnetic (ECAL) and hadron (HCAL) calorimeters are also located inside the solenoid and cover the pseudorapidity range $|\eta| < 3.0$. The HCAL barrel and endcaps are sampling calorimeters composed of brass and scintillator plates. The ECAL consists of lead tungstate crystals arranged in a quasi-projective geometry. Iron and quartz-fiber Čerenkov hadron forward (HF) calorimeters cover the range $3.0 < |\eta| < 5.2$ on either side of the interaction region. These HF calorimeters are azimuthally subdivided into 20° modular wedges and further segmented to form 0.175×0.175 rad ($\Delta\eta \times \Delta\phi$) cells. The ECAL and HCAL cells are grouped to form “towers.” The detailed Monte Carlo (MC) simulation of the CMS detector response is based on GEANT4 [48].

The analysis is performed using data recorded by CMS during the LHC pPb run in 2016 and corresponds to an integrated luminosity of 186 nb^{-1} [49]. The beam energies were 6.5 TeV for protons and 2.56 TeV per nucleon for lead nuclei, resulting in $\sqrt{s_{\text{NN}}} = 8.16$ TeV. The beam directions were reversed during the run allowing a check of potential detector related systematic uncertainties. No significant differences were detected and the merged results are reported. The nucleon-nucleon center-of-mass in the pPb collisions is not at rest with respect to the laboratory frame because of the energy difference between the colliding particles. Massless particles emitted at $\eta_{\text{cm}} = 0$ in the nucleon-nucleon center-of-mass frame will be detected at $\eta = -0.465$ (clockwise proton beam) or 0.465 (counterclockwise proton beam) in the laboratory frame. In this paper, an unsubscripted η symbol is used to denote the laboratory frame pseudorapidity. A sample of $\sqrt{s_{\text{NN}}} = 5.02$ TeV PbPb data collected during the 2015 LHC heavy ion run, corresponding to an integrated luminosity of $1.2 \mu\text{b}^{-1}$, is also analyzed for comparison purposes. The triggers and event selection, as well as track reconstruction and selection, are identical to those used in Ref. [50] and are summarized below.

Minimum bias (MB) pPb events were triggered by requiring at least one track with $p_{\text{T}} > 0.4 \text{ GeV}/c$ in the pixel tracker during a pPb bunch crossing and the presence of at least one tower in one of the two HF detectors having an energy above 1 GeV. In order to select high-multiplicity pPb collisions, a dedicated high-multiplicity trigger was implemented using the CMS level-1 (L1) and high-level trigger (HLT) systems [51]. At L1, the total number of ECAL and HCAL towers with the transverse energies above a threshold of 0.5 GeV is required to exceed 120 and 150 in ECAL and HCAL, respectively. The events which pass the L1 trigger are then subsequently filtered in the HLT. The track reconstruction that is performed online, as part of the HLT trigger, uses the identical reconstruction algorithm as employed in the offline

processing [52]. For each event, the vertex reconstructed with the highest number of pixel detector tracks was selected. The number (multiplicity) of pixel tracks ($N_{\text{trk}}^{\text{online}}$) with $|\eta| < 2.4$, $p_T > 0.4 \text{ GeV}/c$, and a distance of closest approach to this vertex of 0.4 cm or less, was determined for each event. Several multiplicity ranges were defined with prescale factors that were reduced with increasing particle multiplicity until, for the highest-multiplicity events, no prescale was applied.

In the offline analysis, hadronic collisions are selected by the requirement of a coincidence of at least one HF calorimeter tower containing more than 3 GeV of total energy in each of the HF detectors within $3.0 < |\eta| < 5.2$. Events are also required to contain at least one reconstructed primary vertex within 15 cm from the nominal interaction point along the beam axis and within 0.15 cm transverse to the beam trajectory. At least two reconstructed tracks are required to be associated with the primary vertex. Beam-related background is suppressed by rejecting events for which less than 25% of all reconstructed tracks pass the track selection criteria.

Tracks are used that pass the high-purity selection criteria described in Ref. [52]. In addition, a reconstructed track is only considered as a candidate track from the primary vertex if the separation along the beam axis (z) between the track and the best vertex, and the track-vertex impact parameter measured transverse to the beam are each less than three times their respective uncertainties. The relative uncertainty in the p_T measurement is required to be less than 10%. To restrict the analysis to a kinematic region of high tracking efficiency and a low rate of incorrectly reconstructed tracks, only tracks with $|\eta| < 2.4$ and $0.3 < p_T < 3.0 \text{ GeV}/c$ are used.

