



CERN-PH-EP-2016-102
20 April 2016

Correlated event-by-event fluctuations of flow harmonics in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

ALICE Collaboration*

Abstract

We report the measurements of correlations between event-by-event fluctuations of amplitudes of anisotropic flow harmonics in nucleus–nucleus collisions, obtained for the first time using a new analysis method based on multiparticle cumulants in mixed harmonics. This novel method is robust against systematic biases originating from non-flow effects and by construction any dependence on symmetry planes is eliminated. We demonstrate that correlations of flow harmonics exhibit a better sensitivity to medium properties than the individual flow harmonics. The new measurements are performed in Pb–Pb collisions at the centre-of-mass energy per nucleon pair of $\sqrt{s_{\text{NN}}} = 2.76$ TeV by the ALICE experiment at the Large Hadron Collider (LHC). The centrality dependence of correlation between event-by-event fluctuations of the elliptic, v_2 , and quadrangular, v_4 , flow harmonics, as well as of anti-correlation between v_2 and triangular, v_3 , flow harmonics are presented. The results cover two different regimes of the initial state configurations: geometry-dominated (in mid-central collisions) and fluctuation-dominated (in the most central collisions). Comparisons are made to predictions from MC-Glauber, viscous hydrodynamics, AMPT and HIJING models. Together with the existing measurements of individual flow harmonics the presented results provide further constraints on initial conditions and the transport properties of the system produced in heavy-ion collisions.

© 2016 CERN for the benefit of the ALICE Collaboration.

Reproduction of this article or parts of it is allowed as specified in the CC-BY-4.0 license.

*See Appendix A for the list of collaboration members

The properties of an extreme state of matter, the Quark-Gluon Plasma (QGP), are studied by colliding heavy ions at BNL's Relativistic Heavy Ion Collider (RHIC) and at CERN's Large Hadron Collider (LHC). One of the most widely utilized physical phenomena in the exploration of QGP properties is collective anisotropic flow [1, 2]. The large elliptic flow discovered at RHIC energies [3], which at the LHC energy of 2.76 TeV is 30% larger [4] and recently reported in [5] to increase even further at 5.02 TeV, demonstrated that the QGP behaves like a strongly coupled liquid with a very small ratio of the shear viscosity to entropy density (η/s), which is close to a universal lower bound of $1/4\pi$ [6].

Anisotropic flow is traditionally quantified with harmonics v_n and corresponding symmetry plane angles ψ_n in the Fourier series decomposition of particle azimuthal distribution (parameterized with azimuthal angle φ) in the plane transverse to the beam direction [7]:

$$\frac{dN}{d\varphi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \psi_n)]. \quad (1)$$

The shape of the intersecting zone of two identical heavy ions in non-central collisions is approximately ellipsoidal. This initial anisotropy is transferred via interactions among constituents and the pressure gradients developed in the QGP medium to an observable final-state anisotropic emission of particles with respect to the symmetry plane(s) of the intersecting zone. The resulting anisotropic flow for such an idealized ellipsoidal geometry is determined solely by even Fourier harmonics v_{2n} , and only one symmetry plane (the reaction plane) exists. Recently the importance of flow fluctuations and related additional observables have been identified. This has led to new concepts such as: non-vanishing odd harmonics v_{2n-1} at midrapidity [8], non-identical symmetry plane angles ψ_n and their inter-correlations [9–14], stochastic nature of harmonic v_n and its probability density function $P(v_n)$ [15–20], and, finally, the importance of higher order flow moments $\langle v_n^k \rangle$ (where the angular brackets denote an average over all events, and $k \geq 2$) [21]. Two distinct regimes for anisotropic flow development are nowadays scrutinized separately: geometry-dominated (in mid-central collisions) and fluctuation-dominated (in the most central collisions) [11].

Anisotropic flow is generated by the initial anisotropic geometry and its fluctuations coupled with an expansion of the produced medium. The initial coordinate space anisotropy can be quantified in terms of eccentricity coefficients ε_n and corresponding symmetry plane angles Φ_n [8, 15, 22]. A great deal of effort is being invested to understand the relations between momentum space Fourier harmonics v_n and symmetry planes ψ_n on one side, and their spatial counterparts, ε_n and Φ_n , on the other side. These relations describe the response of the produced system to the initial coordinate space anisotropies, and therefore provide a rich repository of constraints for the system properties. In the early studies it was regularly assumed that, for small eccentricities, the harmonics v_n respond linearly to the eccentricities ε_n of the same order, $v_n \propto \varepsilon_n$, and that $\psi_n \simeq \Phi_n$ [8, 10, 23, 24]. However, for sizable eccentricities recent studies argue that the anisotropies in momentum and coordinate space are related instead with the matrix equation connecting a set of anisotropic flow harmonics $\{v_n\}$ and a set of eccentricity coefficients $\{\varepsilon_n\}$; it was demonstrated that the hydrodynamic response is both non-diagonal and non-linear, and that in general $\psi_n \neq \Phi_n$ [9, 11, 25, 26]. The first realization led to the conclusion that a relationship between event-by-event fluctuations of amplitudes of two different flow harmonics v_m and v_n can exist. This is hardly surprising for even flow harmonics in non-central collisions because the ellipsoidal shape generates non-vanishing values for all even harmonics v_{2n} [27], not only for elliptic flow. However, this simple geometrical argument cannot explain the possible relation between even and odd flow harmonics in non-central collisions, and the argument is not applicable in the central collisions, where all initial shapes are equally probable since they originate solely from fluctuations. Recently a linear correlation coefficient $c(a, b)$ was defined in this context, which becomes 1 (-1) if observables a and b are fully linearly (antilinearly) correlated and zero in the absence of correlation [25]. Model calculations of this new observable showed that neither v_2 and v_3 nor v_3 and v_4 are linearly correlated in non-central collisions. Most importantly, it was demonstrated that $c(v_2, v_4)$ depends strongly both on the η/s of the QGP and on

the value of $c(\varepsilon_2, \varepsilon_4)$, which quantifies the relationship between corresponding eccentricities in the initial state [25]. Therefore it was concluded that new observables $c(v_n, v_m)$, depending on the choice of flow harmonics v_n and v_m , are sensitive both to the fluctuations of the initial conditions and to the transport properties of the QGP, with the potential to discriminate between the two respective contributions when combined with a measurement of individual flow harmonics [25].

