


## Multiharmonic Correlations of Different Flow Amplitudes in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

S. Acharya *et al.*\*  
(ALICE Collaboration)

 (Received 24 January 2021; revised 9 June 2021; accepted 13 July 2021; published 27 August 2021)

The event-by-event correlations between three flow amplitudes are measured for the first time in Pb-Pb collisions, using higher-order symmetric cumulants. We find that different three-harmonic correlations develop during the collective evolution of the medium when compared to correlations that exist in the initial state. These new results cannot be interpreted in terms of previous lower-order flow measurements since contributions from two-harmonic correlations are explicitly removed in the new observables. A comparison to Monte Carlo simulations provides new and independent constraints for the initial conditions and system properties of nuclear matter created in heavy-ion collisions.

DOI: [10.1103/PhysRevLett.127.092302](https://doi.org/10.1103/PhysRevLett.127.092302)

Under conditions of extreme temperature and density, the fundamental theory of the strong interaction, quantum chromodynamics (QCD), predicts the existence of a quark-gluon plasma (QGP). In this state, quarks are deconfined from hadrons but, contrary to the initial theoretical expectations, remain strongly coupled and form a liquid state [1]. Results from heavy-ion collision data are consistent with the scenario in which the produced nuclear matter undergoes collective expansion, dominated by its hydrodynamic response to the anisotropies in the initial state geometry. This phenomenon is known as anisotropic flow [2]. This collective dynamics is sensitive to  $\eta/s$  and  $\zeta/s$ , where  $\eta$  and  $\zeta$  are shear and bulk viscosities and  $s$  the entropy density. The successful description of heavy-ion data with hydrodynamic models was essential to determine the low value of  $\eta/s$  of the QGP [3] and established the perfect liquid paradigm, one of the most striking recent discoveries in high-energy physics [4–6].

In models that describe heavy-ion collisions, the produced matter evolves collectively, with particles being emitted independently along the azimuthal direction with a distribution  $f(\varphi)$ . The corresponding Fourier series is given by

$$f(\varphi) = \frac{1}{2\pi} \left[ 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)] \right], \quad (1)$$

\*Full author list given at the end of the article.

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

where the flow amplitude  $v_n$  and the symmetry plane angle  $\Psi_n$  designate the magnitude and orientation of the  $n$ th order anisotropic flow [7]. Experimental challenges of measuring these anisotropic flow observables were overcome with the development of multiparticle azimuthal correlations [8–12]. A great deal of additional information can be extracted from correlations between different flow amplitudes and/or different symmetry planes [13–17].

The correlations between event-by-event fluctuations of two different flow amplitudes were quantified with the “symmetric cumulant” (SC) observables [12,18], defined by  $SC(k, l) \equiv \langle v_k^2 v_l^2 \rangle - \langle v_k^2 \rangle \langle v_l^2 \rangle$ , with the angular brackets denoting an average over all events. The measurements of their centrality and transverse momentum ( $p_T$ ) dependencies revealed that correlations among different flow magnitudes depend on harmonic orders as well as the collision centrality, while showing moderate  $p_T$  dependence in semicentral collisions. The results in Refs. [12,18] showed that the different  $SC(k, l)$  observables have different sensitivities to the initial conditions of a heavy-ion collision and properties of the created system and can therefore help in separating the effects of  $\eta/s$  in the final state anisotropies from the contributions originating in the initial state. Furthermore, it was demonstrated that the SC observables are more sensitive to the temperature dependence  $\eta/s(T)$  than the individual flow amplitudes, which are sensitive only to the average values  $\langle \eta/s \rangle$  [18,19].

In this Letter, a new set of observables, dubbed “higher-order SC,” are analyzed [20]. These higher-order observables extract the genuine correlation among multiple flow amplitudes and provide new and independent constraints for both the initial conditions and the QGP properties. The genuine correlation (or cumulant) of three flow amplitudes, where lower-order two-harmonic correlations have been removed, can be obtained with the following expression [20,21]:

$$\begin{aligned}
 SC(k, l, m) \equiv & \langle v_k^2 v_l^2 v_m^2 \rangle - \langle v_k^2 v_l^2 \rangle \langle v_m^2 \rangle - \langle v_k^2 v_m^2 \rangle \langle v_l^2 \rangle \\
 & - \langle v_l^2 v_m^2 \rangle \langle v_k^2 \rangle + 2 \langle v_k^2 \rangle \langle v_l^2 \rangle \langle v_m^2 \rangle. \quad (2)
 \end{aligned}$$

The observable  $SC(k, l, m)$  is, by definition, the 3rd order cumulant of the three flow amplitudes  $v_k^2$ ,  $v_l^2$ , and  $v_m^2$ . If the previously used low order flow observables like  $v_n\{2\}$ ,  $v_n\{4\}$  [10], or  $SC(k, l)$  [12] would be able to characterize all collective correlations and anisotropic flow in the system,  $SC(k, l, m)$  would be identically zero. On the contrary, the nonvanishing results for  $SC(k, l, m)$  provide access to the information to which these traditionally used flow observables are insensitive. The normalized versions of these observables (NSC) are defined as

$$NSC(k, l, m) \equiv \frac{SC(k, l, m)}{\langle v_k^2 \rangle \langle v_l^2 \rangle \langle v_m^2 \rangle}, \quad (3)$$

which makes it easier to identify the origin of the correlations, either from the initial stage or from the collective expansion [20].

Another important aspect is the sign of the  $SC(k, l, m)$  observables, which is not trivial and can be understood if the definition in Eq. (2) is rewritten as

$$SC(k, l, m) = \left\langle (v_k^2 - \langle v_k^2 \rangle)(v_l^2 - \langle v_l^2 \rangle)(v_m^2 - \langle v_m^2 \rangle) \right\rangle. \quad (4)$$

For  $SC(k, l, m) > 0$ , there are the following two distinct possibilities: (a) if in an event it was found that  $v_k^2 > \langle v_k^2 \rangle$  and  $v_l^2 > \langle v_l^2 \rangle$ , then the probability of finding  $v_m^2 > \langle v_m^2 \rangle$  in that event is enhanced [this case is marked as a  $(+, +, +)$  pattern in the event-by-event flow fluctuations]; (b) if  $v_k^2 > \langle v_k^2 \rangle$  and  $v_l^2 < \langle v_l^2 \rangle$  in an event, this enhances the probability of finding  $v_m^2 < \langle v_m^2 \rangle$  in that event and is marked as a  $(+, -, -)$  pattern. By using the same reasoning, it can be concluded that  $SC(k, l, m) < 0$  permits only the  $(+, +, -)$  and  $(-, -, -)$  patterns. These persistent patterns of event-by-event flow fluctuations are invariant with respect to permutations of amplitudes of flow harmonics in the definition of  $SC(k, l, m)$ , and they are a direct imprint of the three-harmonic correlations.

It was demonstrated in Ref. [20] that  $SC(k, l, m)$ , as defined in Eq. (2), can be estimated reliably in an experiment with the following combination of azimuthal correlators:

$$\begin{aligned}
 SC(k, l, m) = & \langle\langle \cos[k\varphi_1 + l\varphi_2 + m\varphi_3 - k\varphi_4 - l\varphi_5 - m\varphi_6] \rangle\rangle \\
 & - \langle\langle \cos[k\varphi_1 + l\varphi_2 - k\varphi_3 - l\varphi_4] \rangle\rangle \langle\langle \cos[m(\varphi_5 - \varphi_6)] \rangle\rangle \\
 & - \langle\langle \cos[k\varphi_1 + m\varphi_2 - k\varphi_5 - m\varphi_6] \rangle\rangle \langle\langle \cos[l(\varphi_3 - \varphi_4)] \rangle\rangle \\
 & - \langle\langle \cos[l\varphi_3 + m\varphi_4 - l\varphi_5 - m\varphi_6] \rangle\rangle \langle\langle \cos[k(\varphi_1 - \varphi_2)] \rangle\rangle \\
 & + 2 \langle\langle \cos[k(\varphi_1 - \varphi_2)] \rangle\rangle \langle\langle \cos[l(\varphi_3 - \varphi_4)] \rangle\rangle \langle\langle \cos[m(\varphi_5 - \varphi_6)] \rangle\rangle. \quad (5)
 \end{aligned}$$

The double average notation indicates that in the first step averaging is performed over all distinct combinations of 2, 4, or 6 particles within the same event, and then these results are averaged over all events. Each azimuthal correlator in the above estimator can be measured efficiently and exactly with the Generic Framework published in Ref. [12]. By definition, this estimator ensures that large systematic biases from self-correlations and symmetry planes  $\Psi_n$  are eliminated. In the absence of nonflow (correlations between a few particles unrelated to collective phenomena and anisotropic flow), it reduces analytically to Eq. (2) even in the case of large event-by-event flow fluctuations [20].

The results presented in this Letter are obtained with the data from Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV collected with the ALICE detector in 2010. After the event and track selection, the data sample corresponds to about  $8.2 \times 10^6$  minimum bias events for the 0%–50% centrality range. The Pb-Pb dataset from 2011 is not included due to the significantly different detector and trigger conditions.

Detailed descriptions of the ALICE detector and performance can be found in Refs. [22–25]. The time projection chamber (TPC) was used to reconstruct charged particles and measure their momenta [26]. The inner tracking system was used to improve the vertex determination and momentum resolution, while its innermost part, the silicon pixel detector (SPD) [27,28], provided the default centrality estimation. Two scintillator arrays (V0A and V0C) were used for triggering and for an alternative determination of centrality [29–31]. The trigger conditions are identical to those described in Refs. [29,32].

The event and track selection are based on previous SC analyses [18,33]. The reconstructed primary vertex is required to be within  $\pm 10$  cm of the nominal interaction point along the beam axis. The main analysis is performed using tracks reconstructed only with the TPC (referred to as “TPC-only” from now on) in the kinematic range  $0.2 < p_T < 5.0$  GeV/c and  $|\eta| < 0.8$ . The low  $p_T$  cutoff decreases the biases from the smaller reconstruction efficiency, while the high  $p_T$  cutoff reduces the anisotropic

contaminations in the azimuthal distributions from jets. The selected tracks are reconstructed with a minimum of 70 space points out of a maximum of 159 in TPC and the  $\chi^2/\text{NDF}$  of their momentum fit is required to satisfy  $0.1 < \chi^2/\text{NDF} < 4.0$ . Only tracks with a maximum distance of closest approach (DCA) to the primary vertex of 2.4 cm in the transverse plane and 3.2 cm along the beam axis are kept for the analysis. This choice reduces the contributions from secondary tracks and has already been used in Ref. [18] with hybrid tracks, for which the tracking information is combined from the TPC and the inner tracking system detectors to achieve the best transverse momentum resolution and to correct for the nonuniform azimuthal acceptance due to dead zones in the SPD [25,34]. Also, tracks with an abrupt change of direction, e.g., due to multiple scattering or  $K^\pm$  decays, are rejected. With this selection, the contamination from secondaries in TPC-only tracks varies from about 16% at 0.2 GeV/ $c$  to about 7% at 5 GeV/ $c$ . The track reconstruction efficiency is almost constant at about 80%–88% as a function of transverse momentum. Its uncertainties are found to be negligible and thus not propagated in the final results.

Corrections both for nonuniform reconstruction efficiency (NUE) as a function of transverse momentum and nonuniform acceptance (NUA) as a function of azimuthal angle are computed as particle weights, following Ref. [12]. Particle weights for NUE were obtained with the Monte Carlo generator HIJING (Heavy-Ion Jet INteraction Generator) [35], while the ones for NUA are data driven. Only the corrections for NUE are applied to all the selected tracks in the main analysis with the default selection. Effects of NUA in TPC-only tracks were also checked but found to be negligible. The nonflow contributions estimated with HIJING are found to be negligible for all  $SC(k, l, m)$  observables reported in this Letter [20].