The entire pPb data set is divided into classes of reconstructed track multiplicity, $N_{\text{trk}}^{\text{offline}}$, where primary tracks passing the high-purity criteria and with $|\eta| < 2.4$ and $p_T > 0.4 \text{ GeV}/c$ are counted. The HLT p_T cutoff, which is only applied on determination of $N_{\text{trk}}^{\text{offline}}$, is higher than that used for the analysis because of online processing time constraints. The absence of the time constraints in the offline process allows extending the p_T coverage down to $0.3 \text{ GeV}/c$ in the cumulant calculation. The multiplicity classification in this analysis is identical to that used in Ref. [40], where more details are provided, including a table relating $N_{\text{trk}}^{\text{offline}}$ to the fraction of MB triggered events. The PbPb sample is reprocessed using the same event selection and track reconstruction as for the present pPb analysis. A description of the analysis of 2015 PbPb data can be found in Ref. [50].

3 Analysis techniques

The analysis is done using the Q -cumulant method [41]. Here it is possible to determine the n th harmonic moment based on correlations among all possible grouping of m particles, where m also corresponds to the cumulant order. The multiparticle correlations for cumulant orders 2 through 8 can be expressed as:

$$\begin{aligned}\langle\langle 2 \rangle\rangle &\equiv \left\langle\left\langle e^{in(\phi_1 - \phi_2)} \right\rangle\right\rangle, \\ \langle\langle 4 \rangle\rangle &\equiv \left\langle\left\langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \right\rangle\right\rangle, \\ \langle\langle 6 \rangle\rangle &\equiv \left\langle\left\langle e^{in(\phi_1 + \phi_2 + \phi_3 - \phi_4 - \phi_5 - \phi_6)} \right\rangle\right\rangle, \\ \langle\langle 8 \rangle\rangle &\equiv \left\langle\left\langle e^{in(\phi_1 + \phi_2 + \phi_3 + \phi_4 - \phi_5 - \phi_6 - \phi_7 - \phi_8)} \right\rangle\right\rangle,\end{aligned}$$

where ϕ_i ($i = 1, \dots, m$) are the azimuthal angles of one unique combination of m particles in an event, n is the harmonic number (2 for elliptic and 3 for triangular flow, respectively),

and $\langle\langle\cdots\rangle\rangle$ represents the average over all combinations from all events within a given $N_{\text{trk}}^{\text{offline}}$ range. The higher-order cumulants, $c_n\{m\}$, are calculated as [41]

$$\begin{aligned} c_n\{4\} &= \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2, \\ c_n\{6\} &= \langle\langle 6 \rangle\rangle - 9\langle\langle 4 \rangle\rangle\langle\langle 2 \rangle\rangle + 12\langle\langle 2 \rangle\rangle^3, \\ c_n\{8\} &= \langle\langle 8 \rangle\rangle - 16\langle\langle 6 \rangle\rangle\langle\langle 2 \rangle\rangle - 18\langle\langle 4 \rangle\rangle^2 \\ &\quad + 144\langle\langle 4 \rangle\rangle\langle\langle 2 \rangle\rangle^2 - 144\langle\langle 2 \rangle\rangle^4. \end{aligned}$$

The Fourier harmonics $v_n\{m\}$ that characterize the global azimuthal behavior can be related to the m -particle correlations using a generic framework discussed in Ref. [53], with

$$\begin{aligned} v_n\{4\} &= \sqrt[4]{-c_n\{4\}}, v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}, \\ v_n\{8\} &= \sqrt[8]{-\frac{1}{33}c_n\{8\}}. \end{aligned}$$

Each reconstructed track is weighted by a correction factor to account for the reconstruction efficiency, the detector acceptance, and the fraction of misreconstructed tracks. This factor is based on HIJING 1.383 [54] MC simulations, and is determined as a function of p_T , η , and ϕ , as described in Refs. [5, 8]. The $c_n\{4\}$ and $c_n\{8\}$ values need to be negative, and the $c_n\{6\}$ value needs to be positive, in order to have real values for the $v_n\{m\}$ coefficients. The same method has been used in previous CMS analyses [38, 40, 55]. The two-particle correlation $v_n\{2\}$ can be measured as described in Ref. [50]. Increasing the numbers of particles used to determine the correlations for a given harmonic reduces the sensitivity of the results to few-particle correlations that are not related to a global behavior. The ratios between v_n harmonics involving different number of particles can be used to test the system independence of fluctuation-driven initial-state anisotropies in the hydrodynamic picture. In particular, the triangular flow ratio $v_3\{4\}/v_3\{2\}$, which is dominated by fluctuations, can be used to confirm this expectation.