In this Letter we study the relationship between event-by-event fluctuations of magnitudes of two different flow harmonics of order n and m by using a recently proposed 4-particle observable [28]:

$$\begin{aligned} \langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle\rangle_c &= \langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle\rangle \\ &\quad - \langle\langle \cos[m(\varphi_1 - \varphi_2)] \rangle\rangle \langle\langle \cos[n(\varphi_1 - \varphi_2)] \rangle\rangle \\ &= \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle, \end{aligned} \quad (2)$$

with the condition $m \neq n$ for two positive integers m and n . We refer to these new observables as *Symmetric 2-harmonic 4-particle Cumulant*, and use notation $SC(m, n)$, or just SC . The double angular brackets indicate that the averaging procedure has been performed in two steps — first over all distinct particle quadruplets in an event, and then in the second step the single-event averages were weighted with ‘number of combinations’. The latter for single-event average 4-particle correlations is mathematically equivalent to a unit weight for each individual quadruplet when the multiplicity differs event-by-event [29]. In both 2-particle correlators above all distinct particle pairs are considered in each case. The four-particle cumulant in Eq. (2) is less sensitive to non-flow correlations than any 2- or 4-particle correlator on the right-hand side taken individually [30, 31]. The last equality is true only in the absence of non-flow effects [32]. The observable in Eq. (2) is zero in the absence of flow fluctuations, or if the magnitudes of harmonics v_m and v_n are uncorrelated [28]. It is also unaffected by relationship between symmetry plane angles ψ_m and ψ_n . The four-particle cumulant in Eq. (2) is proportional to the linear correlation coefficient $c(a, b)$ introduced in [25] and discussed above, with $a = v_m^2$ and $b = v_n^2$. Experimentally it is more reliable to measure the higher order moments of flow harmonics v_n^k ($k \geq 2$) with 2- and multiparticle correlation techniques [31, 33, 34], than to measure the first moments v_n with the event plane method, due to systematic uncertainties involved in the event-by-event estimation of symmetry planes [35, 36]. Therefore, we have used the new multiparticle observable in Eq. (2) as meant to be the least biased measure of the correlation between event-by-event fluctuations of magnitudes of two different harmonics v_m and v_n [28].

The 2- and 4-particle correlations in Eq. (2) were evaluated in terms of Q -vectors [33]. The Q -vector (or flow vector) in harmonic n for a set of M particles, where throughout this paper M is multiplicity of an event, is defined as $Q_n \equiv \sum_{k=1}^M e^{in\varphi_k}$ [7, 37]. We have used for a single-event average 2-particle correlation, $\langle\langle \cos(n(\varphi_1 - \varphi_2)) \rangle\rangle$, the following definition and analytic result in terms of Q -vectors:

$$\frac{1}{\binom{M}{2} 2!} \sum_{\substack{i,j=1 \\ (i \neq j)}}^M e^{in(\varphi_i - \varphi_j)} = \frac{1}{\binom{M}{2} 2!} [|Q_n|^2 - M]. \quad (3)$$

For 4-particle correlation, $\langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle\rangle$, we used:

$$\begin{aligned} \frac{1}{\binom{M}{4} 4!} \sum_{\substack{i,j,k,l=1 \\ (i \neq j \neq k \neq l)}}^M e^{i(m\varphi_i + n\varphi_j - m\varphi_k - n\varphi_l)} = \\ \frac{1}{\binom{M}{4} 4!} [|Q_m|^2 |Q_n|^2 - 2\Re [Q_{m+n} Q_m^* Q_n^*] - 2\Re [Q_m Q_{m-n}^* Q_n^*] \\ + |Q_{m+n}|^2 + |Q_{m-n}|^2 - (M-4)(|Q_m|^2 + |Q_n|^2) + M(M-6)]. \end{aligned} \quad (4)$$

In order to obtain the all-event average correlations, denoted by $\langle\langle \dots \rangle\rangle$ in Eq. (2), we have weighted single-event expressions in Eqs. (3) and (4) with weights $M(M-1)$ and $M(M-1)(M-2)(M-3)$, respectively [29].

The dataset used in this analysis was obtained with the ALICE detector [38, 39]. It consists of minimum-bias Pb–Pb collisions recorded during 2010 LHC Pb–Pb run at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. With the default event and track selection criteria described below, we have obtained in total about 1.8×10^5 events per 1% centrality bin width. All individual systematic variations were combined in quadrature to obtain the final uncertainty.

The centrality was determined with the V0 detector [40–42]. As a part of systematic checks centrality was determined independently with the Time Projection Chamber (TPC) [43] and the Silicon Pixel Detector (SPD) [44, 45], which have slightly worse resolution [42]. A systematic difference of up to 3% was observed in $\text{SC}(m, n)$ results when using different centrality estimations. Charged particles were reconstructed with the TPC and the Inner Tracking System (ITS) [44, 45] immersed in a 0.5 T solenoidal field. The TPC is capable of detecting charged particles in the transverse momentum range $0.1 < p_{\text{T}} < 100$ GeV/ c , with a p_{T} resolution of less than 6% for tracks below 20 GeV/ c . Due to TPC dead zones between neighboring sectors, the track finding efficiency is about 75% for $p_{\text{T}} = 200$ MeV/ c and then it saturates at about 85% for $p_{\text{T}} > 1$ GeV/ c in Pb–Pb collisions. The TPC covers full azimuth and has a pseudorapidity coverage of $|\eta| < 0.9$. Tracks reconstructed using the TPC and ITS are referred to as *global*, while tracks reconstructed only with the TPC are referred to as *TPC-only*.

For online triggering, the V0 and SPD detectors were used [39]. The reconstructed primary vertex is required to lie within ± 10 cm of the nominal interaction point in the longitudinal direction along the beam axis. The cut on the position of the primary vertex along the beam axis was varied from ± 12 cm to ± 6 cm, the resulting SC measurements are consistent with those obtained with the default cut.

The main analysis was performed with global tracks selected in the transverse momentum interval $0.2 < p_{\text{T}} < 5.0$ GeV/ c and pseudorapidity region $|\eta| < 0.8$. With this choice of low p_{T} cut-off we are reducing event-by-event biases from smaller reconstruction efficiency at lower p_{T} , while the high p_{T} cut-off was introduced to reduce the contribution to the anisotropies from jets. Reconstructed tracks were required to have at least 70 TPC space points (out of a maximum of 159). Only tracks with a transverse distance of closest approach (DCA) to the primary vertex less than 3 mm are accepted to reduce the contamination from secondary tracks. Tracks with kinks (the tracks that appear to change direction due to multiple scattering, K^{\pm} decays) were rejected.

An independent analysis was performed with TPC-only and hybrid tracks (see below). For TPC-only tracks, the DCA cut was relaxed to 3 cm, providing different sensitivity to contamination from secondary tracks. Both the azimuthal acceptance and the reconstruction efficiency as a function of transverse momentum differ between TPC-only and global tracks. The resulting difference between independent analyses with global and TPC-only tracks was found to be 1–5% in all the centrality ranges studied, both for $\text{SC}(3, 2)$ and $\text{SC}(4, 2)$. In another independent analysis with hybrid tracks, three different types of tracks were combined, in order to overcome the non-uniform azimuthal acceptance due to dead zones in SPD, and to achieve the best transverse momentum resolution [39]. In this analysis the DCA cut was set to 3.2 cm in the longitudinal and to 2.4 cm in the transverse direction. The results between global and hybrid tracks differ by 3 to 5%, depending on the observable considered.

One of the largest contributions to the systematic uncertainty originates from the non-uniform reconstruction efficiency as a function of transverse momentum. For the observables $\text{SC}(3, 2)$ and $\text{SC}(4, 2)$ the uncertainty is 7% and 8%, respectively. In order to correct the measurements of these azimuthal correlators for various detector inefficiencies, we have constructed particle weights as a function of azimuthal angle ϕ and transverse momentum p_{T} , and used the prescription outlined in [28]. In particular, p_{T} -weights were constructed as a ratio of transverse momentum distribution obtained from Monte Carlo generated tracks and from tracks reconstructed after they have passed through the detector simulated with GEANT3 [46].