The systematic uncertainties are estimated by varying each selection criterion independently. The values of  $SC(k, l, m)$  with the variation and with the default selection are compared in each centrality interval. If the difference between the two results when taking into account the correlations between their statistical uncertainties is larger than one  $\sigma$  ( $\sigma$  is the uncertainty of the difference), the variation is included in the quadratic sum for the total systematic uncertainty. The importance of each trial depends on the considered  $SC(k, l, m)$ . The data sample was collected with two configurations of the magnetic field polarity in the solenoid magnet surrounding the ALICE central barrel detectors, giving two samples with similar size. The main analysis uses both samples, and no significant systematic effect is seen for the analysis on each individual orientation of the field polarity. Below, the ranges of relative variations observed in semicentral collisions (20%–50%) for each trial are reported. Moreover, the variations observed in collisions with a centrality up to 20% and for  $SC(2, 4, 6)$  and  $SC(3, 4, 5)$  in the range 20%–30%

can be larger than the ones indicated due to the small size of the signal and are therefore not reported. The systematic uncertainties are represented by the shaded boxes around each data point in all figures.

On the other hand, there are variations that impact only some  $SC(k, l, m)$  observables. For example, the variation of the distance of the primary vertex to the nominal interaction point along the beam direction ( $\pm 6$  cm and  $\pm 12$  cm) does not impact  $SC(2, 3, 5)$ ,  $NSC(2, 3, 5)$ , and  $SC(3, 4, 5)$  but results in an uncertainty of about 3.2% for  $SC(2, 3, 4)$  and  $NSC(2, 3, 4)$ . For the DCA variation in the plane transverse to the beam direction (from 2.4 cm to 1 cm and 2 cm), only  $SC(2, 4, 6)$  is not affected, while there is an effect of about 12% for  $NSC(2, 3, 4)$  to about 36% for  $SC(2, 3, 5)$ . The default analysis uses the centrality estimated with the SPD, while the systematic check is based on the determination of the centrality with the V0 detector. This change impacts the final results for all combinations with the exception of  $SC(3, 4, 5)$ , ranging from about 15% for  $SC(2, 3, 4)$  and  $NSC(2, 3, 4)$  to 21% for  $SC(2, 3, 5)$ . The variation of the minimum number of space points in the TPC (from 70 to 50 and 100 space points) leads to systematic biases in  $SC(2, 3, 4)$ ,  $SC(2, 3, 5)$ , and  $NSC(2, 3, 5)$ , ranging from 5% for  $SC(2, 3, 4)$  to 14% for  $SC(2, 3, 5)$ . This is also the case for the quality of fit  $\chi^2/\text{NDF}$  for  $0.3 < \chi^2/\text{NDF} < 4.0$  and  $0.1 < \chi^2/\text{NDF} < 3.5$ . This leads to significant differences for  $SC(2, 4, 6)$ ,  $SC(3, 4, 5)$ , and  $NSC(2, 3, 5)$  [about 12% for  $NSC(2, 3, 5)$ ]. For the tightening of the DCA criterion along the beam axis from 3.2 cm to 2.1 cm, we report the systematic bias of about 8%–10% for  $SC(2, 3, 5)$  and  $NSC(2, 3, 5)$ . Finally, non-negligible systematic effects are seen when repeating the analysis with hybrid tracks, which have a smaller contamination from secondaries, allowing an estimation of their systematic effects in the default selection. For this last check, all  $SC(k, l, m)$  see significant changes [between 4% and 19% for  $SC(2, 3, 4)$  and  $NSC(2, 3, 5)$ , respectively].

The centrality dependence of  $SC(k, l, m)$  and  $NSC(k, l, m)$  for the different combinations of flow amplitudes is shown in Fig. 1(a) and Fig. 1(b), respectively. When moving from central to semicentral collisions, the magnitude of both  $SC(2, 3, 4)$  and  $SC(2, 3, 5)$  increases, albeit with opposite sign. These nonzero values for semicentral collisions are the first experimental indications of correlations between three flow amplitudes. The results for  $SC(2, 3, 5)$  provide new and independent constraints on the nonlinear response contribution in  $v_5$  from  $v_2$  and  $v_3$ , which for the first time do not require any assumption in the derivation on the nature of two-harmonic correlations [36]. For the higher-order flow amplitudes, the measurements for  $SC(2, 4, 6)$  and  $SC(3, 4, 5)$  are compatible with zero for all centralities. The negative increasing trend observed for  $SC(2, 3, 4)$  is also present for  $NSC(2, 3, 4)$ . However, this is not the case for  $SC(2, 3, 5)$  and  $NSC(2, 3, 5)$ . The

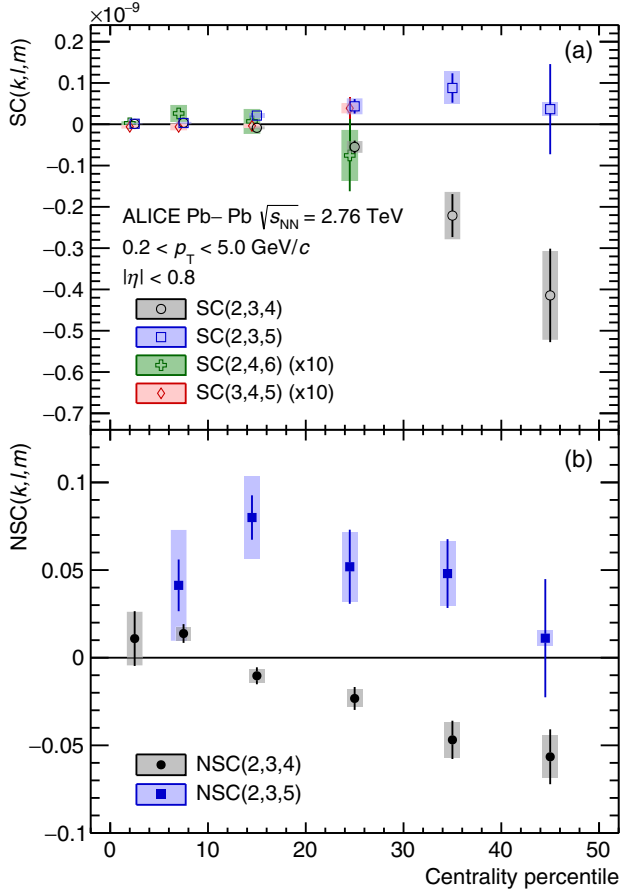


FIG. 1. Centrality dependence of  $SC(2,3,4)$ ,  $SC(2,3,5)$ ,  $SC(2,4,6)$ , and  $SC(3,4,5)$  (a) and of  $NSC(2,3,4)$  and  $NSC(2,3,5)$  (b) in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. The statistical (systematic) uncertainties are shown with the lines (boxes). The data points are shifted horizontally for visibility.

increase seen in the former cannot be found in the latter, which shows a decrease for semicentral events. This different behavior originates from the fact that the nonlinear response introduces a correlation among all three amplitudes in  $SC(2,3,5)$ , while the contribution from nonlinear response is not present in  $SC(2,3,4)$ .

The results for the higher-order SC observables are compared to the event-by-event Eskola-Kajantie-Ruuskanen-Tuominen (EKRT) + viscous [19] and  $T_{\text{R}}\text{ENTo} + \text{iEBE-VISHNU}$  hydrodynamic models [37]. In the EKRT model, the initial energy density profiles are calculated using a next-to-leading order perturbative-QCD + saturation model [38,39]. The subsequent space-time evolution is described by relativistic dissipative fluid dynamics with different temperature parameterizations  $\eta/s(T)$ . This state-of-the-art model gives a good description of the charged hadron multiplicity and the low- $p_T$  region of the charged hadron spectra at BNL’s Relativistic Heavy Ion Collider and at CERN’s Large Hadron Collider. Each of the  $\eta/s(T)$  parameterizations is adjusted to reproduce the measured  $v_n$  from central to

semiperipheral collisions. The model calculations in which the temperature of the phase transition is larger than for the “param1” parameterization are ruled out by the previous measurements [18,33]. In the study presented in this Letter, the EKRT prediction for the centrality dependence of  $SC(k, l, m)$  was obtained from a sample consisting of 40 000 events in the 0%–100% centrality range.

The calculations for the  $\eta/s(T) = \text{“param 1”}$  parameterization, which gives a good description of the lower-order SC results, are thus compared to our new results for higher-order SC in Fig. 2. They can describe the overall trends of all combinations in the centrality dependence. However,  $SC(2, 4, 6)$  is found to be strictly positive in models.

The hybrid hydrodynamic model  $T_{\text{R}}\text{ENTo} + \text{iEBE-VISHNU}$  has successfully described the previous ALICE measurements [37]. It consists of the  $T_{\text{R}}\text{ENTo}$  model [40] for the initial condition, which is connected with a free streaming to a 2 + 1 dimensional causal hydrodynamic model VISH2 + 1 [41,42]. The evolution is continued in the hadronic phase via the ultrarelativistic quantum molecular dynamics model [43,44]. The initial conditions,  $\eta/s(T)$ ,  $\zeta/s(T)$  and other free parameters of the hybrid model are extracted by the global Bayesian analysis. We perform a model calculation with the best-fit parameter points chosen by maximum *a posteriori* (MAP) for Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV as they are reported in Ref. [37]. All the kinematic cuts such as transverse momentum and pseudorapidity intervals are matched with the data reported in this Letter.

In heavy-ion collisions, the main source of anisotropy in the azimuthal distribution in the final state originates from anisotropies in the initial state geometry. The initial state geometry can be described by quantities called eccentricities,  $\epsilon_n$ , that are the moments of the initial energy (or entropy) density. For instance, the values of  $\epsilon_2$  and  $\epsilon_3$  indicate to what extent the initial geometry is elliptical and triangular, respectively. For small values of eccentricities, one can approximate the response of the collective evolution to the initial state geometry as a linear relation  $v_n = k_n \epsilon_n$  [45,46]. For  $n = 2, 3$ , this linear approximation is more accurate than for higher harmonics where nonlinear terms play a non-negligible role [13]. If the higher-order eccentricity cumulants are normalized by their averages [analogous to Eq. (3)], the response coefficients  $k_n$  can cancel between numerator and denominator. Therefore, any difference in the NSC values calculated from the eccentricities in the initial state to those obtained from the measured flow amplitudes in the final state is an indication of a hydrodynamic nonlinear response.