A number of potential sources of systematic uncertainties affecting the experimental $v_n\{m\}$ values are considered. The sensitivity of the results to the selection criteria for valid tracks was studied by varying the criteria. The sensitivity to the primary vertex position was explored by performing the analysis for different vertex z ranges. The potential for an HLT trigger bias was investigated by changing the trigger thresholds. Pileup effects, where two or more interactions occur in the same bunch crossing, were studied by comparing results obtained during different beam differential luminosity periods. For the pPb results, the beam directions were reversed, allowing for potential detector acceptance effects to be explored. No evident $N_{\text{trk}}^{\text{offline}}$ dependent systematic effects are observed. The total systematic uncertainties, obtained by combining the individual uncertainties in quadrature, are found to be 1–2.4% for the v_2 coefficients for both pPb and PbPb collisions and 5 (2.6)% for the pPb (PbPb) v_3 results. The pPb (PbPb) $v_n\{4\}/v_n\{2\}$ ratios systematic uncertainties are found to be 3 (1)%. The pPb $v_2\{6\}/v_2\{4\}$ and $v_2\{8\}/v_2\{6\}$ ratios systematic uncertainties are found to be 3%.

4 Results

The second- and third-order harmonic multiparticle cumulant results v_2 and v_3 for charged particles with $0.3 < p_T < 3.0 \text{ GeV}/c$ and $|\eta| < 2.4$ are shown in Fig. 1 for pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$ and for PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$. The two-particle correlation results $v_2^{\text{sub}}\{2\}(|\Delta\eta| > 2)$ and $v_3^{\text{sub}}\{2\}(|\Delta\eta| > 2)$, with low-multiplicity subtraction to remove jet

correlations, are taken from Ref. [50]. The multiparticle elliptic flow harmonics $v_2\{4\}$, $v_2\{6\}$, and $v_2\{8\}$ are found to be real and of similar magnitude. The four-particle triangular flow harmonic, $v_3\{4\}$, is also found to be real, with an amplitude consistent with the earlier ATLAS $c_3\{4\}$ results [43]. These results indicate collective behavior in high multiplicity pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [44, 45]. Comparing the different systems, the v_2 values for PbPb collisions are higher than those for pPb collisions, which is consistent with the lenticular-shaped overlap geometry dominating this harmonic for PbPb collisions. The two-particle correlation v_2 and v_3 results are systematically higher than the multiparticle results for both pPb and PbPb collision. This is expected if there is a significant fluctuation component, which is expected to increase the two-particle correlation results and decrease the multiparticle correlation results, as compared to case where fluctuations are absent [46]. With increasing $N_{\text{trk}}^{\text{offline}}$, the $v_2\{4\}$, $v_2\{6\}$, and $v_2\{8\}$ values all rise in PbPb collisions, while they fall slightly in pPb collisions. This might suggest that the fluctuation-driven component of the eccentricity, as compared to the component arising from the lenticular overlap geometry, is decreasing with increasing multiplicity in the PbPb system. The v_3 values are comparable for both systems, as expected if this higher-order harmonic is dominated by fluctuation behavior. A (3+1)D event-by-event viscous hydrodynamic calculation of the four-particle cumulant $v_3\{4\}$ for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [56] is also shown in Fig. 1 as a gray band. This calculation, with an entropy distribution taken as a two-dimensional Gaussian of width $\sigma = 0.4$ fm and having a shear viscosity-to-entropy ratio of $\eta/s = 0.08$, is found to be consistent with the data.

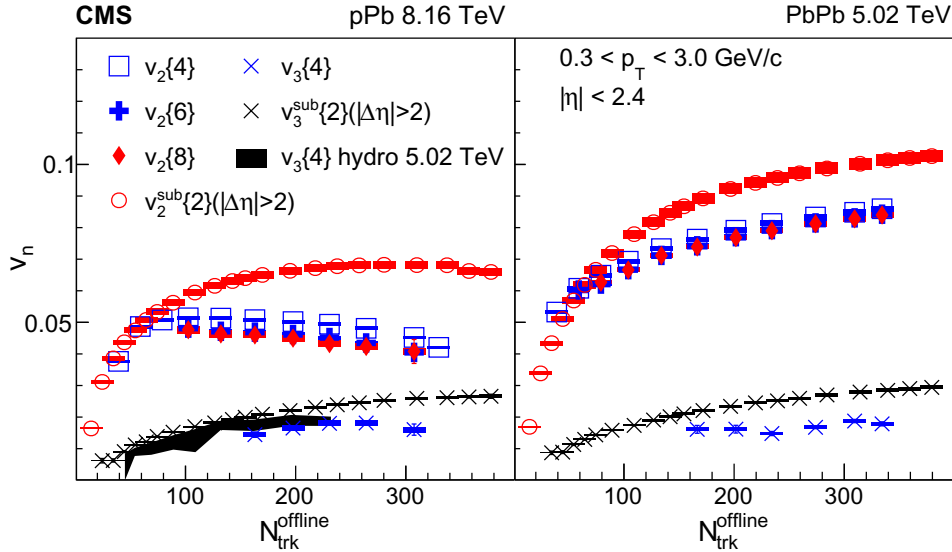


Figure 1: The multiparticle $v_2\{4, 6, 8\}$ and $v_3\{4\}$ harmonics are shown for pPb 8.16 TeV (left) and PbPb 5.02 TeV (right) collisions as a function of $N_{\text{trk}}^{\text{offline}}$. Two-particle results $v_2^{\text{sub}}\{2\}(|\Delta\eta| > 2)$ and $v_3^{\text{sub}}\{2\}(|\Delta\eta| > 2)$ are from Ref. [50]. Error bars and shaded boxes denote statistical and systematic uncertainties, respectively. The shaded area shows the hydrodynamic prediction of $v_3\{4\}$ in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [56].