We have used four Monte Carlo models in this paper. The HIJING model [47, 48] was utilized to

obtain the p_T -weights [28]. Secondly, the HIJING model was used to estimate the strength of non-flow correlations (typically few-particle correlations insensitive to the collision geometry). We have evaluated the observables of interest in coordinate space by modeling the initial conditions with a MC-Glauber model [49]. We have compared the centrality dependence of our observables with theoretical model from [50], where the initial energy density profiles are calculated using a next-to-leading order perturbative-QCD+saturation model [51, 52]. The subsequent spacetime evolution is described by relativistic dissipative fluid dynamics with different parametrizations for the temperature dependence of the shear viscosity to entropy density ratio $\eta/s(T)$. Each of the $\eta/s(T)$ parametrizations is adjusted to reproduce the measured v_n from central to mid-peripheral collisions. Finally, we provide an independent estimate of the centrality dependence of our observables by utilizing the AMPT model [53].

The centrality dependence of SC(4,2) (red squares) and SC(3,2) (blue circles) are presented in Fig. 1. Positive values of SC(4,2) are observed for all centralities. This suggests a correlation between the event-by-event fluctuations of v_2 and v_4 , which indicates that finding v_2 larger than $\langle v_2 \rangle$ in an event enhances the probability of finding v_4 larger than $\langle v_4 \rangle$ in that event. On the other hand, the negative results of SC(3,2) show the anti-correlation between v_2 and v_3 magnitudes, which further imply that finding v_2 larger than $\langle v_2 \rangle$ enhances the probability of finding v_3 smaller than $\langle v_3 \rangle$. We have calculated the SC

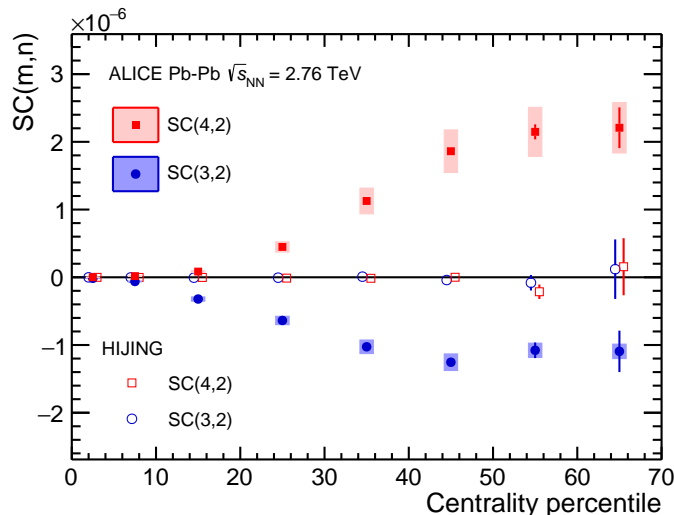


Fig. 1: Centrality dependence of observables SC(4,2) (red filled squares) and SC(3,2) (blue filled circles) in Pb-Pb collisions at 2.76 TeV. Systematical errors are represented with boxes. Results for HIJING model are shown with hollow markers.

observables using HIJING which does not include anisotropic collectivity but e.g. azimuthal correlations due to jet production [47, 48]. It is found that in HIJING both $\langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle$ and $\langle\langle\cos[m(\varphi_1-\varphi_2)]\rangle\rangle\langle\langle\cos[n(\varphi_1-\varphi_2)]\rangle\rangle$ are non-zero. However, the calculation of SC observables from HIJING are compatible with zero for all centralities, which suggests that the SC measurements are nearly insensitive to non-flow correlations. We have also performed a study using the like-sign technique, which is another powerful approach to estimate the non-flow effects [4]. It was found that the difference between correlations for like-sign and all charged combinations are within 10%. This demonstrates that non-zero values of SC measurements cannot be explained by non-flow effects.

A study based on the AMPT model showed that the observed (anti-)correlations are also sensitive to the transport properties, e.g. the partonic and hadronic interactions [20, 28]. Fig. 2 shows the comparison of SC(3,2) and SC(4,2) to the AMPT calculations which generally predict the correct sign but underestimate their magnitude. The comparison between experimental data and the theoretical calculations [50],

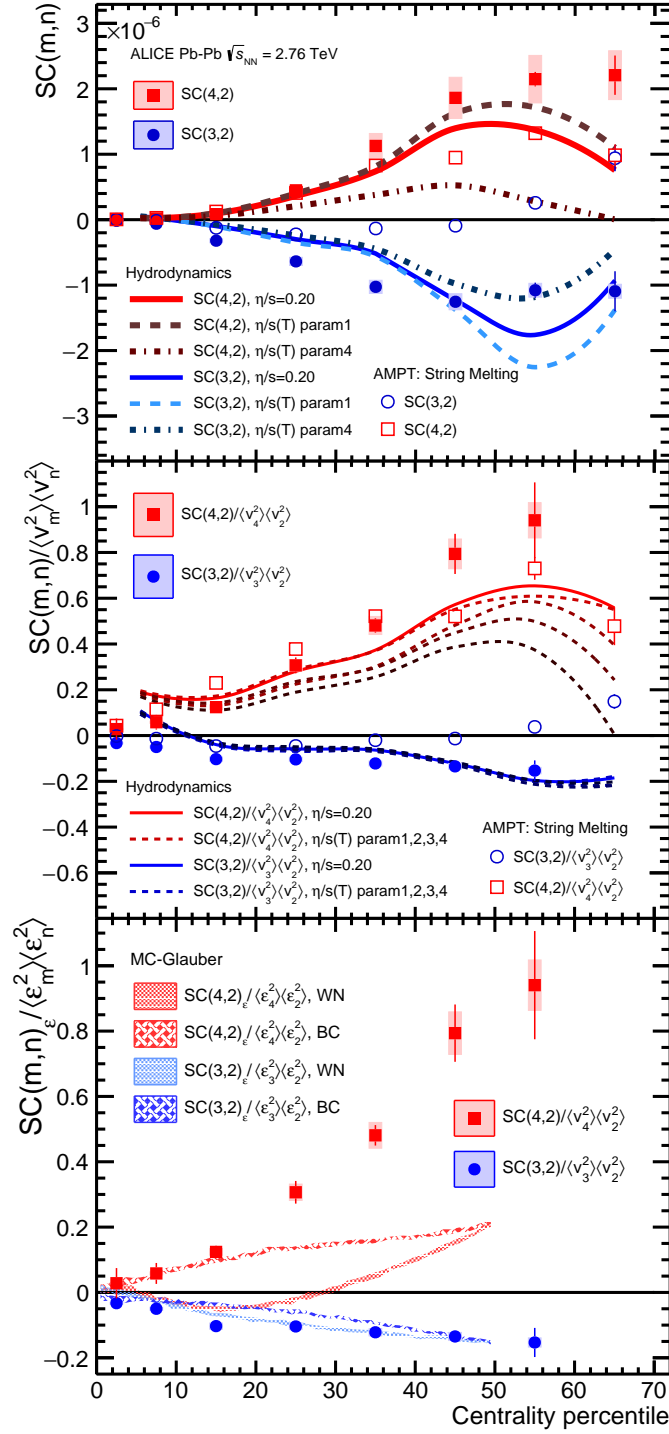


Fig. 2: AMPT model predictions are shown as hollow symbols in the (top) and (middle) panels. (top) Comparison of observables $SC(4,2)$ (red filled squares) and $SC(3,2)$ (blue filled circles) to theoretical model from [50]. Solid lines indicate the predictions with constant η/s , while the dashed lines indicate predictions for different parameterizations of η/s temperature dependence (labeled in the same way as in Fig. 1 in [50]). (middle) Results divided by $\langle v_m^2 \rangle \langle v_n^2 \rangle$. (bottom) Comparison to MC-Glauber using wounded nucleon (WN) and binary collisions (BC) weights.