The comparison to the  $T_{\text{R}}\text{ENTo} + \text{iEBE-VISHNU}$  calculation is also shown in Fig. 2. The overall trends in the centrality dependence are captured by this model. However, both  $SC(2,3,4)$  and  $SC(2,3,5)$  are clearly underestimated, while  $NSC(2,3,4)$  and  $NSC(2,3,5)$  are in a better agreement with the data. In the case of  $NSC(k, l, m)$ , predictions from

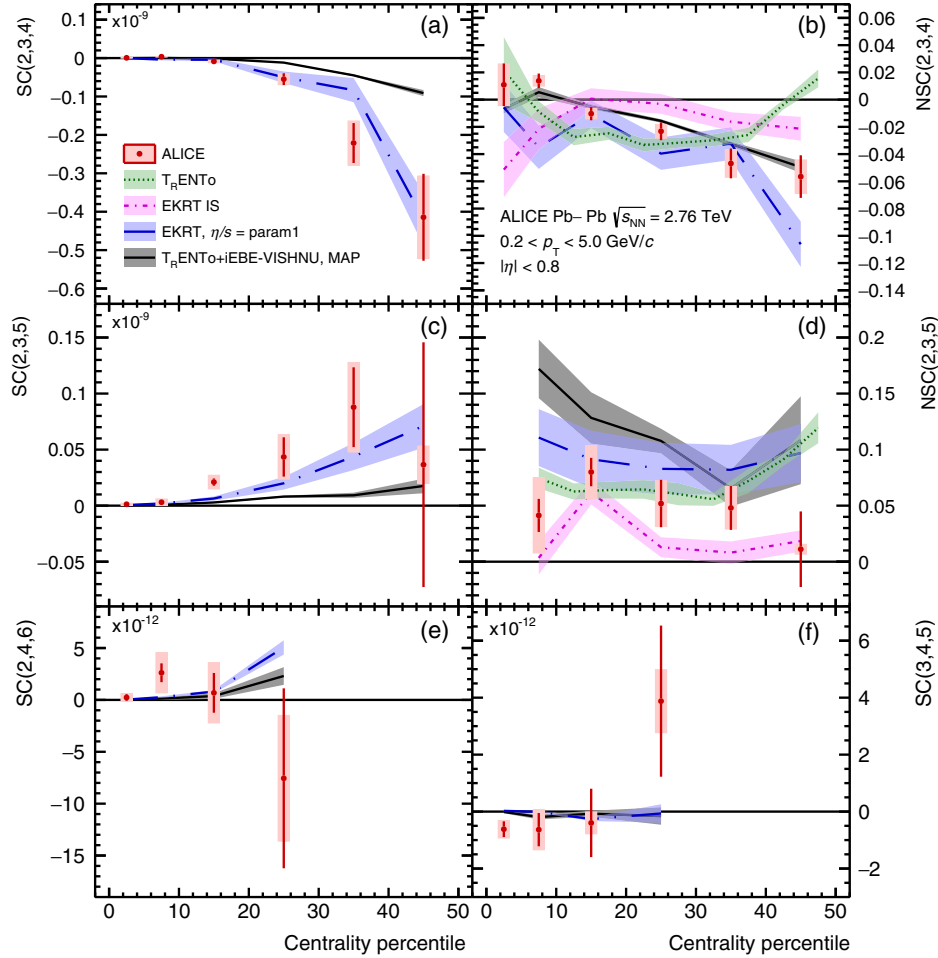


FIG. 2. Predictions from the hydrodynamical models for the centrality dependence for the  $SC(k, l, m)$  [panels (a), (c), (e), and (f)] and  $NSC(k, l, m)$  [panels (b) and (d)] in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. The statistical uncertainties are shown with colored bands. The predictions are compared to the ALICE results from Fig. 1 shown with red markers. The bands represent the statistical uncertainty of each model.

$T_{R}ENTo$  for the initial state are shown in Fig. 2(b) and Fig. 2(d). As iEBE-VISHNU uses  $T_{R}ENTo$  as input, the comparisons between the two sets of predictions can give insights about the development of multiharmonic correlations in the system. The relative change in  $NSC(2,3,4)$  for iEBE-VISHNU calculations from the ones from  $T_{R}ENTo$  for 10%–30% centralities indicates that in addition different correlations have developed during the hydrodynamic evolution of the medium. The same phenomenon is hinted at within uncertainties in  $NSC(2,3,5)$ . In this latter case, this can be explained by the nonlinear response contribution to  $v_5$  induced by the low order  $v_2$  and  $v_3$  found in Refs. [47,48]. For  $SC(2,4,6)$  and  $SC(3,4,5)$ , iEBE-VISHNU is in agreement with the predictions from EKRT within uncertainties.

Recent Bayesian analyses [37,49] show that the  $T_{R}ENTo$  model reproduces certain features of EKRT models with the energy deposition parameter,  $p \approx 0.0$ . However, as shown in Fig. 2(b) and Fig. 2(d), in semicentral collisions the  $T_{R}ENTo$  model shows stronger initial-state correlations

among eccentricities than the EKRT model, and the resulting final-state multiharmonic correlations obtained with  $SC(k, l, m)$  show differences as well. This difference can originate from the fact that EKRT does not include effects from bulk viscosity, while the extracted bulk viscosities from two different Bayesian analyses give sizable differences.

In summary, we have presented the first measurements of correlations between three flow amplitudes, obtained with higher-order SC observables in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. The nonzero values of  $SC(k, l, m)$  for semicentral collisions are the first experimental indication of correlations (cumulants) between three flow amplitudes. The relative changes between  $T_{R}ENTo$  and iEBE-VISHNU for  $NSC(2,3,4)$  and  $NSC(2,3,5)$  are consistent with the development of different correlations during the collective evolution of the medium. A similar conclusion can be extracted from the EKRT model. These results provide the first constraints on the nonlinear response contribution in  $v_5$  from  $v_2$  and  $v_3$ , which do

not require any assumption on the nature of lower-order two-harmonic correlations. The new results for  $SC(k, l, m)$  provide independent constraints for the initial conditions, system properties, nonlinear response, and possible patterns of event-by-event flow fluctuations when compared to the previous flow measurements obtained with lower-order observables.

The ALICE Collaboration would like to thank Harri Niemi for providing the latest predictions from the state-of-the-art hydrodynamic model. The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centers and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF): [M 2467-N36] and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (Finep), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), and Universidade Federal do Rio Grande do Sul (UFRGS), Brazil; Ministry of Education of China (MOEC), Ministry of Science and Technology of China (MSTC), and National Natural Science Foundation of China (NSFC), China; Ministry of Science and Education and Croatian Science Foundation, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research | Natural Sciences, the VILLUM FONDEN, and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l'Énergie Atomique (CEA) and Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS), France; Bundesministerium für Bildung und Forschung (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy Government of India (DAE), Department of Science and Technology, Government of India (DST), University

Grants Commission, Government of India (UGC), and Council of Scientific and Industrial Research (CSIR), India; Indonesian Institute of Science, Indonesia; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Institute for Innovative Science and Technology, Nagasaki Institute of Applied Science (IIST), Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT), and Japan Society for the Promotion of Science (JSPS) KAKENHI, Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Académico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Commission on Science and Technology for Sustainable Development in the South (COMSATS), Pakistan; Pontificia Universidad Católica del Perú, Peru; Ministry of Science and Higher Education, National Science Centre, and WUT ID-UB, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics and Ministry of Research and Innovation, and Institute of Atomic Physics, Romania; Joint Institute for Nuclear Research (JINR), Ministry of Education and Science of the Russian Federation, National Research Centre Kurchatov Institute, Russian Science Foundation, and Russian Foundation for Basic Research, Russia; Ministry of Education, Science, Research, and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut and Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; Suranaree University of Technology (SUT), National Science and Technology Development Agency (NSDTA), and Office of the Higher Education Commission under NRU project of Thailand, Thailand; Turkish Atomic Energy Agency (TAEK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and United States Department of Energy, Office of Nuclear Physics (DOE NP), United States of America.

- 
- [1] B. Jacak and P. Steinberg, Creating the perfect liquid in heavy-ion collisions, *Phys. Today* **63**, No. 5, 39 (2010).
  - [2] J.-Y. Ollitrault, Anisotropy as a signature of transverse collective flow, *Phys. Rev. D* **46**, 229 (1992).
  - [3] P. K. Kovtun, D. T. Son, and A. O. Starinets, Viscosity in Strongly Interacting Quantum Field Theories from Black Hole Physics, *Phys. Rev. Lett.* **94**, 111601 (2005).

- [4] U. Heinz and R. Snellings, Collective flow and viscosity in relativistic heavy-ion collisions, *Annu. Rev. Nucl. Part. Sci.* **63**, 123 (2013).
- [5] P. Braun-Munzinger, V. Koch, T. Schäfer, and J. Stachel, Properties of hot and dense matter from relativistic heavy ion collisions, *Phys. Rep.* **621**, 76 (2016).
- [6] W. Busza, K. Rajagopal, and W. van der Schee, Heavy ion collisions: The big picture, and the big questions, *Annu. Rev. Nucl. Part. Sci.* **68**, 339 (2018).
- [7] S. Voloshin and Y. Zhang, Flow study in relativistic nuclear collisions by Fourier expansion of Azimuthal particle distributions, *Z. Phys. C* **70**, 665 (1996).
- [8] S. Wang, Y. Z. Jiang, Y. M. Liu, D. Keane, D. Beavis, S. Y. Chu, S. Y. Fung, M. Vient, C. Hartnack, and H. Stoecker, Measurement of collective flow in heavy ion collisions using particle pair correlations, *Phys. Rev. C* **44**, 1091 (1991).
- [9] J. Jiang *et al.*, High Order Collective Flow Correlations in Heavy Ion Collisions, *Phys. Rev. Lett.* **68**, 2739 (1992).
- [10] N. Borghini, P. M. Dinh, and J.-Y. Ollitrault, Flow analysis from multiparticle azimuthal correlations, *Phys. Rev. C* **64**, 054901 (2001).
- [11] A. Bilandzic, R. Snellings, and S. Voloshin, Flow analysis with cumulants: Direct calculations, *Phys. Rev. C* **83**, 044913 (2011).
- [12] A. Bilandzic, C. H. Christensen, K. Gulbrandsen, A. Hansen, and Y. Zhou, Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations, *Phys. Rev. C* **89**, 064904 (2014).
- [13] H. Niemi, G. S. Denicol, H. Holopainen, and P. Huovinen, Event-by-event distributions of azimuthal asymmetries in ultrarelativistic heavy-ion collisions, *Phys. Rev. C* **87**, 054901 (2013).
- [14] G. Aad *et al.* (ATLAS Collaboration), Measurement of event-plane correlations in  $\sqrt{s_{NN}} = 2.76$  TeV lead-lead collisions with the ATLAS detector, *Phys. Rev. C* **90**, 024905 (2014).
- [15] J. Jia, Event-shape fluctuations and flow correlations in ultra-relativistic heavy-ion collisions, *J. Phys. G* **41**, 124003 (2014).
- [16] G. Aad *et al.* (ATLAS Collaboration), Measurement of the correlation between flow harmonics of different order in lead-lead collisions at  $\sqrt{s_{NN}} = 2.76$  TeV with the ATLAS detector, *Phys. Rev. C* **92**, 034903 (2015).
- [17] J. Qian and U. Heinz, Hydrodynamic flow amplitude correlations in event-by-event fluctuating heavy-ion collisions, *Phys. Rev. C* **94**, 024910 (2016).
- [18] J. Adam *et al.* (ALICE Collaboration), Correlated Event-by-Event Fluctuations of Flow Harmonics in Pb-Pb Collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, *Phys. Rev. Lett.* **117**, 182301 (2016).
- [19] H. Niemi, K. J. Eskola, and R. Paatelainen, Event-by-event fluctuations in a perturbative QCD + saturation + hydrodynamics model: Determining QCD matter shear viscosity in ultrarelativistic heavy-ion collisions, *Phys. Rev. C* **93**, 024907 (2016).
- [20] C. Mordasini, A. Bilandzic, D. Karakoç, and S. F. Taghavi, Higher order symmetric cumulants, *Phys. Rev. C* **102**, 024907 (2020).
- [21] R. Kubo, Generalized cumulant expansion method, *J. Phys. Soc. Jpn.* **17**, 1100 (1962).
- [22] K. Aamodt *et al.* (ALICE Collaboration), The ALICE experiment at the CERN LHC, *J. Instrum.* **3**, S08002 (2008).
- [23] C. W. Fabjan *et al.* (ALICE Collaboration), ALICE: Physics performance report, volume I, *J. Phys. G* **30**, 1517 (2004).
- [24] P. Cortese *et al.* (ALICE Collaboration), ALICE: Physics performance report, volume II, *J. Phys. G* **32**, 1295 (2006).
- [25] B. B. Abelev *et al.* (ALICE Collaboration), Performance of the ALICE experiment at the CERN LHC, *Int. J. Mod. Phys. A* **29**, 1430044 (2014).
- [26] J. Alme *et al.*, The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events, *Nucl. Instrum. Meth. A* **622**, 316 (2010).
- [27] G. Dellacasa *et al.* (ALICE Collaboration), ALICE technical design report of the inner tracking system (ITS), Report No. CERN-LHCC-99-12, 1999.
- [28] K. Aamodt *et al.* (ALICE Collaboration), Alignment of the ALICE Inner Tracking System with cosmic-ray tracks, *J. Instrum.* **5**, P03003 (2010).
- [29] K. Aamodt *et al.* (ALICE Collaboration), Centrality Dependence of the Charged-Particle Multiplicity Density at Mid-Rapidity in Pb-Pb Collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, *Phys. Rev. Lett.* **106**, 032301 (2011).
- [30] E. Abbas *et al.* (ALICE Collaboration), Performance of the ALICE VZERO system, *J. Instrum.* **8**, P10016 (2013).
- [31] J. Adam *et al.* (ALICE Collaboration), Centrality Dependence of the Charged-Particle Multiplicity Density at Mid-rapidity in Pb-Pb Collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *Phys. Rev. Lett.* **116**, 222302 (2016).
- [32] K. Aamodt *et al.* (ALICE Collaboration), Elliptic Flow of Charged Particles in Pb-Pb Collisions at 2.76 TeV, *Phys. Rev. Lett.* **105**, 252302 (2010).
- [33] S. Acharya *et al.* (ALICE Collaboration), Systematic studies of correlations between different order flow harmonics in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, *Phys. Rev. C* **97**, 024906 (2018).
- [34] S. Acharya *et al.* (ALICE Collaboration), Constraining the Chiral Magnetic Effect with charge-dependent azimuthal correlations in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  and 5.02 TeV, *J. High Energy Phys.* **09** (2020) 160.
- [35] M. Gyulassy and X.-N. Wang, HIJING 1.0: A Monte Carlo program for parton and particle production in high-energy hadronic and nuclear collisions, *Comput. Phys. Commun.* **83**, 307 (1994).
- [36] L. Yan and J.-Y. Ollitrault,  $\nu_4, \nu_5, \nu_6, \nu_7$ : Nonlinear hydrodynamic response versus LHC data, *Phys. Lett. B* **744**, 82 (2015).
- [37] J. E. Bernhard, J. S. Moreland, and S. A. Bass, Bayesian estimation of the specific shear and bulk viscosity of quark-gluon plasma, *Nat. Phys.* **15**, 1113 (2019).
- [38] R. Paatelainen, K. J. Eskola, H. Holopainen, and K. Tuominen, Multiplicities and  $p_T$  spectra in ultrarelativistic heavy ion collisions from a next-to-leading order improved perturbative QCD + saturation + hydrodynamics model, *Phys. Rev. C* **87**, 044904 (2013).
- [39] R. Paatelainen, K. J. Eskola, H. Niemi, and K. Tuominen, Fluid dynamics with saturated minijet initial conditions in ultrarelativistic heavy-ion collisions, *Phys. Lett. B* **731**, 126 (2014).