Figure 2 shows the ratios $v_2\{4\}/v_2\{2\}$ and $v_3\{4\}/v_3\{2\}$ for both the pPb and PbPb systems. For pPb collisions, the ratios for v_2 and v_3 are similar within uncertainties, which is consistent with having both the second- and third-order harmonics arising from the same initial-state fluctuation mechanism. Comparing the pPb and PbPb systems, the v_3 ratios are comparable for both systems, while the v_2 ratios are higher in PbPb than in pPb for higher $N_{\text{trk}}^{\text{offline}}$ values, again reflecting the larger geometric contribution for the heavier system collisions. The v_2 ratio for PbPb collisions saturates at large multiplicity while, for pPb collisions, the ratio continues

to decrease as the multiplicity increases.

Cumulants can also be constructed for the eccentricities of the matter distribution in the initial state, $\varepsilon_n\{m\}$. In the hydrodynamic picture, the $v_n\{m\}$ values are proportional to $\varepsilon_n\{m\}$, with $v_n\{m\} = k_n \varepsilon_n\{m\}$, where k_n reflects the medium properties and does not depend on the order of the cumulant. Therefore, ratios of different cumulant v_n values can directly probe properties of initial-state eccentricity. This is shown in Fig. 2 based on Glauber model initial condition simulated using the TRENTo framework [57], and assuming a width $\sigma = 0.3$ fm of the source associated with each nucleon [45]. The calculations were done for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV by varying the geometric overlap of the colliding nuclei. It should be noted that the two-particle correlation results were obtained with a large pseudorapidity gap of $|\Delta\eta| > 2$. Earlier experimental pPb results at $\sqrt{s_{NN}} = 5.02$ TeV have shown that this gap can lead to a reduction in the observed $v_2^{\text{sub}}\{2\}(|\Delta\eta| > 2)$ values by 10% resulting from event-plane fluctuations [58]. This gap dependence is not directly determined in the current measurement and, consequently, the reported values are not corrected for this effect. However, assuming a 10% gap-related reduction in the two-particle $v_2\{2\}$ values with, in the absence of a gap, the $v_2\{4\}$ values not being similarly affected, the reported values of $v_2\{4\}/v_2\{2\}$ might be too high by 10%.

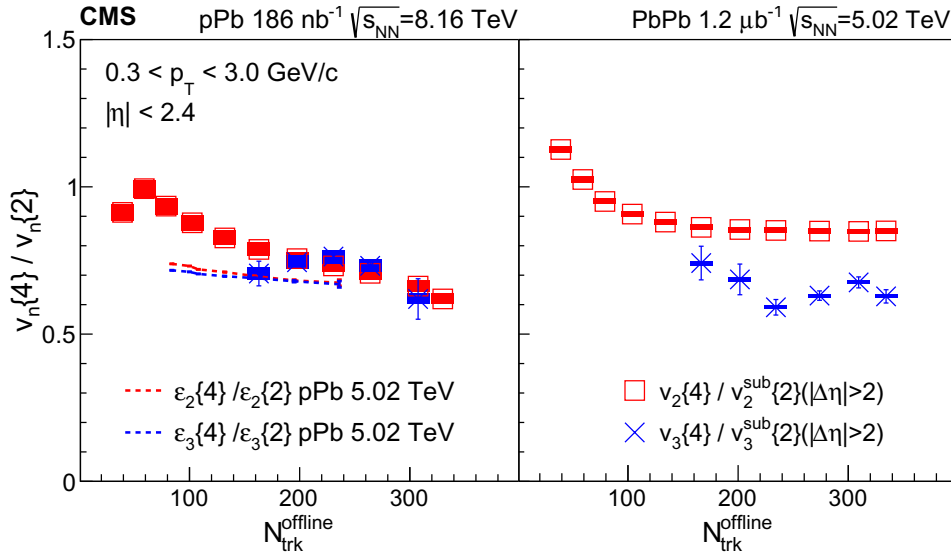


Figure 2: The ratios of four- and two-particle harmonics ($v_2\{4\}/v_2\{2\}$ and $v_3\{4\}/v_3\{2\}$) are shown for pPb $\sqrt{s_{NN}} = 8.16$ TeV (left) and PbPb $\sqrt{s_{NN}} = 5.02$ TeV (right) collisions as a function of $N_{\text{trk}}^{\text{offline}}$. Error bars and shaded boxes denote statistical and systematic uncertainties, respectively. The dashed curves show a hydrodynamics-motivated initial-state fluctuation calculation of eccentricities $\varepsilon_n\{m\}$ for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [45].