which incorporate both the initial conditions and system evolution, is shown in Fig. 2 (top). The model captures qualitatively the centrality dependence, but not quantitatively. Most notably, there is no single centrality for which a given $\eta/s(T)$ parameterization describes simultaneously both SC(4,2) and SC(3,2). On the other hand, the same theoretical model captures quantitatively the centrality dependence of individual v_2 , v_3 and v_4 harmonics with a precision better than 10% in central and mid-central collisions [50]. We therefore conclude that individual flow harmonics v_n and new SC(m,n) observables together provide a better handle on the initial conditions and $\eta/s(T)$ than each of them alone. This is emphasized in Fig. 2 (middle), where SC(3,2) and SC(4,2) observables were divided with the products $\langle v_3^2 \rangle \langle v_2^2 \rangle$ and $\langle v_4^2 \rangle \langle v_2^2 \rangle$, respectively, in order to obtain the normalized SC observables (the result for 60–70% is omitted due to large statistical uncertainty). These products were obtained with 2-particle correlations and using a pseudorapidity gap of $|\Delta\eta| > 1.0$ to suppress biases from few-particle non-flow correlations. We have found that the normalized SC(4,2) observable exhibits much better sensitivity to different $\eta/s(T)$ parameterizations than the normalized SC(3,2) observable, see Fig. 2 (middle), and than the individual flow harmonics [50]. These findings indicate that the normalized SC(3,2) observable is sensitive mainly to the initial conditions, while the normalized SC(4,2) observable is sensitive to both the initial conditions and the system properties, which is consistent with the prediction from [25].

It can be seen in Fig. 1 that SC(4,2) and SC(3,2) increase non-linearly up to centrality 60%. Assuming only linear response $v_n \propto \varepsilon_n$, we expect that the normalized SC(m,n) evaluated in coordinate space can capture the measurement of centrality dependence of normalized SC(m,n) in the momentum space. The correlations between the n^{th} and m^{th} order harmonics were estimated with calculations of $(\langle \varepsilon_n^2 \varepsilon_m^2 \rangle - \langle \varepsilon_n^2 \rangle \langle \varepsilon_m^2 \rangle) / \langle \varepsilon_n^2 \rangle \langle \varepsilon_m^2 \rangle$, i.e. a normalized SC observable in the coordinate space, which we denote $\text{SC}(m,n)_\varepsilon / \langle \varepsilon_n^2 \rangle \langle \varepsilon_m^2 \rangle$. Here the ε_n (or ε_m) is the n^{th} (or m^{th}) order coordinate space anisotropy, following the definition in [8]. Different scenarios of the MC-Glauber model, named wounded nucleon (WN) and binary collisions (BC) weights, have been used. An increasing trend from central to peripheral collisions with different sign has been observed in Fig. 2 (bottom) for SC(4,2) and SC(3,2). A dramatic deviation of SC(4,2) between data and model calculation is observed for non-central collisions. This deviation increases from mid-central to peripheral, which could be understood as the contribution of the non-linear response (ε_2 contributes to v_4) increasing as a function of centrality, which is consistent with that reported in [54]. Since the normalized SC(3,2) appears to be sensitive only to initial conditions and not to $\eta/s(T)$, see Fig. 2 (middle), MC-Glauber model captures better its centrality dependence than for normalized SC(4,2) observable, see Fig. 2 (bottom).

The relationship between the flow harmonics v_2 , v_3 , v_4 have also been investigated by the ATLAS Collaboration using the ESE technique [54–56]. For events with a larger v_2 , the ATLAS Collaboration showed these have a smaller than average v_3 , and a larger than average v_4 . For events with a smaller v_2 , the opposite trend occurred. These observations are consistent with the patterns observed via the SC measurements presented in this Letter. The SC observables, however, provide a compact quantitative measure of these correlations, without fitting correlations between v_n and v_m . This simplifies the quantitative comparison of the SC observables with hydrodynamical calculations as shown in Fig. 2.

In the most central collisions the anisotropies originate mainly from fluctuations, i.e. the initial ellipsoidal geometry characteristic for mid-central collisions plays little role in this regime. Therefore we have performed a separate analysis for centrality range 0–10% in centrality bins of 1%. The results are presented in Fig. 3. We observe that event-by-event fluctuations of v_2 and v_4 remain correlated, and of v_2 and v_3 anti-correlated, also in this regime. However, the strength of the (anti)-correlations exhibits a different centrality dependence than for the wider centrality range shown in Fig. 1. As seen in Fig. 3 (top) the centrality dependence cannot be linearly extrapolated from the 0–10% region to the full centrality range. Comparison with two different parameterizations of the MC-Glauber initial conditions for normalized SC observables presented in Fig. 3 (bottom) suggests that the BC parameterization (binary collisions weights) is favored by the data in most central collisions. This agreement may suggest the scaling with

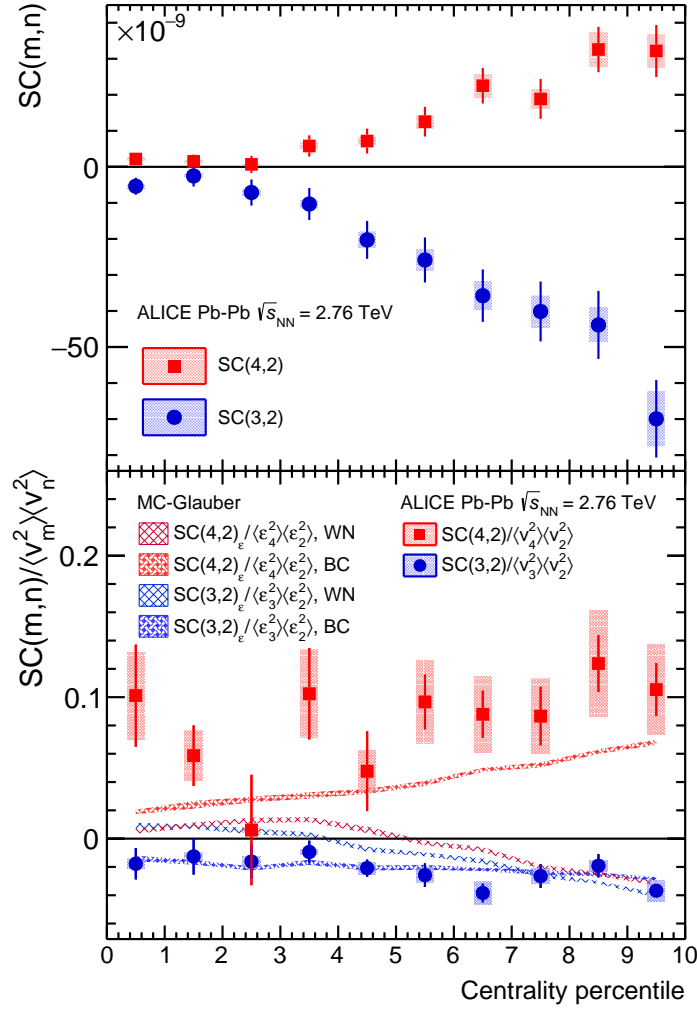


Fig. 3: Correlated and anti-correlated event-by-event fluctuations in coordinate (MC-Glauber) and momentum space (data). On the bottom panel we present the normalized SC observables, where pseudorapidity gap $|\Delta\eta| > 1.0$ was applied in both two-particle correlations in denominator used to estimate individual flow harmonics.

the number of quark participants [57–61] in central collisions at the LHC energies.