- [40] J. S. Moreland, J. E. Bernhard, and S. A. Bass, Alternative ansatz to wounded nucleon and binary collision scaling in high-energy nuclear collisions, *Phys. Rev. C* **92**, 011901(R) (2015).
- [41] C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass, and U. Heinz, The iEBE-VISHNU code package for relativistic heavy-ion collisions, *Comput. Phys. Commun.* **199**, 61 (2016).
- [42] H. Song and U. W. Heinz, Causal viscous hydrodynamics in  $2 + 1$  dimensions for relativistic heavy-ion collisions, *Phys. Rev. C* **77**, 064901 (2008).
- [43] S. Bass *et al.*, Microscopic models for ultrarelativistic heavy ion collisions, *Prog. Part. Nucl. Phys.* **41**, 255 (1998).
- [44] M. Bleicher *et al.*, Relativistic hadron hadron collisions in the ultrarelativistic quantum molecular dynamics model, *J. Phys. G* **25**, 1859 (1999).
- [45] D. Teaney and L. Yan, Triangularity and dipole asymmetry in heavy ion collisions, *Phys. Rev. C* **83**, 064904 (2011).
- [46] F. G. Gardim, F. Grassi, M. Luzum, and J.-Y. Ollitrault, Mapping the hydrodynamic response to the initial geometry in heavy-ion collisions, *Phys. Rev. C* **85**, 024908 (2012).
- [47] S. Acharya *et al.* (ALICE Collaboration), Linear and non-linear flow modes in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, *Phys. Lett. B* **773**, 68 (2017).
- [48] S. Acharya *et al.* (ALICE Collaboration), Higher harmonic non-linear flow modes of charged hadrons in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *J. High Energy Phys.* **05** (2020) 085.
- [49] J. E. Bernhard, J. S. Moreland, S. A. Bass, J. Liu, and U. Heinz, Applying Bayesian parameter estimation to relativistic heavy-ion collisions: simultaneous characterization of the initial state and quark-gluon plasma medium, *Phys. Rev. C* **94**, 024907 (2016).

S. Acharya,<sup>142</sup> D. Adamová,<sup>97</sup> A. Adler,<sup>75</sup> J. Adolfsson,<sup>82</sup> G. Aglieri Rinella,<sup>35</sup> M. Agnello,<sup>31</sup> N. Agrawal,<sup>55</sup> Z. Ahammed,<sup>142</sup> S. Ahmad,<sup>16</sup> S. U. Ahn,<sup>77</sup> Z. Akbar,<sup>52</sup> A. Akindinov,<sup>94</sup> M. Al-Turany,<sup>109</sup> D. S. D. Albuquerque,<sup>124</sup> D. Aleksandrov,<sup>90</sup> B. Alessandro,<sup>60</sup> H. M. Alfanda,<sup>7</sup> R. Alfaro Molina,<sup>72</sup> B. Ali,<sup>16</sup> Y. Ali,<sup>14</sup> A. Alici,<sup>26</sup> N. Alizadehvandchali,<sup>127</sup> A. Alkin,<sup>35</sup> J. Alme,<sup>21</sup> T. Alt,<sup>69</sup> L. Altenkamper,<sup>21</sup> I. Altsybeev,<sup>115</sup> M. N. Anaam,<sup>7</sup> C. Andrei,<sup>49</sup> D. Andreou,<sup>92</sup> A. Andronic,<sup>145</sup> V. Anguelov,<sup>106</sup> T. Antičić,<sup>110</sup> F. Antinori,<sup>58</sup> P. Antonioli,<sup>55</sup> C. Anuj,<sup>16</sup> N. Apadula,<sup>81</sup> L. Aphecetche,<sup>117</sup> H. Appelshäuser,<sup>69</sup> S. Arcelli,<sup>26</sup> R. Arnaldi,<sup>60</sup> M. Arratia,<sup>81</sup> I. C. Arsene,<sup>20</sup> M. Arslanodk,<sup>147,106</sup> A. Augustinus,<sup>35</sup> R. Averbeck,<sup>109</sup> S. Aziz,<sup>79</sup> M. D. Azmi,<sup>16</sup> A. Badalà,<sup>57</sup> Y. W. Baek,<sup>42</sup> X. Bai,<sup>109</sup> R. Bailhache,<sup>69</sup> R. Bala,<sup>103</sup> A. Balbino,<sup>31</sup> A. Baldisseri,<sup>139</sup> M. Ball,<sup>44</sup> D. Banerjee,<sup>4</sup> R. Barbera,<sup>27</sup> L. Barioglio,<sup>25</sup> M. Barlou,<sup>86</sup> G. G. Barnaföldi,<sup>146</sup> L. S. Barnby,<sup>96</sup> V. Barret,<sup>136</sup> C. Bartels,<sup>129</sup> K. Barth,<sup>35</sup> E. Bartsch,<sup>69</sup> F. Baruffaldi,<sup>28</sup> N. Bastid,<sup>136</sup> S. Basu,<sup>82,144</sup> G. Batigne,<sup>117</sup> B. Batyunya,<sup>76</sup> D. Bauri,<sup>50</sup> J. L. Bazo Alba,<sup>114</sup> I. G. Bearden,<sup>91</sup> C. Beattie,<sup>147</sup> I. Belikov,<sup>138</sup> A. D. C. Bell Hechavarria,<sup>145</sup> F. Bellini,<sup>35</sup> R. Bellwied,<sup>127</sup> S. Belokurova,<sup>115</sup> V. Belyaev,<sup>95</sup> G. Bencedi,<sup>70,146</sup> S. Beole,<sup>25</sup> A. Bercuci,<sup>49</sup> Y. Berdnikov,<sup>100</sup> A. Berdnikova,<sup>106</sup> D. Berenyi,<sup>146</sup> L. Bergmann,<sup>106</sup> M. G. Besoiu,<sup>68</sup> L. Betev,<sup>35</sup> P. P. Bhaduri,<sup>142</sup> A. Bhasin,<sup>103</sup> I. R. Bhat,<sup>103</sup> M. A. Bhat,<sup>4</sup> B. Bhattacharjee,<sup>43</sup> P. Bhattacharya,<sup>23</sup> A. Bianchi,<sup>25</sup> L. Bianchi,<sup>25</sup> N. Bianchi,<sup>53</sup> J. Bielčik,<sup>38</sup> J. Bielčíková,<sup>97</sup> A. Bilandzic,<sup>107</sup> G. Biro,<sup>146</sup> S. Biswas,<sup>4</sup> J. T. Blair,<sup>121</sup> D. Blau,<sup>90</sup> M. B. Blidaru,<sup>109</sup> C. Blume,<sup>69</sup> G. Boca,<sup>29</sup> F. Bock,<sup>98</sup> A. Bogdanov,<sup>95</sup> S. Boi,<sup>23</sup> J. Bok,<sup>62</sup> L. Boldizsár,<sup>146</sup> A. Bolognina,<sup>95</sup> M. Bombara,<sup>39</sup> P. M. Bond,<sup>35</sup> G. Bonomi,<sup>141</sup> H. Borel,<sup>139</sup> A. Borissov,<sup>83,95</sup> H. Bossi,<sup>147</sup> E. Botta,<sup>25</sup> L. Bratrud,<sup>69</sup> P. Braun-Munzinger,<sup>109</sup> M. Bregant,<sup>123</sup> M. Broz,<sup>38</sup> G. E. Bruno,<sup>108,34</sup> M. D. Buckland,<sup>129</sup> D. Budnikov,<sup>111</sup> H. Buesching,<sup>69</sup> S. Bufalino,<sup>31</sup> O. Bugnon,<sup>117</sup> P. Buhler,<sup>116</sup> P. Buncic,<sup>35</sup> Z. Buthelezi,<sup>73,133</sup> J. B. Butt,<sup>14</sup> S. A. Bysiak,<sup>120</sup> D. Caffarri,<sup>92</sup> A. Caliva,<sup>109</sup> E. Calvo Villar,<sup>114</sup> J. M. M. Camacho,<sup>122</sup> R. S. Camacho,<sup>46</sup> P. Camerini,<sup>24</sup> F. D. M. Canedo,<sup>123</sup> A. A. Capon,<sup>116</sup> F. Carnesecchi,<sup>26</sup> R. Caron,<sup>139</sup> J. Castillo Castellanos,<sup>139</sup> E. A. R. Casula,<sup>23</sup> F. Catalano,<sup>31</sup> C. Ceballos Sanchez,<sup>76</sup> P. Chakraborty,<sup>50</sup> S. Chandra,<sup>142</sup> W. Chang,<sup>7</sup> S. Chapeland,<sup>35</sup> M. Chartier,<sup>129</sup> S. Chattopadhyay,<sup>142</sup> S. Chattopadhyay,<sup>112</sup> A. Chauvin,<sup>23</sup> T. G. Chavez,<sup>46</sup> C. Cheshkov,<sup>137</sup> B. Cheynis,<sup>137</sup> V. Chibante Barroso,<sup>35</sup> D. D. Chinellato,<sup>124</sup> S. Cho,<sup>62</sup> P. Chochula,<sup>35</sup> P. Christakoglou,<sup>92</sup> C. H. Christensen,<sup>91</sup> P. Christiansen,<sup>82</sup> T. Chujo,<sup>135</sup> C. Cicalo,<sup>56</sup> L. Cifarelli,<sup>26</sup> F. Cindolo,<sup>55</sup> M. R. Ciupek,<sup>109</sup> G. Clai,<sup>55,b</sup> J. Cleymans,<sup>126</sup> F. Colamaria,<sup>54</sup> J. S. Colburn,<sup>113</sup> D. Colella,<sup>54,146</sup> A. Collu,<sup>81</sup> M. Colocci,<sup>35,26</sup> M. Concas,<sup>60,c</sup> G. Conesa Balbastre,<sup>80</sup> Z. Conesa del Valle,<sup>79</sup> G. Contin,<sup>24</sup> J. G. Contreras,<sup>38</sup> T. M. Cormier,<sup>98</sup> P. Cortese,<sup>32</sup> M. R. Cosentino,<sup>125</sup> F. Costa,<sup>35</sup> S. Costanza,<sup>29</sup> P. Crochet,<sup>136</sup> E. Cuautele,<sup>70</sup> P. Cui,<sup>7</sup> L. Cunqueiro,<sup>98</sup> A. Dainese,<sup>58</sup> F. P. A. Damas,<sup>117,139</sup> M. C. Danisch,<sup>106</sup> A. Danu,<sup>68</sup> I. Das,<sup>112</sup> P. Das,<sup>88</sup> P. Das,<sup>4</sup> S. Das,<sup>4</sup> S. Dash,<sup>50</sup> S. De,<sup>88</sup> A. De Caro,<sup>30</sup> G. de Cataldo,<sup>54</sup> L. De Cilladi,<sup>25</sup> J. de Cuveland,<sup>40</sup> A. De Falco,<sup>23</sup> D. De Gruttola,<sup>30</sup> N. De Marco,<sup>60</sup> C. De Martin,<sup>24</sup> S. De Pasquale,<sup>30</sup> S. Deb,<sup>51</sup> H. F. Degenhardt,<sup>123</sup> K. R. Deja,<sup>143</sup> L. Dello Stritto,<sup>30</sup> S. Delsanto,<sup>25</sup> W. Deng,<sup>7</sup> P. Dhankher,<sup>19</sup> D. Di Bari,<sup>34</sup> A. Di Mauro,<sup>35</sup> R. A. Diaz,<sup>8</sup> T. Dietel,<sup>126</sup> Y. Ding,<sup>7</sup> R. Divià,<sup>35</sup> D. U. Dixit,<sup>19</sup> Ø. Djuvsland,<sup>21</sup> U. Dmitrieva,<sup>64</sup> J. Do,<sup>62</sup> A. Dobrin,<sup>68</sup> B. Dönigus,<sup>69</sup> O. Dordic,<sup>20</sup> A. K. Dubey,<sup>142</sup> A. Dubla,<sup>109,92</sup> S. Dudi,<sup>102</sup> M. Dukhishyam,<sup>88</sup> P. Dupieux,<sup>136</sup> T. M. Eder,<sup>145</sup> R. J. Ehlers,<sup>98</sup> V. N. Eikeland,<sup>21</sup> D. Elia,<sup>54</sup> B. Erasmus,<sup>117</sup> F. Ercolessi,<sup>26</sup> F. Erhardt,<sup>101</sup>