In Fig. 3, the ratios $v_2\{6\}/v_2\{4\}$ and $v_2\{8\}/v_2\{6\}$ are shown as a function of the ratio $v_2\{4\}/v_2\{2\}$ for pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and compared to calculations based on fluctuation-driven eccentricities [42] with a universal power law distribution assumed for the eccentricities instead of a two-dimensional Gaussian distribution. These results are similar to those previously reported in Ref. [38] for pPb at $\sqrt{s_{NN}} = 5.02$ TeV, as shown in the figure, but with greatly reduced statistical uncertainties. Within the uncertainties, the model calculations for both the $v_2\{6\}/v_2\{4\}$ and $v_2\{8\}/v_2\{6\}$ ratios agree with the experimental results. The agreement improves if the reduced correlation resulting from the $v_2^{\text{sub}}\{2\}(|\Delta\eta| > 2)$ pseudorapidity gap is also considered. The agreement of the calculations with the data shows that the differences found among the multiparticle cumulant results for the v_2 harmonic can be described by non-

Gaussian initial-state fluctuations. The precise measurement of the ratio results confirms the hypothesis that the multiparticle correlations originate from the product of single-particle correlations arising from source fluctuations with respect to overall collision geometry. This is a fundamental assumption of both the hydrodynamic [45] and the Color Glass Condensate model calculations [34].

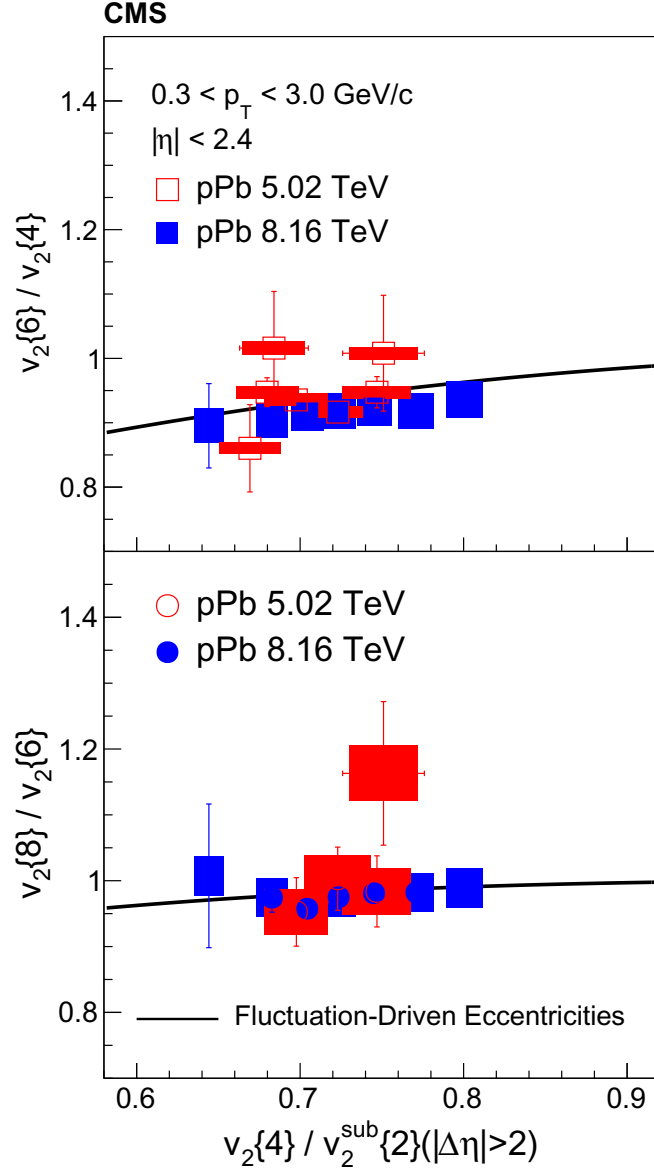


Figure 3: Cumulant ratios $v_2\{6\}/v_2\{4\}$ (upper) and $v_2\{8\}/v_2\{6\}$ (lower) as a function of $v_2\{4\}/v_2^{\text{sub}}\{2\}$ in pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ [38] and 8.16 TeV. Error bars and shaded areas denote statistical and systematic uncertainties, respectively. The solid curves show the expected behavior based on a hydrodynamics-motivated study of the role of initial-state fluctuations [42].