In summary, we have measured for the first time the new multiparticle observables, the Symmetric 2-harmonic 4-particle Cumulants (SC), which quantify the relationship between event-by-event fluctuations of two different flow harmonics. We have found that fluctuations of v_2 and v_3 are anti-correlated in all centralities, however the details of the centrality dependence differ in the fluctuation-dominated (most central) and the geometry-dominated (mid-central) regimes. Fluctuations of v_2 and v_4 are correlated for all centralities. The SC observables were used to discriminate between the state-of-the-art hydro model calculations with different parameterizations of the temperature dependence of η/s , for all of which the centrality dependence of elliptic, triangular and quadrangular flow has weaker sensitivity at the LHC. In particular, the centrality dependence of $SC(4,2)$ cannot be captured with the constant η/s . We have also used our results to discriminate between two different parameterizations of initial conditions and have demonstrated that in the fluctuation-dominated regime (in central collisions) MC-Glauber initial conditions with binary collisions weights are favored over wounded nucleon weights.

Acknowledgements

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 centres 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: State Committee of Science, World Federation of Scientists (WFS) and Swiss Fonds Kidagan, Armenia; 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); Ministry of Science and Technology of China (MSTC), National Natural Science Foundation of China (NSFC) and Ministry of Education of China (MOEC)”; Ministry of Science, Education and Sports of Croatia and Unity through Knowledge Fund, Croatia; Ministry of Education and Youth of the Czech Republic; Danish Natural Science Research Council, the Carlsberg Foundation and the Danish National Research Foundation; The European Research Council under the European Community’s Seventh Framework Programme; Helsinki Institute of Physics and the Academy of Finland; French CNRS-IN2P3, the ‘Region Pays de Loire’, ‘Region Alsace’, ‘Region Auvergne’ and CEA, France; German Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF) and the Helmholtz Association; General Secretariat for Research and Technology, Ministry of Development, Greece; National Research, Development and Innovation Office (NKFIH), Hungary; Council of Scientific and Industrial Research (CSIR), New Delhi; Department of Atomic Energy and Department of Science and Technology of the Government of India; Istituto Nazionale di Fisica Nucleare (INFN) and Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, Italy; Japan Society for the Promotion of Science (JSPS) KAKENHI and MEXT, Japan; National Research Foundation of Korea (NRF); Consejo Nacional de Ciencia y Tecnología (CONACYT), Dirección General de Asuntos del Personal Académico (DGAPA), México, Amérique Latine Formation académique - European Commission (ALFA-EC) and the EPLANET Program (European Particle Physics Latin American Network); Stichting voor Fundamenteel Onderzoek der Materie (FOM) and the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; Research Council of Norway (NFR); Pontificia Universidad Católica del Perú; National Science Centre, Poland; Ministry of National Education/Institute for Atomic Physics and National Council of Scientific Research in Higher Education (CNCSI-UEFISCDI), Romania; Joint Institute for Nuclear Research, Dubna; Ministry of Education and Science of Russian Federation, Russian Academy of Sciences, Russian Federal Agency of Atomic Energy, Russian Federal Agency for Science and Innovations and The Russian Foundation for Basic Research; Ministry of Education of Slovakia; Department of Science and Technology, South Africa; Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), E-Infrastructure shared between Europe and Latin America (EELA), Ministerio de Economía y Competitividad (MINECO) of Spain, Xunta de Galicia (Consellería de Educación), Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba, and IAEA (International Atomic Energy Agency); Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW); National Science and Technology Development Agency (NSDTA), Suranaree University of Technology (SUT) and Office of the Higher Education Commission under NRU project of Thailand; Ukraine Ministry of Education and Science; United Kingdom Science and Technology Facilities Council (STFC); The United States Department of Energy, the United States National Science Foundation, the State of Texas, and the State of Ohio.

References

- [1] J.-Y. Ollitrault, “Anisotropy as a signature of transverse collective flow,” *Phys. Rev.* **D46** (1992) 229–245.
- [2] S. A. Voloshin, A. M. Poskanzer, and R. Snellings, “Collective phenomena in non-central nuclear collisions,” arXiv:0809.2949 [nucl-ex].
- [3] **STAR** Collaboration, K. H. Ackermann *et al.*, “Elliptic flow in Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV,” *Phys. Rev. Lett.* **86** (2001) 402–407, arXiv:nucl-ex/0009011 [nucl-ex].
- [4] **ALICE** Collaboration, K. Aamodt *et al.*, “Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV,” *Phys. Rev. Lett.* **105** (2010) 252302, arXiv:1011.3914 [nucl-ex].
- [5] **ALICE** Collaboration, J. Adam *et al.*, “Anisotropic flow of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV,” *Phys. Rev. Lett.* **116** no. 13, (2016) 132302, arXiv:1602.01119 [nucl-ex].
- [6] P. Kovtun, D. T. Son, and A. O. Starinets, “Viscosity in strongly interacting quantum field theories from black hole physics,” *Phys. Rev. Lett.* **94** (2005) 111601, arXiv:hep-th/0405231 [hep-th].
- [7] S. Voloshin and Y. Zhang, “Flow study in relativistic nuclear collisions by Fourier expansion of Azimuthal particle distributions,” *Z. Phys.* **C70** (1996) 665–672, arXiv:hep-ph/9407282 [hep-ph].
- [8] B. Alver and G. Roland, “Collision geometry fluctuations and triangular flow in heavy-ion collisions,” *Phys. Rev.* **C81** (2010) 054905, arXiv:1003.0194 [nucl-th]. [Erratum: *Phys. Rev.* **C82**,039903(2010)].
- [9] G.-Y. Qin, H. Petersen, S. A. Bass, and B. Muller, “Translation of collision geometry fluctuations into momentum anisotropies in relativistic heavy-ion collisions,” *Phys. Rev.* **C82** (2010) 064903, arXiv:1009.1847 [nucl-th].
- [10] D. Teaney and L. Yan, “Triangularity and Dipole Asymmetry in Heavy Ion Collisions,” *Phys. Rev.* **C83** (2011) 064904, arXiv:1010.1876 [nucl-th].
- [11] Z. Qiu and U. W. Heinz, “Event-by-event shape and flow fluctuations of relativistic heavy-ion collision fireballs,” *Phys. Rev.* **C84** (2011) 024911, arXiv:1104.0650 [nucl-th].
- [12] **ALICE** Collaboration, K. Aamodt *et al.*, “Higher harmonic anisotropic flow measurements of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV,” *Phys. Rev. Lett.* **107** (2011) 032301, arXiv:1105.3865 [nucl-ex].
- [13] **PHENIX** Collaboration, A. Adare *et al.*, “Measurements of Higher-Order Flow Harmonics in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV,” *Phys. Rev. Lett.* **107** (2011) 252301, arXiv:1105.3928 [nucl-ex].
- [14] **ATLAS** Collaboration, G. Aad *et al.*, “Measurement of event-plane correlations in $\sqrt{s_{NN}} = 2.76$ TeV lead-lead collisions with the ATLAS detector,” *Phys. Rev.* **C90** no. 2, (2014) 024905, arXiv:1403.0489 [hep-ex].
- [15] S. A. Voloshin, A. M. Poskanzer, A. Tang, and G. Wang, “Elliptic flow in the Gaussian model of eccentricity fluctuations,” *Phys. Lett.* **B659** (2008) 537–541, arXiv:0708.0800 [nucl-th].
- [16] C. Gale, S. Jeon, B. Schenke, P. Tribedy, and R. Venugopalan, “Initial state fluctuations and higher harmonic flow in heavy-ion collisions,” *Nucl. Phys.* **A904-905** (2013) 409c–412c, arXiv:1210.5144 [hep-ph].