A. Erokhin,<sup>115</sup> M. R. Ersdal,<sup>21</sup> B. Espagnon,<sup>79</sup> G. Eulisse,<sup>35</sup> D. Evans,<sup>113</sup> S. Evdokimov,<sup>93</sup> L. Fabbietti,<sup>107</sup> M. Faggin,<sup>28</sup>  
 J. Faivre,<sup>80</sup> F. Fan,<sup>7</sup> A. Fantoni,<sup>53</sup> M. Fasel,<sup>98</sup> P. Fecchio,<sup>31</sup> A. Feliciello,<sup>60</sup> G. Feofilov,<sup>115</sup> A. Fernández Téllez,<sup>46</sup>  
 A. Ferrero,<sup>139</sup> A. Ferretti,<sup>25</sup> A. Festanti,<sup>35</sup> V. J. G. Feuillard,<sup>106</sup> J. Figiel,<sup>120</sup> S. Filchagin,<sup>111</sup> D. Finogeev,<sup>64</sup> F. M. Fionda,<sup>21</sup>  
 G. Fiorenza,<sup>54</sup> F. Flor,<sup>127</sup> A. N. Flores,<sup>121</sup> S. Foertsch,<sup>73</sup> P. Foka,<sup>109</sup> S. Fokin,<sup>90</sup> E. Fragiaco,<sup>61</sup> U. Fuchs,<sup>35</sup> N. Funicello,<sup>30</sup>  
 C. Furget,<sup>80</sup> A. Furs,<sup>64</sup> M. Fusco Girard,<sup>30</sup> J. J. Gaardhøje,<sup>91</sup> M. Gagliardi,<sup>25</sup> A. M. Gago,<sup>114</sup> A. Gal,<sup>138</sup> C. D. Galvan,<sup>122</sup>  
 P. Ganoti,<sup>86</sup> C. Garabatos,<sup>109</sup> J. R. A. Garcia,<sup>46</sup> E. Garcia-Solis,<sup>10</sup> K. Garg,<sup>117</sup> C. Gargiulo,<sup>35</sup> A. Garibli,<sup>89</sup> K. Garner,<sup>145</sup>  
 P. Gasik,<sup>107</sup> E. F. Gauger,<sup>121</sup> M. B. Gay Ducati,<sup>71</sup> M. Germain,<sup>117</sup> J. Ghosh,<sup>112</sup> P. Ghosh,<sup>142</sup> S. K. Ghosh,<sup>4</sup> M. Giacalone,<sup>26</sup>  
 P. Gianotti,<sup>53</sup> P. Giubellino,<sup>109,60</sup> P. Giubilato,<sup>28</sup> A. M. C. Glaenger,<sup>139</sup> P. Glässel,<sup>106</sup> V. Gonzalez,<sup>144</sup>  
 L. H. González-Trueba,<sup>72</sup> S. Gorbunov,<sup>40</sup> L. Görlich,<sup>120</sup> S. Gotovac,<sup>36</sup> V. Grabski,<sup>72</sup> L. K. Graczykowski,<sup>143</sup>  
 K. L. Graham,<sup>113</sup> L. Greiner,<sup>81</sup> A. Grelli,<sup>63</sup> C. Grigoras,<sup>35</sup> V. Grigoriev,<sup>95</sup> A. Grigoryan,<sup>1,a</sup> S. Grigoryan,<sup>76,1</sup>  
 O. S. Groettvik,<sup>21</sup> F. Grosa,<sup>60</sup> J. F. Grosse-Oetringhaus,<sup>35</sup> R. Grosso,<sup>109</sup> R. Guernane,<sup>80</sup> M. Guilbaud,<sup>117</sup> M. Guittiere,<sup>117</sup>  
 K. Gulbrandsen,<sup>91</sup> T. Gunji,<sup>134</sup> A. Gupta,<sup>103</sup> R. Gupta,<sup>103</sup> I. B. Guzman,<sup>46</sup> R. Haake,<sup>147</sup> M. K. Habib,<sup>109</sup> C. Hadjidakis,<sup>79</sup>  
 H. Hamagaki,<sup>84</sup> G. Hamar,<sup>146</sup> M. Hamid,<sup>7</sup> R. Hannigan,<sup>121</sup> M. R. Haque,<sup>143,88</sup> A. Harlenderova,<sup>109</sup> J. W. Harris,<sup>147</sup>  
 A. Harton,<sup>10</sup> J. A. Hasenbichler,<sup>35</sup> H. Hassan,<sup>98</sup> D. Hatzifotiadou,<sup>55</sup> P. Hauer,<sup>44</sup> L. B. Havener,<sup>147</sup> S. Hayashi,<sup>134</sup>  
 S. T. Heckel,<sup>107</sup> E. Hellbär,<sup>69</sup> H. Helstrup,<sup>37</sup> T. Herman,<sup>38</sup> E. G. Hernandez,<sup>46</sup> G. Herrera Corral,<sup>9</sup> F. Herrmann,<sup>145</sup>  
 K. F. Hetland,<sup>37</sup> H. Hillemanns,<sup>35</sup> C. Hills,<sup>129</sup> B. Hippolyte,<sup>138</sup> B. Hohlweger,<sup>107</sup> J. Honermann,<sup>145</sup> G. H. Hong,<sup>148</sup>  
 D. Horak,<sup>38</sup> S. Hornung,<sup>109</sup> R. Hosokawa,<sup>15</sup> P. Hristov,<sup>35</sup> C. Huang,<sup>79</sup> C. Hughes,<sup>132</sup> P. Huhn,<sup>69</sup> T. J. Humanic,<sup>99</sup>  
 H. Hushnud,<sup>112</sup> L. A. Husova,<sup>145</sup> N. Hussain,<sup>43</sup> D. Hutter,<sup>40</sup> J. P. Iddon,<sup>35,129</sup> R. Ilkaev,<sup>111</sup> H. Ilyas,<sup>14</sup> M. Inaba,<sup>135</sup>  
 G. M. Innocenti,<sup>35</sup> M. Ippolitov,<sup>90</sup> A. Isakov,<sup>38,97</sup> M. S. Islam,<sup>112</sup> M. Ivanov,<sup>109</sup> V. Ivanov,<sup>100</sup> V. Izucheev,<sup>93</sup> B. Jacak,<sup>81</sup>  
 N. Jacazio,<sup>35,55</sup> P. M. Jacobs,<sup>81</sup> S. Jadlovská,<sup>119</sup> J. Jadlovsky,<sup>119</sup> S. Jaelani,<sup>63</sup> C. Jahnke,<sup>123</sup> M. J. Jakubowska,<sup>143</sup>  
 M. A. Janik,<sup>143</sup> T. Janson,<sup>75</sup> M. Jercic,<sup>101</sup> O. Jevons,<sup>113</sup> M. Jin,<sup>127</sup> F. Jonas,<sup>98,145</sup> P. G. Jones,<sup>113</sup> J. Jung,<sup>69</sup> M. Jung,<sup>69</sup>  
 A. Junique,<sup>35</sup> A. Jusko,<sup>113</sup> P. Kalinak,<sup>65</sup> A. Kalweit,<sup>35</sup> V. Kaplin,<sup>95</sup> S. Kar,<sup>7</sup> A. Karasu Uysal,<sup>78</sup> D. Karatovic,<sup>101</sup>  
 O. Karavichev,<sup>64</sup> T. Karavicheva,<sup>64</sup> P. Karczmarczyk,<sup>143</sup> E. Karpechev,<sup>64</sup> A. Kazantsev,<sup>90</sup> U. Kebschull,<sup>75</sup> R. Keidel,<sup>48</sup>  
 M. Keil,<sup>35</sup> B. Ketzer,<sup>44</sup> Z. Khabanova,<sup>92</sup> A. M. Khan,<sup>7</sup> S. Khan,<sup>16</sup> A. Khanzadeev,<sup>100</sup> Y. Kharlov,<sup>93</sup> A. Khatun,<sup>16</sup>  
 A. Khuntia,<sup>120</sup> B. Kileng,<sup>37</sup> B. Kim,<sup>62</sup> D. Kim,<sup>148</sup> D. J. Kim,<sup>128</sup> E. J. Kim,<sup>74</sup> H. Kim,<sup>17</sup> J. Kim,<sup>148</sup> J. S. Kim,<sup>42</sup> J. Kim,<sup>106</sup>  