5 Summary

In summary, the azimuthal anisotropy for pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$ and PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ are studied as a function of the final-state particle multiplicities with

the CMS experiment. The v_2 Fourier coefficient is determined using cumulants obtained with four-, six-, and eight-particle correlations with greatly increased precision compared to previous measurements. The higher-order $v_3\{4\}$ coefficient is reported for the first time for a small system. For pPb collisions, the ratios $v_2\{4\}/v_2\{2\}$ and $v_3\{4\}/v_3\{2\}$ are comparable, consistent with a purely fluctuation-driven origin for the azimuthal asymmetry. Both the pPb and PbPb systems have very similar v_3 coefficients for the cumulant orders studied, indicating a similar, fluctuation-driven initial-state geometry. In contrast, both the magnitude of the v_2 coefficients and the $v_2\{4\}/v_2\{2\}$ ratio is larger for PbPb collisions, as expected if the overall collision geometry dominates. The v_2 cumulant ratios for pPb collisions are consistent with a collective flow behavior that originates from and is proportional to the initial-state anisotropy.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, V.M. Ghete, J. Hrubec, M. Jeitler¹, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck¹, R. Schöffbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov², D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

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

H. Bakhshiansohi, O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaître, A. Magitteri, K. Piotrkowski, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

F.L. Alves, G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

S. Ahuja^a, C.A. Bernardes^a, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, SandraS. Padula^a

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

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

University of Sofia, Sofia, Bulgaria

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

Beihang University, Beijing, China

W. Fang⁵, X. Gao⁵, L. Yuan

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, S.M. Shaheen⁶, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang⁶, J. Zhao

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

Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang

Tsinghua University, Beijing, China

Y. Wang

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

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

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov⁷, T. Susa

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Finger⁸, M. Finger Jr.⁸

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. Ellithi Kamel⁹, M.A. Mahmoud^{10,11}, E. Salama^{11,12}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

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

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

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

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

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

A. Abdulsalam¹³, C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, C. Martin Perez, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

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

J.-L. Agram¹⁴, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte¹⁴, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Berner, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaüd, M. Lethuillier, L. Mirabito, S. Perries, A. Popov¹⁵, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia

T. Toriashvili¹⁶

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze⁸

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

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

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

A. Albert, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, A. Pozdnyakov, M. Radziej, H. Reithler, M. Rieger, A. Schmidt, D. Teyssier, S. Thüer

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

G. Flügge, O. Hlushchenko, T. Kress, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁷

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras¹⁸, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁹, A. Geiser, J.M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Leonard, K. Lipka, W. Lohmann²⁰, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, T. Dreyer, A. Ebrahimi, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaupt, M. Niedziela, C.E.N. Niemeyer, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann¹⁷, S.M. Heindl, U. Husemann, I. Katkov¹⁵, S. Kudella, S. Mitra, M.U. Mozer, Th. Müller, M. Musich, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, C. Wöhrmann, R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, G. Paspalaki

National and Kapodistrian University of Athens, Athens, Greece

A. Agapitos, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Vellidis

National Technical University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece

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

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

M. Bartók²¹, M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²², . Hunyadi, F. Sikler, T.. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

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

S. Bahinipati²⁴, C. Kar, P. Mal, K. Mandal, A. Nayak²⁵, S. Roy Chowdhury, D.K. Sahoo²⁴, S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, A. Mehta, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi, G. Walia

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj²⁶, M. Bharti²⁶, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁶, D. Bhowmik, S. Dey, S. Dutt²⁶, S. Dutta, S. Ghosh, M. Maity²⁷, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, G. Saha, S. Sarkar, T. Sarkar²⁷, M. Sharan, B. Singh²⁶, S. Thakur²⁶

Indian Institute of Technology Madras, Madras, India

P.K. Behera, A. Muhammad

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla, P. Suggisetti

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo

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

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

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

S. Chenarani²⁸, E. Eskandari Tadavani, S.M. Etesami²⁸, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh²⁹, M. Zeinali

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}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, F. Errico^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, G. Iaselli^{a,c}, M. Ince^{a,b}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^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,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b}, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, E. Fontanesi, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Lo Meo^{a,30}, S. Marcellini^a, G. Masetti^a, A. Montanari^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}, N. Tosi^a

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

S. Albergo^{a,b}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

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

G. Barbagli^a, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, G. Latino, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,31}, G. Sguazzoni^a, D. Strom^a, L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

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

F. Ferro^a, R. Mulargia^{a,b}, E. Robutti^a, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^a, A. Beschi^b, F. Brivio^{a,b}, V. Ciriolo^{a,b,17}, S. Di Guida^{a,b,17}, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, D. Menasce^a, F. Monti, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, 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, Università G. Marconi ^d, Roma, Italy

S. Buontempo^a, N. Cavallo^{a,c}, A. De Iorio^{a,b}, A. Di Crescenzo^{a,b}, F. Fabozzi^{a,c}, F. Fienga^a, G. Galati^a, A.O.M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,d,17}, P. Paolucci^{a,17}, C. Sciacca^{a,b}, E. Voevodina^{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, D. Bisello^{a,b}, A. Boletti^{a,b}, A. Bragagnolo, R. Carlin^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S.Y. Hoh, S. Lacaprara^a, P. Lujan, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, M. Presilla^b, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, A. Tiko, E. Torassa^a, M. Tosi^{a,b}, M. Zanetti^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