- [17] **ATLAS** Collaboration, G. Aad *et al.*, “Measurement of the distributions of event-by-event flow harmonics in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC,” *JHEP* **11** (2013) 183, arXiv:1305.2942 [hep-ex].
- [18] L. Yan and J.-Y. Ollitrault, “Universal fluctuation-driven eccentricities in proton-proton, proton-nucleus and nucleus-nucleus collisions,” *Phys. Rev. Lett.* **112** (2014) 082301, arXiv:1312.6555 [nucl-th].
- [19] L. Yan, J.-Y. Ollitrault, and A. M. Poskanzer, “Eccentricity distributions in nucleus-nucleus collisions,” *Phys. Rev.* **C90** no. 2, (2014) 024903, arXiv:1405.6595 [nucl-th].
- [20] Y. Zhou, K. Xiao, Z. Feng, F. Liu, and R. Snellings, “Anisotropic distributions in a multi-phase transport model,” arXiv:1508.03306 [nucl-ex].
- [21] R. S. Bhalerao, J.-Y. Ollitrault, and S. Pal, “Characterizing flow fluctuations with moments,” *Phys. Lett.* **B742** (2015) 94–98, arXiv:1411.5160 [nucl-th].
- [22] **PHOBOS** Collaboration, B. Alver *et al.*, “System size, energy, pseudorapidity, and centrality dependence of elliptic flow,” *Phys. Rev. Lett.* **98** (2007) 242302, arXiv:nucl-ex/0610037 [nucl-ex].
- [23] B. H. Alver, C. Gombeaud, M. Luzum, and J.-Y. Ollitrault, “Triangular flow in hydrodynamics and transport theory,” *Phys. Rev.* **C82** (2010) 034913, arXiv:1007.5469 [nucl-th].
- [24] R. A. Lacey, D. Reynolds, A. Taranenko, N. N. Ajitanand, J. M. Alexander, F.-H. Liu, Y. Gu, and A. Mwai, “Acoustic scaling of anisotropic flow in shape-engineered events: implications for extraction of the specific shear viscosity of the quark gluon plasma,” arXiv:1311.1728 [nucl-ex].
- [25] H. Niemi, G. S. Denicol, H. Holopainen, and P. Huovinen, “Event-by-event distributions of azimuthal asymmetries in ultrarelativistic heavy-ion collisions,” *Phys. Rev.* **C87** no. 5, (2013) 054901, arXiv:1212.1008 [nucl-th].
- [26] L. Yan and J.-Y. Ollitrault, “ v_4, v_5, v_6, v_7 : nonlinear hydrodynamic response versus LHC data,” *Phys. Lett.* **B744** (2015) 82–87, arXiv:1502.02502 [nucl-th].
- [27] P. F. Kolb, “ v_4 : A Small, but sensitive observable for heavy ion collisions,” *Phys. Rev.* **C68** (2003) 031902, arXiv:nucl-th/0306081 [nucl-th].
- [28] A. Bilandzic, C. H. Christensen, K. Gulbrandsen, A. Hansen, and Y. Zhou, “Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations,” *Phys. Rev.* **C89** no. 6, (2014) 064904, arXiv:1312.3572 [nucl-ex].
- [29] A. Bilandzic, *Anisotropic flow measurements in ALICE at the large hadron collider (see Section 3.1.4)*. PhD thesis, Utrecht U., 2012.
<https://inspirehep.net/record/1186272/files/CERN-THESIS-2012-018.pdf>.
- [30] N. Borghini, P. M. Dinh, and J.-Y. Ollitrault, “A New method for measuring azimuthal distributions in nucleus-nucleus collisions,” *Phys. Rev.* **C63** (2001) 054906, arXiv:nucl-th/0007063 [nucl-th].
- [31] N. Borghini, P. M. Dinh, and J.-Y. Ollitrault, “Flow analysis from multiparticle azimuthal correlations,” *Phys. Rev.* **C64** (2001) 054901, arXiv:nucl-th/0105040 [nucl-th].

- [32] R. S. Bhalerao, M. Luzum, and J.-Y. Ollitrault, “Determining initial-state fluctuations from flow measurements in heavy-ion collisions,” *Phys. Rev.* **C84** (2011) 034910, arXiv:1104.4740 [nucl-th].
- [33] A. Bilandzic, R. Snellings, and S. Voloshin, “Flow analysis with cumulants: Direct calculations,” *Phys. Rev.* **C83** (2011) 044913, arXiv:1010.0233 [nucl-ex].
- [34] 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.* **C44** (1991) 1091–1095.
- [35] A. M. Poskanzer and S. A. Voloshin, “Methods for analyzing anisotropic flow in relativistic nuclear collisions,” *Phys. Rev.* **C58** (1998) 1671–1678, arXiv:nucl-ex/9805001 [nucl-ex].
- [36] M. Luzum and J.-Y. Ollitrault, “Eliminating experimental bias in anisotropic-flow measurements of high-energy nuclear collisions,” *Phys. Rev.* **C87** no. 4, (2013) 044907, arXiv:1209.2323 [nucl-ex].
- [37] **E877** Collaboration, J. Barrette *et al.*, “Observation of anisotropic event shapes and transverse flow in Au + Au collisions at AGS energy,” *Phys. Rev. Lett.* **73** (1994) 2532–2535, arXiv:hep-ex/9405003 [hep-ex].
- [38] **ALICE** Collaboration, K. Aamodt *et al.*, “The ALICE experiment at the CERN LHC,” *JINST* **3** (2008) S08002.
- [39] **ALICE** Collaboration, B. B. Abelev *et al.*, “Performance of the ALICE Experiment at the CERN LHC,” *Int. J. Mod. Phys.* **A29** (2014) 1430044, arXiv:1402.4476 [nucl-ex].
- [40] **ALICE** Collaboration, P. Cortese *et al.*, “ALICE technical design report on forward detectors: FMD, T0 and V0, CERN-LHCC-2004-025,”.
- [41] **ALICE** Collaboration, E. Abbas *et al.*, “Performance of the ALICE VZERO system,” *JINST* **8** (2013) P10016, arXiv:1306.3130 [nucl-ex].
- [42] **ALICE** Collaboration, B. Abelev *et al.*, “Centrality determination of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE,” *Phys. Rev.* **C88** no. 4, (2013) 044909, arXiv:1301.4361 [nucl-ex].
- [43] J. Alme *et al.*, “The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events,” *Nucl. Instrum. Meth.* **A622** (2010) 316–367, arXiv:1001.1950 [physics.ins-det].
- [44] **ALICE** Collaboration, G. Dellacasa *et al.*, “ALICE technical design report of the inner tracking system (ITS), CERN-LHCC-99-12,”.
- [45] **ALICE** Collaboration, K. Aamodt *et al.*, “Alignment of the ALICE Inner Tracking System with cosmic-ray tracks,” *JINST* **5** (2010) P03003, arXiv:1001.0502 [physics.ins-det].
- [46] R. Brun, F. Carminati, and S. Giani, “GEANT Detector Description and Simulation Tool, CERN-W5013, 1994,”.
- [47] X.-N. Wang and M. Gyulassy, “HIJING: A Monte Carlo model for multiple jet production in pp, pA and AA collisions,” *Phys. Rev.* **D44** (1991) 3501–3516.
- [48] M. Gyulassy and X.-N. Wang, “HIJING 1.0: A Monte Carlo program for parton and particle production in high-energy hadronic and nuclear collisions,” *Comput. Phys. Commun.* **83** (1994) 307, arXiv:nucl-th/9502021 [nucl-th].