 J. Kim,<sup>148</sup> J. Kim,<sup>74</sup> M. Kim,<sup>106</sup> S. Kim,<sup>18</sup> T. Kim,<sup>148</sup> S. Kirsch,<sup>69</sup> I. Kisel,<sup>40</sup> S. Kiselev,<sup>94</sup> A. Kisiel,<sup>143</sup> J. L. Klay,<sup>6</sup>  
 J. Klein,<sup>35,60</sup> S. Klein,<sup>81</sup> C. Klein-Bösing,<sup>145</sup> M. Kleiner,<sup>69</sup> T. Klemenz,<sup>107</sup> A. Kluge,<sup>35</sup> A. G. Knospe,<sup>127</sup> C. Kobdaj,<sup>118</sup>  
 M. K. Köhler,<sup>106</sup> T. Kollegger,<sup>109</sup> A. Kondratyev,<sup>76</sup> N. Kondratyeva,<sup>95</sup> E. Kondratyuk,<sup>93</sup> J. König,<sup>69</sup> S. A. Königstorfer,<sup>107</sup>  
 P. J. Konopka,<sup>2,35</sup> G. Kornakov,<sup>143</sup> S. D. Koryciak,<sup>2</sup> L. Koska,<sup>119</sup> O. Kovalenko,<sup>87</sup> V. Kovalenko,<sup>115</sup> M. Kowalski,<sup>120</sup>  
 I. Králik,<sup>65</sup> A. Kravčáková,<sup>39</sup> L. Kreis,<sup>109</sup> M. Krivda,<sup>113,65</sup> F. Krizek,<sup>97</sup> K. Krizkova Gajdosova,<sup>38</sup> M. Kroesen,<sup>106</sup>  
 M. Krüger,<sup>69</sup> E. Kryshen,<sup>100</sup> M. Krzewicki,<sup>40</sup> V. Kučera,<sup>35</sup> C. Kuhn,<sup>138</sup> P. G. Kuijer,<sup>92</sup> T. Kumaoka,<sup>135</sup> L. Kumar,<sup>102</sup>  
 S. Kundu,<sup>88</sup> P. Kurashvili,<sup>87</sup> A. Kurepin,<sup>64</sup> A. B. Kurepin,<sup>64</sup> A. Kuryakin,<sup>111</sup> S. Kuschpil,<sup>97</sup> J. Kvapil,<sup>113</sup> M. J. Kweon,<sup>62</sup>  
 J. Y. Kwon,<sup>62</sup> Y. Kwon,<sup>148</sup> S. L. La Pointe,<sup>40</sup> P. La Rocca,<sup>27</sup> Y. S. Lai,<sup>81</sup> A. Lakrathok,<sup>118</sup> M. Lamanna,<sup>35</sup> R. Langoy,<sup>131</sup>  
 K. Lapidus,<sup>35</sup> P. Larionov,<sup>53</sup> E. Laudi,<sup>35</sup> L. Lautner,<sup>35</sup> R. Lavicka,<sup>38</sup> T. Lazareva,<sup>115</sup> R. Lea,<sup>24</sup> J. Lee,<sup>135</sup> J. Lehrbach,<sup>40</sup>  
 R. C. Lemmon,<sup>96</sup> I. León Monzón,<sup>122</sup> E. D. Lesser,<sup>19</sup> M. Lettrich,<sup>35</sup> P. Lévai,<sup>146</sup> X. Li,<sup>11</sup> X. L. Li,<sup>7</sup> J. Lien,<sup>131</sup> R. Lietava,<sup>113</sup>  
 B. Lim,<sup>17</sup> S. H. Lim,<sup>17</sup> V. Lindenstruth,<sup>40</sup> A. Lindner,<sup>49</sup> C. Lippmann,<sup>109</sup> A. Liu,<sup>19</sup> J. Liu,<sup>129</sup> I. M. Lofnes,<sup>21</sup> V. Loginov,<sup>95</sup>  
 C. Loizides,<sup>98</sup> P. Loncar,<sup>36</sup> J. A. Lopez,<sup>106</sup> X. Lopez,<sup>136</sup> E. López Torres,<sup>8</sup> J. R. Luhder,<sup>145</sup> M. Lunardon,<sup>28</sup> G. Luparello,<sup>61</sup>  
 Y. G. Ma,<sup>41</sup> A. Maevskaya,<sup>64</sup> M. Mager,<sup>35</sup> S. M. Mahmood,<sup>20</sup> T. Mahmoud,<sup>44</sup> A. Maire,<sup>138</sup> R. D. Majka,<sup>147,a</sup> M. Malaev,<sup>100</sup>  
 Q. W. Malik,<sup>20</sup> L. Malinina,<sup>76,d</sup> D. Mal'Kevich,<sup>94</sup> N. Mallick,<sup>51</sup> P. Malzacher,<sup>109</sup> G. Mandaglio,<sup>33,57</sup> V. Manko,<sup>90</sup>  
 F. Manso,<sup>136</sup> V. Manzari,<sup>54</sup> Y. Mao,<sup>7</sup> J. Mareš,<sup>67</sup> G. V. Margagliotti,<sup>24</sup> A. Margotti,<sup>55</sup> A. Marín,<sup>109</sup> C. Markert,<sup>121</sup>  
 M. Marquard,<sup>69</sup> N. A. Martin,<sup>106</sup> P. Martinengo,<sup>35</sup> J. L. Martinez,<sup>127</sup> M. I. Martínez,<sup>46</sup> G. Martínez García,<sup>117</sup>  
 S. Masciocchi,<sup>109</sup> M. Maserà,<sup>25</sup> A. Masoni,<sup>56</sup> L. Massacrier,<sup>79</sup> A. Mastroserio,<sup>140,54</sup> A. M. Mathis,<sup>107</sup> O. Matonoha,<sup>82</sup>  
 P. F. T. Matuoka,<sup>123</sup> A. Matyja,<sup>120</sup> C. Mayer,<sup>120</sup> A. L. Mazuecos,<sup>35</sup> F. Mazzaschi,<sup>25</sup> M. Mazzilli,<sup>35,54</sup> M. A. Mazzoni,<sup>59</sup>  
 A. F. Mechler,<sup>69</sup> F. Meddi,<sup>22</sup> Y. Melikyan,<sup>64</sup> A. Menchaca-Rocha,<sup>72</sup> C. Mengke,<sup>28,7</sup> E. Meninno,<sup>116,30</sup> A. S. Menon,<sup>127</sup>  
 M. Meres,<sup>13</sup> S. Mhlanga,<sup>126</sup> Y. Miake,<sup>135</sup> L. Micheletti,<sup>25</sup> L. C. Migliorin,<sup>137</sup> D. L. Mihaylov,<sup>107</sup> K. Mikhaylov,<sup>76,94</sup>  
 A. N. Mishra,<sup>146,70</sup> D. Miśkowiec,<sup>109</sup> A. Modak,<sup>4</sup> N. Mohammadi,<sup>35</sup> A. P. Mohanty,<sup>63</sup> B. Mohanty,<sup>88</sup> M. Mohisin Khan,<sup>16</sup>  
 Z. Moravcova,<sup>91</sup> C. Mordasini,<sup>107</sup> D. A. Moreira De Godoy,<sup>145</sup> L. A. P. Moreno,<sup>46</sup> I. Morozov,<sup>64</sup> A. Morsch,<sup>35</sup> T. Mrnjavac,<sup>35</sup>  
 V. Muccifora,<sup>53</sup> E. Mudnic,<sup>36</sup> D. Mühlheim,<sup>145</sup> S. Muhuri,<sup>142</sup> J. D. Mulligan,<sup>81</sup> A. Mulliri,<sup>23</sup> M. G. Munhoz,<sup>123</sup>  
 R. H. Munzer,<sup>69</sup> H. Murakami,<sup>134</sup> S. Murray,<sup>126</sup> L. Musa,<sup>35</sup> J. Musinsky,<sup>65</sup> C. J. Myers,<sup>127</sup> J. W. Myrcha,<sup>143</sup> B. Naik,<sup>50</sup>