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

A. Braghieri^a, A. Magnani^a, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, M. Ressegotti^{a,b}, 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

M. Biasini^{a,b}, G.M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{a,b}, E. Manoni^a, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Rossi^{a,b}, A. Santocchia^{a,b}, D. Spiga^a

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, L. Bianchini^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^a, F. Fiori^{a,c}, L. Giannini^{a,c}, A. Giassi^a, M.T. Grippo^a, F. Ligabue^{a,c}, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, G. Rolandi^{a,32}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

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

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, S. Gelli^{a,b},
E. Longo^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, F. Pandolfi^a, R. Paramatti^{a,b},
F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{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},
C. Biino^a, A. Cappati^{a,b}, N. Cartiglia^a, F. Cenna^{a,b}, S. Cometti^a, M. Costa^{a,b}, R. Covarelli^{a,b},
N. Demaria^a, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b},
E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a,
G.L. Pinna Angioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, R. Salvatico^{a,b}, K. Shchelina^{a,b},
V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a

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},
F. Vazzoler^{a,b}, A. Zanetti^a

Kyungpook National University, Daegu, Korea

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

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

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

Hanyang University, Seoul, Korea

B. Francois, J. Goh³³, T.J. Kim

Korea University, Seoul, Korea

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

Sejong University, Seoul, Korea

H.S. Kim

Seoul National University, Seoul, Korea

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo,
U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

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

Riga Technical University, Riga, Latvia

V. Veckalns³⁴

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

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

Z.A. Ibrahim, M.A.B. Md Ali³⁵, F. Mohamad Idris³⁶, W.A.T. Wan Abdullah, M.N. Yusli,
Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada

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

H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz³⁷, R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, M. Ramirez-Garcia, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

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

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

S. Bheesette, P.H. Butler

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

A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

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

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

K. Bunkowski, A. Byszuk³⁸, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev^{39,40}, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim⁴¹, E. Kuznetsova⁴², P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

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

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev

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

M. Chadeeva⁴³, P. Parygin, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin⁴⁰, M. Kirakosyan, A. Terkulov

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

A. Belyaev, E. Boos, A. Ershov, A. Gribushin, A. Kaminskiy⁴⁴, O. Kodolova, V. Korotkikh, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

Novosibirsk State University (NSU), Novosibirsk, Russia

A. Barnyakov⁴⁵, V. Blinov⁴⁵, T. Dimova⁴⁵, L. Kardapoltsev⁴⁵, Y. Skovpen⁴⁵

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

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

National Research Tomsk Polytechnic University, Tomsk, Russia

A. Babaev, S. Baidali, V. Okhotnikov

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences

P. Adzic⁴⁶, P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic⁴⁷, J. Milosevic

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

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

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz

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

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, J.M. Vizan Garcia

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

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

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

N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita⁴⁸, D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, V. Innocente, G.M. Innocenti, A. Jafari, P. Janot, O. Karacheban²⁰, J. Kieseler, A. Kornmayer, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo¹⁷, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁹, A. Stakia, J. Stegmann, D. Treille, A. Tsirou, A. Vartak, M. Verzetti, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁵⁰, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

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

M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Reichmann, C. Reissel, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁵¹, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, S. Leontsinis, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, S. Wertz, A. Zucchetta

National Central University, Chung-Li, Taiwan

T.H. Doan, R. Khurana, C.M. Kuo, W. Lin, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

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

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

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

A. Bat, F. Boran, S. Cerci⁵², S. Damarseckin, Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos⁵³, C. Isik, E.E. Kangal⁵⁴, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵⁵, S. Ozturk⁵⁶, D. Sunar Cerci⁵², B. Tali⁵², U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁵⁷, G. Karapinar⁵⁸, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁵⁹, O. Kaya⁶⁰, S. Ozkorucuklu⁶¹, S. Tekten, E.A. Yetkin⁶²

Istanbul Technical University, Istanbul, Turkey

M.N. Agaras, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen⁶³

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

B. Grynyov

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

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Ball, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold⁶⁴, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom

A. Belyaev⁶⁵, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom

R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, P. Everaerts, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash⁶⁶, A. Nikitenko⁷, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee¹⁷, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington, DC, USA

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

D. Arcaro, T. Bose, Z. Demiragli, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, D. Sperka, I. Suarez, L. Sulak, D. Zou

Brown University, Providence, USA

G. Benelli, B. Burkley, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶⁷, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir⁶⁸, R. Syarif, E. Usai, D. Yu