- [49] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, “Glauber modeling in high energy nuclear collisions,” *Ann. Rev. Nucl. Part. Sci.* **57** (2007) 205–243, arXiv:nuc1-ex/0701025 [nuc1-ex].
- [50] H. Niemi, K. J. Eskola, and R. Paatelainen, “Event-by-event fluctuations in perturbative QCD + saturation + hydro model: pinning down QCD matter shear viscosity in ultrarelativistic heavy-ion collisions,” arXiv:1505.02677 [hep-ph].
- [51] 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.* **C87** no. 4, (2013) 044904, arXiv:1211.0461 [hep-ph].
- [52] R. Paatelainen, K. J. Eskola, H. Niemi, and K. Tuominen, “Fluid dynamics with saturated minijet initial conditions in ultrarelativistic heavy-ion collisions,” *Phys. Lett.* **B731** (2014) 126–130, arXiv:1310.3105 [hep-ph].
- [53] Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang, and S. Pal, “A Multi-phase transport model for relativistic heavy ion collisions,” *Phys. Rev.* **C72** (2005) 064901, arXiv:nuc1-th/0411110 [nuc1-th].
- [54] ATLAS Collaboration, G. Aad *et al.*, “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.* **C92** no. 3, (2015) 034903, arXiv:1504.01289 [hep-ex].
- [55] J. Schukraft, A. Timmins, and S. A. Voloshin, “Ultra-relativistic nuclear collisions: event shape engineering,” *Phys. Lett.* **B719** (2013) 394–398, arXiv:1208.4563 [nuc1-ex].
- [56] H. Petersen and B. Muller, “Possibility of event shape selection in relativistic heavy ion collisions,” *Phys. Rev.* **C88** no. 4, (2013) 044918, arXiv:1305.2735 [nuc1-th].
- [57] S. Eremín and S. Voloshin, “Nucleon participants or quark participants?,” *Phys. Rev.* **C67** (2003) 064905, arXiv:nuc1-th/0302071 [nuc1-th].
- [58] M. Miller and R. Snellings, “Eccentricity fluctuations and its possible effect on elliptic flow measurements,” arXiv:nuc1-ex/0312008 [nuc1-ex].
- [59] STAR Collaboration, L. Adamczyk *et al.*, “Azimuthal anisotropy in U+U and Au+Au collisions at RHIC,” *Phys. Rev. Lett.* **115** no. 22, (2015) 222301, arXiv:1505.07812 [nuc1-ex].
- [60] PHENIX Collaboration, A. Adare *et al.*, “Transverse energy production and charged-particle multiplicity at midrapidity in various systems from $\sqrt{s_{NN}} = 7.7$ to 200 GeV,” *Phys. Rev.* **C93** no. 2, (2016) 024901, arXiv:1509.06727 [nuc1-ex].
- [61] C. Loizides, “Glauber modeling of high-energy nuclear collisions at sub-nucleon level,” arXiv:1603.07375 [nuc1-ex].