R. Nair,<sup>87</sup> B. K. Nandi,<sup>50</sup> R. Nania,<sup>55</sup> E. Nappi,<sup>54</sup> M. U. Naru,<sup>14</sup> A. F. Nassirpour,<sup>82</sup> C. Natrass,<sup>132</sup> S. Nazarenko,<sup>111</sup>  
A. Neagu,<sup>20</sup> L. Nellen,<sup>70</sup> S. V. Nesbo,<sup>37</sup> G. Neskovic,<sup>40</sup> D. Nesterov,<sup>115</sup> B. S. Nielsen,<sup>91</sup> S. Nikolaev,<sup>90</sup> S. Nikulin,<sup>90</sup>  
V. Nikulin,<sup>100</sup> F. Noferini,<sup>55</sup> S. Noh,<sup>12</sup> P. Nomokonov,<sup>76</sup> J. Norman,<sup>129</sup> N. Novitzky,<sup>135</sup> P. Nowakowski,<sup>143</sup> A. Nyanin,<sup>90</sup>  
J. Nystrand,<sup>21</sup> M. Ogino,<sup>84</sup> A. Ohlson,<sup>82</sup> J. Oleniacz,<sup>143</sup> A. C. Oliveira Da Silva,<sup>132</sup> M. H. Oliver,<sup>147</sup> A. Onnerstad,<sup>128</sup>  
C. Oppedisano,<sup>60</sup> A. Ortiz Velasquez,<sup>70</sup> T. Osako,<sup>47</sup> A. Oskarsson,<sup>82</sup> J. Otwinowski,<sup>120</sup> K. Oyama,<sup>84</sup> Y. Pachmayer,<sup>106</sup>  
S. Padhan,<sup>50</sup> D. Pagano,<sup>141</sup> G. Pačić,<sup>70</sup> A. Palasciano,<sup>54</sup> J. Pan,<sup>144</sup> S. Panebianco,<sup>139</sup> P. Pareek,<sup>142</sup> J. Park,<sup>62</sup> J. E. Parkkila,<sup>128</sup>  
S. Parmar,<sup>102</sup> S. P. Pathak,<sup>127</sup> B. Paul,<sup>23</sup> J. Pazzini,<sup>141</sup> H. Pei,<sup>7</sup> T. Peitzmann,<sup>63</sup> X. Peng,<sup>7</sup> L. G. Pereira,<sup>71</sup>  
H. Pereira Da Costa,<sup>139</sup> D. Peresunko,<sup>90</sup> G. M. Perez,<sup>8</sup> S. Perrin,<sup>139</sup> Y. Pestov,<sup>5</sup> V. Petráček,<sup>38</sup> M. Petrovici,<sup>49</sup> R. P. Pezzi,<sup>71</sup>  
S. Piano,<sup>61</sup> M. Pikna,<sup>13</sup> P. Pillot,<sup>117</sup> O. Pinazza,<sup>55,35</sup> L. Pinsky,<sup>127</sup> C. Pinto,<sup>27</sup> S. Pisano,<sup>53</sup> M. Płoskoń,<sup>81</sup> M. Planinic,<sup>101</sup>  
F. Pliquett,<sup>69</sup> M. G. Poghosyan,<sup>98</sup> B. Polichtchouk,<sup>93</sup> N. Poljak,<sup>101</sup> A. Pop,<sup>49</sup> S. Porteboeuf-Houssais,<sup>136</sup> J. Porter,<sup>81</sup>  
V. Pozdniakov,<sup>76</sup> S. K. Prasad,<sup>4</sup> R. Preghenella,<sup>55</sup> F. Prino,<sup>60</sup> C. A. Pruneau,<sup>144</sup> I. Pshenichnov,<sup>64</sup> M. Puccio,<sup>35</sup> S. Qiu,<sup>92</sup>  
L. Quaglia,<sup>25</sup> R. E. Quishpe,<sup>127</sup> S. Ragoni,<sup>113</sup> A. Rakotozafindrabe,<sup>139</sup> L. Ramello,<sup>32</sup> F. Rami,<sup>138</sup> S. A. R. Ramirez,<sup>46</sup>  
A. G. T. Ramos,<sup>34</sup> R. Raniwala,<sup>104</sup> S. Raniwala,<sup>104</sup> S. S. Räsänen,<sup>45</sup> R. Rath,<sup>51</sup> I. Ravasenga,<sup>92</sup> K. F. Read,<sup>98,132</sup>  
A. R. Redelbach,<sup>40</sup> K. Redlich,<sup>87,e</sup> A. Rehman,<sup>21</sup> P. Reichelt,<sup>69</sup> F. Reidt,<sup>35</sup> R. Renfordt,<sup>69</sup> Z. Rescakova,<sup>39</sup> K. Reygers,<sup>106</sup>  
A. Riabov,<sup>100</sup> V. Riabov,<sup>100</sup> T. Richert,<sup>82,91</sup> M. Richter,<sup>20</sup> P. Riedler,<sup>35</sup> W. Riegler,<sup>35</sup> F. Riggi,<sup>27</sup> C. Ristea,<sup>68</sup> S. P. Rode,<sup>51</sup>  
M. Rodríguez Cahuantzi,<sup>46</sup> K. Røed,<sup>20</sup> R. Rogalev,<sup>93</sup> E. Rogochaya,<sup>76</sup> T. S. Rogoschinski,<sup>69</sup> D. Rohr,<sup>35</sup> D. Röhrich,<sup>21</sup>  
P. F. Rojas,<sup>46</sup> P. S. Rokita,<sup>143</sup> F. Ronchetti,<sup>53</sup> A. Rosano,<sup>33,57</sup> E. D. Rosas,<sup>70</sup> A. Rossi,<sup>58</sup> A. Rotondi,<sup>29</sup> A. Roy,<sup>51</sup> P. Roy,<sup>112</sup>  
N. Rubini,<sup>26</sup> O. V. Rueda,<sup>82</sup> R. Rui,<sup>24</sup> B. Rumyantsev,<sup>76</sup> A. Rustamov,<sup>89</sup> E. Ryabinkin,<sup>90</sup> Y. Ryabov,<sup>100</sup> A. Rybicki,<sup>120</sup>  
H. Rytkonen,<sup>128</sup> W. Rzesza,<sup>143</sup> O. A. M. Saarimäki,<sup>45</sup> R. Sadek,<sup>117</sup> S. Sadovsky,<sup>93</sup> J. Saetre,<sup>21</sup> K. Šafařík,<sup>38</sup> S. K. Saha,<sup>142</sup>  
S. Saha,<sup>88</sup> B. Sahoo,<sup>50</sup> P. Sahoo,<sup>50</sup> R. Sahoo,<sup>51</sup> S. Sahoo,<sup>66</sup> D. Sahu,<sup>51</sup> P. K. Sahu,<sup>66</sup> J. Saini,<sup>142</sup> S. Sakai,<sup>135</sup> S. Sambyal,<sup>103</sup>  
V. Samsonov,<sup>100,95,a</sup> D. Sarkar,<sup>144</sup> N. Sarkar,<sup>142</sup> P. Sarma,<sup>43</sup> V. M. Sarti,<sup>107</sup> M. H. P. Sas,<sup>147,63</sup> J. Schambach,<sup>98,121</sup>  
H. S. Scheid,<sup>69</sup> C. Schiaua,<sup>49</sup> R. Schicker,<sup>106</sup> A. Schmah,<sup>106</sup> C. Schmidt,<sup>109</sup> H. R. Schmidt,<sup>105</sup> M. O. Schmidt,<sup>106</sup>  
M. Schmidt,<sup>105</sup> N. V. Schmidt,<sup>98,69</sup> A. R. Schmier,<sup>132</sup> R. Schotter,<sup>138</sup> J. Schukraft,<sup>35</sup> Y. Schutz,<sup>138</sup> K. Schwarz,<sup>109</sup>  
K. Schweda,<sup>109</sup> G. Scioli,<sup>26</sup> E. Scomparin,<sup>60</sup> J. E. Seger,<sup>15</sup> Y. Sekiguchi,<sup>134</sup> D. Sekihata,<sup>134</sup> I. Selyuzhenkov,<sup>109,95</sup>  
S. Senyukov,<sup>138</sup> J. J. Seo,<sup>62</sup> D. Serebryakov,<sup>64</sup> L. Šerkšnytė,<sup>107</sup> A. Sevcenco,<sup>68</sup> A. Shabanov,<sup>64</sup> A. Shabetai,<sup>117</sup>  
R. Shahoyan,<sup>35</sup> W. Shaikh,<sup>112</sup> A. Shangaraev,<sup>93</sup> A. Sharma,<sup>102</sup> H. Sharma,<sup>120</sup> M. Sharma,<sup>103</sup> N. Sharma,<sup>102</sup> S. Sharma,<sup>103</sup>  
O. Sheibani,<sup>127</sup> A. I. Sheikh,<sup>142</sup> K. Shigaki,<sup>47</sup> M. Shimomura,<sup>85</sup> S. Shirinkin,<sup>94</sup> Q. Shou,<sup>41</sup> Y. Sibirak,<sup>90</sup> S. Siddhanta,<sup>56</sup>  
T. Siemiarczuk,<sup>87</sup> T. F. D. Silva,<sup>123</sup> D. Silvermyr,<sup>82</sup> G. Simatovic,<sup>92</sup> G. Simonetti,<sup>35</sup> B. Singh,<sup>107</sup> R. Singh,<sup>88</sup> R. Singh,<sup>103</sup>  
R. Singh,<sup>51</sup> V. K. Singh,<sup>142</sup> V. Singhal,<sup>142</sup> T. Sinha,<sup>112</sup> B. Sitar,<sup>13</sup> M. Sitta,<sup>32</sup> T. B. Skaali,<sup>20</sup> G. Skorodumovs,<sup>106</sup>  
M. Slupecki,<sup>45</sup> N. Smirnov,<sup>147</sup> R. J. M. Snellings,<sup>63</sup> C. Soncco,<sup>114</sup> J. Song,<sup>127</sup> A. Songmoolnak,<sup>118</sup> F. Soramel,<sup>28</sup>  
S. Sorensen,<sup>132</sup> I. Sputowska,<sup>120</sup> J. Stachel,<sup>106</sup> I. Stan,<sup>68</sup> P. J. Steffanic,<sup>132</sup> S. F. Stiefelmaier,<sup>106</sup> D. Stocco,<sup>117</sup>  
M. M. Storetvedt,<sup>37</sup> C. P. Stylianidis,<sup>92</sup> A. A. P. Suaide,<sup>123</sup> T. Sugitate,<sup>47</sup> C. Suire,<sup>79</sup> M. Suljic,<sup>35</sup> R. Sultanov,<sup>94</sup>  
M. Šumbera,<sup>97</sup> V. Sumberia,<sup>103</sup> S. Sumowidagdo,<sup>52</sup> S. Swain,<sup>66</sup> A. Szabo,<sup>13</sup> I. Szarka,<sup>13</sup> U. Tabassam,<sup>14</sup> S. F. Taghavi,<sup>107</sup>  
G. TAILLEPIED,<sup>136</sup> J. Takahashi,<sup>124</sup> G. J. Tambave,<sup>21</sup> S. Tang,<sup>136,7</sup> Z. Tang,<sup>130</sup> M. Tarhini,<sup>117</sup> M. G. Tazila,<sup>49</sup> A. Tauro,<sup>35</sup>  
G. Tejada Muñoz,<sup>46</sup> A. Telesca,<sup>35</sup> L. Terlizzi,<sup>25</sup> C. Terrevoli,<sup>127</sup> G. Tersimonov,<sup>3</sup> S. Thakur,<sup>142</sup> D. Thomas,<sup>121</sup> R. Tieulent,<sup>137</sup>  
A. Tikhonov,<sup>64</sup> A. R. Timmins,<sup>127</sup> M. Tkacik,<sup>119</sup> A. Toia,<sup>69</sup> N. Topilskaya,<sup>64</sup> M. Toppi,<sup>53</sup> F. Torales-Acosta,<sup>19</sup> S. R. Torres,<sup>38</sup>  
A. Trifiró,<sup>33,57</sup> S. Tripathy,<sup>70</sup> T. Tripathy,<sup>50</sup> S. Trogolo,<sup>28</sup> G. Trombetta,<sup>34</sup> V. Trubnikov,<sup>3</sup> W. H. Trzaska,<sup>128</sup> T. P. Trzcinski,<sup>143</sup>  
B. A. Trzeciak,<sup>38</sup> A. Tumkin,<sup>111</sup> R. Turrisi,<sup>58</sup> T. S. Tveter,<sup>20</sup> K. Ullaland,<sup>21</sup> E. N. Umaka,<sup>127</sup> A. Uras,<sup>137</sup> M. Urioni,<sup>141</sup>  
G. L. Usai,<sup>23</sup> M. Vala,<sup>39</sup> N. Valle,<sup>29</sup> S. Vallero,<sup>60</sup> N. van der Kolk,<sup>63</sup> L. V. R. van Doremalen,<sup>63</sup> M. van Leeuwen,<sup>92</sup>  
P. Vande Vyvre,<sup>35</sup> D. Varga,<sup>146</sup> Z. Varga,<sup>146</sup> M. Varga-Kofarago,<sup>146</sup> A. Vargas,<sup>46</sup> M. Vasileiou,<sup>86</sup> A. Vasiliev,<sup>90</sup>  
O. Vázquez Doce,<sup>107</sup> V. Vechernin,<sup>115</sup> E. Vercellin,<sup>25</sup> S. Vergara Limón,<sup>46</sup> L. Vermunt,<sup>63</sup> R. Vértesi,<sup>146</sup> M. Verweij,<sup>63</sup>  
L. Vickovic,<sup>36</sup> Z. Vilakazi,<sup>133</sup> O. Villalobos Baillie,<sup>113</sup> G. VINO,<sup>54</sup> A. Vinogradov,<sup>90</sup> T. Virgili,<sup>30</sup> V. Vislavicius,<sup>91</sup>  
A. Vodopyanov,<sup>76</sup> B. Volkel,<sup>35</sup> M. A. Völkl,<sup>105</sup> K. Voloshin,<sup>94</sup> S. A. Voloshin,<sup>144</sup> G. Volpe,<sup>34</sup> B. von Haller,<sup>35</sup> I. Vorobyev,<sup>107</sup>  
D. Voscek,<sup>119</sup> J. Vrláková,<sup>39</sup> B. Wagner,<sup>21</sup> M. Weber,<sup>116</sup> A. Wegrzynek,<sup>35</sup> S. C. Wenzel,<sup>35</sup> J. P. Wessels,<sup>145</sup> J. Wiechula,<sup>69</sup>  
J. Wikne,<sup>20</sup> G. Wilk,<sup>87</sup> J. Wilkinson,<sup>109</sup> G. A. Willems,<sup>145</sup> E. Willsher,<sup>113</sup> B. Windelband,<sup>106</sup> M. Winn,<sup>139</sup> W. E. Witt,<sup>132</sup>  
J. R. Wright,<sup>121</sup> Y. Wu,<sup>130</sup> R. Xu,<sup>7</sup> S. Yalcin,<sup>78</sup> Y. Yamaguchi,<sup>47</sup> K. Yamakawa,<sup>47</sup> S. Yang,<sup>21</sup> S. Yano,<sup>47,139</sup> Z. Yin,<sup>7</sup>  
H. Yokoyama,<sup>63</sup> I.-K. Yoo,<sup>17</sup> J. H. Yoon,<sup>62</sup> S. Yuan,<sup>21</sup> A. Yuncu,<sup>106</sup> V. Yurchenko,<sup>3</sup> V. Zaccolo,<sup>24</sup> A. Zaman,<sup>14</sup> C. Zampolli,<sup>35</sup>  
H. J. C. Zanolí,<sup>63</sup> N. Zardoshti,<sup>35</sup> A. Zarochentsev,<sup>115</sup> P. Závada,<sup>67</sup> N. Zaviyalov,<sup>111</sup> H. Zbroszczyk,<sup>143</sup> M. Zhalov,<sup>100</sup>