University of California, Davis, Davis, USA

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

University of California, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

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

University of California, San Diego, La Jolla, USA

J.G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, D. Olivito, S. Padhi, M. Pieri, V. Sharma, M. Tadel, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, H. Mei, A. Ovcharova, H. Qu, J. Richman, D. Stuart, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA

D. Anderson, A. Bornheim, J.M. Lawhorn, N. Lu, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA

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

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, F. Ravera, A. Reinsvold, L. Ristori, A. Savoy-Navarro⁶⁹, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, USA

Y.R. Joshi, S. Linn

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, V. Bhopalkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, M. Saunders, F. Yumiceva

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

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

The University of Iowa, Iowa City, USA

M. Alhusseini, B. Bilki⁷⁰, W. Clarida, K. Dilsiz⁷¹, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁷², Y. Onel, F. Ozok⁷³, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

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

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

A.C. Benvenuti[†], R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, S. Kalafut, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M.A. Wadud

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA

A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D.M. Morse, T. Orimoto, A. Tishelman-charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA

S. Bhattacharya, J. Bueghly, O. Charaf, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁹, M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

S. Cooperstein, G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

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

Purdue University Northwest, Hammond, USA

T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, Z. Tu, A. Zhang

University of Rochester, Rochester, USA

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

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

B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

University of Tennessee, Knoxville, USA

H. Acharya, A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

Texas A&M University, College Station, USA

O. Bouhali⁷⁴, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷⁵, S. Luo, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

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

University of Wisconsin - Madison, Madison, WI, USA

J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, B. Gomer⁷⁶, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, V. Sharma, N. Smith, W.H. Smith, N. Woods

†: Deceased

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

2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

3: Also at Universidade Estadual de Campinas, Campinas, Brazil

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

5: Also at Université Libre de Bruxelles, Bruxelles, Belgium

6: Also at University of Chinese Academy of Sciences, Beijing, China

7: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

8: Also at Joint Institute for Nuclear Research, Dubna, Russia

9: Now at Cairo University, Cairo, Egypt

10: Also at Fayoum University, El-Fayoum, Egypt

11: Now at British University in Egypt, Cairo, Egypt

12: Now at Ain Shams University, Cairo, Egypt

13: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia

14: Also at Université de Haute Alsace, Mulhouse, France

15: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

16: Also at Tbilisi State University, Tbilisi, Georgia

17: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

18: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

19: Also at University of Hamburg, Hamburg, Germany

20: Also at Brandenburg University of Technology, Cottbus, Germany

21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary

- 22: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 23: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
- 24: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
- 25: Also at Institute of Physics, Bhubaneswar, India
- 26: Also at Shoolini University, Solan, India
- 27: Also at University of Visva-Bharati, Santiniketan, India
- 28: Also at Isfahan University of Technology, Isfahan, Iran
- 29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 30: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- 31: Also at Università degli Studi di Siena, Siena, Italy
- 32: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 33: Also at Kyung Hee University, Department of Physics, Seoul, Korea
- 34: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
- 35: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 36: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 37: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 38: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 39: Also at Institute for Nuclear Research, Moscow, Russia
- 40: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 41: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 42: Also at University of Florida, Gainesville, USA
- 43: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 44: Also at INFN Sezione di Padova ^a, Università di Padova ^b, Padova, Italy, Università di Trento ^c, Trento, Italy, Padova, Italy
- 45: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 46: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 47: Also at University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia
- 48: Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy, Pavia, Italy
- 49: Also at National and Kapodistrian University of Athens, Athens, Greece
- 50: Also at Universität Zürich, Zurich, Switzerland
- 51: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
- 52: Also at Adiyaman University, Adiyaman, Turkey
- 53: Also at Istanbul Aydin University, Istanbul, Turkey
- 54: Also at Mersin University, Mersin, Turkey
- 55: Also at Piri Reis University, Istanbul, Turkey
- 56: Also at Gaziosmanpasa University, Tokat, Turkey
- 57: Also at Ozyegin University, Istanbul, Turkey
- 58: Also at Izmir Institute of Technology, Izmir, Turkey
- 59: Also at Marmara University, Istanbul, Turkey
- 60: Also at Kafkas University, Kars, Turkey
- 61: Also at Istanbul University, Istanbul, Turkey
- 62: Also at Istanbul Bilgi University, Istanbul, Turkey
- 63: Also at Hacettepe University, Ankara, Turkey
- 64: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom

- 65: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 66: Also at Monash University, Faculty of Science, Clayton, Australia
- 67: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
- 68: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 69: Also at Purdue University, West Lafayette, USA
- 70: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
- 71: Also at Bingol University, Bingol, Turkey
- 72: Also at Sinop University, Sinop, Turkey
- 73: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 74: Also at Texas A&M University at Qatar, Doha, Qatar
- 75: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea
- 76: Also at University of Hyderabad, Hyderabad, India