S. Zhang,<sup>41</sup> X. Zhang,<sup>7</sup> Y. Zhang,<sup>130</sup> V. Zherebchevskii,<sup>115</sup> Y. Zhi,<sup>11</sup> D. Zhou,<sup>7</sup> Y. Zhou,<sup>91</sup> J. Zhu,<sup>7,109</sup> Y. Zhu,<sup>7</sup> A. Zichichi,<sup>26</sup>  
G. Zinovjev,<sup>3</sup> and N. Zurlo<sup>141</sup>

(ALICE Collaboration)

- <sup>1</sup>A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia  
<sup>2</sup>AGH University of Science and Technology, Cracow, Poland  
<sup>3</sup>Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine  
<sup>4</sup>Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India  
<sup>5</sup>Budker Institute for Nuclear Physics, Novosibirsk, Russia  
<sup>6</sup>California Polytechnic State University, San Luis Obispo, California, USA  
<sup>7</sup>Central China Normal University, Wuhan, China  
<sup>8</sup>Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba  
<sup>9</sup>Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico  
<sup>10</sup>Chicago State University, Chicago, Illinois, USA  
<sup>11</sup>China Institute of Atomic Energy, Beijing, China  
<sup>12</sup>Chungbuk National University, Cheongju, Republic of Korea  
<sup>13</sup>Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovakia  
<sup>14</sup>COMSATS University Islamabad, Islamabad, Pakistan  
<sup>15</sup>Creighton University, Omaha, Nebraska, USA  
<sup>16</sup>Department of Physics, Aligarh Muslim University, Aligarh, India  
<sup>17</sup>Department of Physics, Pusan National University, Pusan, Republic of Korea  
<sup>18</sup>Department of Physics, Sejong University, Seoul, Republic of Korea  
<sup>19</sup>Department of Physics, University of California, Berkeley, California, USA  
<sup>20</sup>Department of Physics, University of Oslo, Oslo, Norway  
<sup>21</sup>Department of Physics and Technology, University of Bergen, Bergen, Norway  
<sup>22</sup>Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, Italy  
<sup>23</sup>Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy  
<sup>24</sup>Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy  
<sup>25</sup>Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy  
<sup>26</sup>Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy  
<sup>27</sup>Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy  
<sup>28</sup>Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy  
<sup>29</sup>Dipartimento di Fisica e Nucleare e Teorica, Università di Pavia and Sezione INFN, Pavia, Italy  
<sup>30</sup>Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy  
<sup>31</sup>Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy  
<sup>32</sup>Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy  
<sup>33</sup>Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy  
<sup>34</sup>Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy  
<sup>35</sup>European Organization for Nuclear Research (CERN), Geneva, Switzerland  
<sup>36</sup>Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia  
<sup>37</sup>Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway  
<sup>38</sup>Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic  
<sup>39</sup>Faculty of Science, P.J. Šafárik University, Košice, Slovakia  
<sup>40</sup>Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany  
<sup>41</sup>Fudan University, Shanghai, China  
<sup>42</sup>Gangneung-Wonju National University, Gangneung, Republic of Korea  
<sup>43</sup>Gauhati University, Department of Physics, Guwahati, India  
<sup>44</sup>Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany  
<sup>45</sup>Helsinki Institute of Physics (HIP), Helsinki, Finland  
<sup>46</sup>High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico  
<sup>47</sup>Hiroshima University, Hiroshima, Japan  
<sup>48</sup>Hochschule Worms, Zentrum für Technologietransfer und Telekommunikation (ZTT), Worms, Germany  
<sup>49</sup>Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania  
<sup>50</sup>Indian Institute of Technology Bombay (IIT), Mumbai, India  
<sup>51</sup>Indian Institute of Technology Indore, Indore, India  
<sup>52</sup>Indonesian Institute of Sciences, Jakarta, Indonesia

- <sup>53</sup>INFN, Laboratori Nazionali di Frascati, Frascati, Italy  
<sup>54</sup>INFN, Sezione di Bari, Bari, Italy  
<sup>55</sup>INFN, Sezione di Bologna, Bologna, Italy  
<sup>56</sup>INFN, Sezione di Cagliari, Cagliari, Italy  
<sup>57</sup>INFN, Sezione di Catania, Catania, Italy  
<sup>58</sup>INFN, Sezione di Padova, Padova, Italy  
<sup>59</sup>INFN, Sezione di Roma, Rome, Italy  
<sup>60</sup>INFN, Sezione di Torino, Turin, Italy  
<sup>61</sup>INFN, Sezione di Trieste, Trieste, Italy  
<sup>62</sup>Inha University, Incheon, Republic of Korea  
<sup>63</sup>Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef, Utrecht, Netherlands  
<sup>64</sup>Institute for Nuclear Research, Academy of Sciences, Moscow, Russia  
<sup>65</sup>Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia  
<sup>66</sup>Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India  
<sup>67</sup>Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic  
<sup>68</sup>Institute of Space Science (ISS), Bucharest, Romania  
<sup>69</sup>Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany  
<sup>70</sup>Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico  
<sup>71</sup>Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil  
<sup>72</sup>Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico  
<sup>73</sup>iThemba LABS, National Research Foundation, Somerset West, South Africa  
<sup>74</sup>Jeonbuk National University, Jeonju, Republic of Korea  
<sup>75</sup>Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany  
<sup>76</sup>Joint Institute for Nuclear Research (JINR), Dubna, Russia  
<sup>77</sup>Korea Institute of Science and Technology Information, Daejeon, Republic of Korea  
<sup>78</sup>KTO Karatay University, Konya, Turkey  
<sup>79</sup>Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie, Orsay, France  
<sup>80</sup>Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France  
<sup>81</sup>Lawrence Berkeley National Laboratory, Berkeley, California, USA  
<sup>82</sup>Lund University Department of Physics, Division of Particle Physics, Lund, Sweden  
<sup>83</sup>Moscow Institute for Physics and Technology, Moscow, Russia  
<sup>84</sup>Nagasaki Institute of Applied Science, Nagasaki, Japan  
<sup>85</sup>Nara Women's University (NWU), Nara, Japan  
<sup>86</sup>National and Kapodistrian University of Athens, School of Science, Department of Physics, Athens, Greece  
<sup>87</sup>National Centre for Nuclear Research, Warsaw, Poland  
<sup>88</sup>National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India  
<sup>89</sup>National Nuclear Research Center, Baku, Azerbaijan  
<sup>90</sup>National Research Centre Kurchatov Institute, Moscow, Russia  
<sup>91</sup>Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark  
<sup>92</sup>Nikhef, National institute for subatomic physics, Amsterdam, Netherlands  
<sup>93</sup>NRC Kurchatov Institute IHEP, Protvino, Russia  
<sup>94</sup>NRC « Kurchatov»what Institute—ITEP, Moscow, Russia  
<sup>95</sup>NRNU Moscow Engineering Physics Institute, Moscow, Russia  
<sup>96</sup>Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom  
<sup>97</sup>Nuclear Physics Institute of the Czech Academy of Sciences, Řež u Prahy, Czech Republic  
<sup>98</sup>Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA  
<sup>99</sup>Ohio State University, Columbus, Ohio, USA  
<sup>100</sup>Petersburg Nuclear Physics Institute, Gatchina, Russia  
<sup>101</sup>Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia  
<sup>102</sup>Physics Department, Panjab University, Chandigarh, India  
<sup>103</sup>Physics Department, University of Jammu, Jammu, India  
<sup>104</sup>Physics Department, University of Rajasthan, Jaipur, India  
<sup>105</sup>Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany  
<sup>106</sup>Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany  
<sup>107</sup>Physik Department, Technische Universität München, Munich, Germany  
<sup>108</sup>Politecnico di Bari and Sezione INFN, Bari, Italy  
<sup>109</sup>Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany  
<sup>110</sup>Rudjer Bošković Institute, Zagreb, Croatia  
<sup>111</sup>Russian Federal Nuclear Center (VNIIEF), Sarov, Russia

- <sup>112</sup>*Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India*  
<sup>113</sup>*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*  
<sup>114</sup>*Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru*  
<sup>115</sup>*St. Petersburg State University, St. Petersburg, Russia*  
<sup>116</sup>*Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria*  
<sup>117</sup>*SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France*  
<sup>118</sup>*Suranaree University of Technology, Nakhon Ratchasima, Thailand*  
<sup>119</sup>*Technical University of Košice, Košice, Slovakia*  
<sup>120</sup>*The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland*  
<sup>121</sup>*The University of Texas at Austin, Austin, Texas, USA*  
<sup>122</sup>*Universidad Autónoma de Sinaloa, Culiacán, Mexico*  
<sup>123</sup>*Universidade de São Paulo (USP), São Paulo, Brazil*  
<sup>124</sup>*Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil*  
<sup>125</sup>*Universidade Federal do ABC, Santo Andre, Brazil*  
<sup>126</sup>*University of Cape Town, Cape Town, South Africa*  
<sup>127</sup>*University of Houston, Houston, Texas, USA*  
<sup>128</sup>*University of Jyväskylä, Jyväskylä, Finland*  
<sup>129</sup>*University of Liverpool, Liverpool, United Kingdom*  
<sup>130</sup>*University of Science and Technology of China, Hefei, China*  
<sup>131</sup>*University of South-Eastern Norway, Tonsberg, Norway*  
<sup>132</sup>*University of Tennessee, Knoxville, Tennessee, USA*  
<sup>133</sup>*University of the Witwatersrand, Johannesburg, South Africa*  
<sup>134</sup>*University of Tokyo, Tokyo, Japan*  
<sup>135</sup>*University of Tsukuba, Tsukuba, Japan*  
<sup>136</sup>*Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*  
<sup>137</sup>*Université de Lyon, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon, Lyon, France*  
<sup>138</sup>*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France*  
<sup>139</sup>*Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Département de Physique Nucléaire (DPHn), Saclay, France*  
<sup>140</sup>*Università degli Studi di Foggia, Foggia, Italy*  
<sup>141</sup>*Università di Brescia and Sezione INFN, Brescia, Italy*  
<sup>142</sup>*Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India*  
<sup>143</sup>*Warsaw University of Technology, Warsaw, Poland*  
<sup>144</sup>*Wayne State University, Detroit, Michigan, USA*  
<sup>145</sup>*Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany*  
<sup>146</sup>*Wigner Research Centre for Physics, Budapest, Hungary*  
<sup>147</sup>*Yale University, New Haven, Connecticut, USA*  
<sup>148</sup>*Yonsei University, Seoul, Republic of Korea*

<sup>a</sup>Deceased.

<sup>b</sup>Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy.

<sup>c</sup>Also at Dipartimento DET del Politecnico di Torino, Turin, Italy.

<sup>d</sup>Also at M.V. Lomonosov Moscow State University, D.V. Skobel'syn Institute of Nuclear, Physics, Moscow, Russia.

<sup>e</sup>Also at Institute of Theoretical Physics, University of Wrocław, Poland.