A The ALICE Collaboration

J. Adam³⁹, D. Adamová⁸⁵, M.M. Aggarwal⁸⁹, G. Aglieri Rinella³⁵, M. Agnello^{112,31}, N. Agrawal⁴⁸, Z. Ahammed¹³⁶, S. Ahmad¹⁸, S.U. Ahn⁶⁹, S. Aiola¹⁴⁰, A. Akindinov⁵⁵, S.N. Alam¹³⁶, D.S.D. Albuquerque¹²³, D. Aleksandrov⁸¹, B. Alessandro¹¹², D. Alexandre¹⁰³, R. Alfaro Molina⁶⁴, A. Alici^{12,106}, A. Alkin³, J.R.M. Almaraz¹²¹, J. Alme^{37,22}, T. Alt⁴², S. Altinpinar²², I. Altsybeev¹³⁵, C. Alves Garcia Prado¹²², C. Andrei⁷⁹, A. Andronic⁹⁹, V. Anguelov⁹⁵, T. Antičić¹⁰⁰, F. Antinori¹⁰⁹, P. Antonioli¹⁰⁶, L. Aphecetche¹¹⁵, H. Appelshäuser⁶¹, S. Arcelli²⁷, R. Arnaldi¹¹², O.W. Arnold^{36,96}, I.C. Arsene²¹, M. Arslanok⁶¹, B. Audurier¹¹⁵, A. Augustinus³⁵, R. Averbeck⁹⁹, M.D. Azmi¹⁸, A. Badalà¹⁰⁸, Y.W. Baek⁶⁸, S. Bagnasco¹¹², R. Bailhache⁶¹, R. Bala⁹², S. Balasubramanian¹⁴⁰, A. Baldisseri¹⁵, R.C. Baral⁵⁸, A.M. Barbano²⁶, R. Barbera²⁸, F. Barile³³, G.G. Barnaföldi¹³⁹, L.S. Barnby^{35,103}, V. Barret⁷¹, P. Bartalini⁷, K. Barth³⁵, J. Bartke^{119,i}, E. Bartsch⁶¹, M. Basile²⁷, N. Bastid⁷¹, S. Basu¹³⁶, B. Bathen⁶², G. Batigne¹¹⁵, A. Batista Camejo⁷¹, B. Batyunya⁶⁷, P.C. Batzing²¹, I.G. Bearden⁸², H. Beck^{95,61}, C. Bedda¹¹², N.K. Behera^{51,49}, I. Belikov⁶⁵, F. Bellini²⁷, H. Bello Martinez², R. Bellwied¹²⁵, R. Belmont¹³⁸, E. Belmont-Moreno⁶⁴, L.G.E. Beltran¹²¹, V. Belyaev⁷⁶, G. Bencedi¹³⁹, S. Beole²⁶, I. Berceanu⁷⁹, A. Bercuci⁷⁹, Y. Berdnikov⁸⁷, D. Berenyi¹³⁹, R.A. Bertens⁵⁴, D. Berzano³⁵, L. Betev³⁵, A. Bhasin⁹², I.R. Bhat⁹², A.K. Bhati⁸⁹, B. Bhattacharjee⁴⁴, J. Bhom^{119,131}, L. Bianchi¹²⁵, N. Bianchi⁷³, C. Bianchin¹³⁸, J. Bielčik³⁹, J. Bielčíková⁸⁵, A. Bilandzic^{82,36,96}, G. Biro¹³⁹, R. Biswas⁴, S. Biswas^{80,4}, S. Bjelogrić⁵⁴, J.T. Blair¹²⁰, D. Blau⁸¹, C. Blume⁶¹, F. Bock^{75,95}, A. Bogdanov⁷⁶, H. Bøggild⁸², L. Boldizsár¹³⁹, M. Bombara⁴⁰, J. Book⁶¹, H. Borel¹⁵, A. Borissov⁹⁸, M. Borri^{127,84}, F. Bossu⁶⁶, E. Botta²⁶, C. Bourjau⁸², P. Braun-Munzinger⁹⁹, M. Bregant¹²², T. Breitner⁶⁰, T.A. Broker⁶¹, T.A. Browning⁹⁷, M. Broz³⁹, E.J. Brucken⁴⁶, E. Bruna¹¹², G.E. Bruno³³, D. Budnikov¹⁰¹, H. Buesching⁶¹, S. Bufalino^{35,31}, S.A.I. Buitron⁶³, P. Buncic³⁵, O. Busch¹³¹, Z. Buthelezi⁶⁶, J.B. Butt¹⁶, J.T. Buxton¹⁹, J. Cabala¹¹⁷, D. Caffarri³⁵, X. Cai⁷, H. Caines¹⁴⁰, L. Calero Diaz⁷³, A. Caliva⁵⁴, E. Calvo Villar¹⁰⁴, P. Camerini²⁵, F. Carena³⁵, W. Carena³⁵, F. Carnesecchi^{27,12}, J. Castillo Castellanos¹⁵, A.J. Castro¹²⁸, E.A.R. Casula²⁴, C. Ceballos Sanchez⁹, J. Cepila³⁹, P. Cerello¹¹², J. Cerkala¹¹⁷, B. Chang¹²⁶, S. Chapeland³⁵, M. Chartier¹²⁷, J.L. Charvet¹⁵, S. Chattopadhyay¹³⁶, S. Chattopadhyay¹⁰², A. Chauvin^{96,36}, V. Chelnokov³, M. Cherny⁸⁸, C. Cheshkov¹³³, B. Cheynis¹³³, V. Chibante Barroso³⁵, D.D. Chinellato¹²³, S. Cho⁵¹, P. Chochula³⁵, K. Choi⁹⁸, M. Chojnacki⁸², S. Choudhury¹³⁶, P. Christakoglou⁸³, C.H. Christensen⁸², P. Christiansen³⁴, T. Chujo¹³¹, S.U. Chung⁹⁸, C. Cicalo¹⁰⁷, L. Cifarelli^{12,27}, F. Cindolo¹⁰⁶, J. Cleymans⁹¹, F. Colamaria³³, D. Colella^{56,35}, A. Collu⁷⁵, M. Colocci²⁷, G. Conesa Balbastre⁷², Z. Conesa del Valle⁵², M.E. Connors^{140,ii}, J.G. Contreras³⁹, T.M. Cormier⁸⁶, Y. Corrales Morales^{112,26}, I. Cortés Maldonado², P. Cortese³², M.R. Cosentino^{124,122}, F. Costa³⁵, P. Crochet⁷¹, R. Cruz Albino¹¹, E. Cuautle⁶³, L. Cunqueiro^{62,35}, T. Dahms^{36,96}, A. Dainese¹⁰⁹, M.C. Danisch⁹⁵, A. Danu⁵⁹, D. Das¹⁰², I. Das¹⁰², S. Das⁴, A. Dash⁸⁰, S. Dash⁴⁸, S. De¹²², A. De Caro^{12,30}, G. de Cataldo¹⁰⁵, C. de Conti¹²², J. de Cuveland⁴², A. De Falco²⁴, D. De Gruttola^{30,12}, N. De Marco¹¹², S. De Pasquale³⁰, R.D. De Souza¹²³, A. Deisting^{95,99}, A. Deloff⁷⁸, E. Dénes^{139,i}, C. Deplano⁸³, P. Dhankher⁴⁸, D. Di Bari³³, A. Di Mauro³⁵, P. Di Nezza⁷³, B. Di Ruzza¹⁰⁹, M.A. Diaz Corchero¹⁰, T. Dietel⁹¹, P. Dillenseger⁶¹, R. Divià³⁵, Ø. Djuzhland²², A. Dobrin^{83,35}, D. Domenicis Gimenez¹²², B. Dönigus⁶¹, O. Dordic²¹, T. Drozhzhova⁶¹, A.K. Dubey¹³⁶, A. Dubla^{99,54}, L. Ducroux¹³³, P. Dupieux⁷¹, R.J. Ehlers¹⁴⁰, D. Elia¹⁰⁵, E. Endress¹⁰⁴, H. Engel⁶⁰, E. Eppe^{96,140,36}, B. Erazmus¹¹⁵, I. Erdemir⁶¹, F. Erhardt¹³², B. Espagnon⁵², M. Estienne¹¹⁵, S. Esumi¹³¹, J. Eum⁹⁸, D. Evans¹⁰³, S. Evdokimov¹¹³, G. Eyyubova³⁹, L. Fabbietti^{36,96}, D. Fabris¹⁰⁹, J. Faivre⁷², A. Fantoni⁷³, M. Fasel⁷⁵, L. Feldkamp⁶², A. Feliciello¹¹², G. Feofilov¹³⁵, J. Ferencei⁸⁵, A. Fernández Téllez², E.G. Ferreira¹⁷, A. Ferretti²⁶, A. Festanti²⁹, V.J.G. Feuillard^{71,15}, J. Figiel¹¹⁹, M.A.S. Figueredo^{127,122}, S. Filchagin¹⁰¹, D. Finogeev⁵³, F.M. Fionda²⁴, E.M. Fiore³³, M.G. Fleck⁹⁵, M. Floris³⁵, S. Foertsch⁶⁶, P. Foka⁹⁹, S. Fokin⁸¹, E. Fragiaco¹¹¹, A. Francescon^{35,29}, A. Francisco¹¹⁵, U. Frankenfeld⁹⁹, G.G. Fronze²⁶, U. Fuchs³⁵, C. Furget⁷², A. Furs⁵³, M. Fusco Girard³⁰, J.J. Gaardhøje⁸², M. Gagliardi²⁶, A.M. Gago¹⁰⁴, K. Gajdosova⁸², M. Gallio²⁶, C.D. Galvan¹²¹, D.R. Gangadharan⁷⁵, P. Ganoti⁹⁰, C. Gao⁷, C. Garabatos⁹⁹, E. Garcia-Solis¹³, C. Gargiulo³⁵, P. Gasik^{96,36}, E.F. Gauger¹²⁰, M. Germain¹¹⁵, M. Gheata^{59,35}, P. Ghosh¹³⁶, S.K. Ghosh⁴, P. Gianotti⁷³, P. Giubellino^{35,112}, P. Giubilato²⁹, E. Gladysz-Dziadus¹¹⁹, P. Glässel⁹⁵, D.M. Gómez Coral⁶⁴, A. Gomez Ramirez⁶⁰, A.S. Gonzalez³⁵, V. Gonzalez¹⁰, P. González-Zamora¹⁰, S. Gorbunov⁴², L. Görlich¹¹⁹, S. Gotovac¹¹⁸, V. Grabski⁶⁴, O.A. Grachov¹⁴⁰, L.K. Graczykowski¹³⁷, K.L. Graham¹⁰³, A. Grelli⁵⁴, A. Grigoras³⁵, C. Grigoras³⁵, V. Grigoriev⁷⁶, A. Grigoryan¹, S. Grigoryan⁶⁷, B. Grinyov³, N. Grion¹¹¹, J.M. Gronefeld⁹⁹, J.F. Grosse-Oetringhaus³⁵, R. Grosso⁹⁹, L. Gruber¹¹⁴, F. Guber⁵³, R. Guernane⁷², B. Guerzoni²⁷, K. Gulbrandsen⁸², T. Gunji¹³⁰, A. Gupta⁹², R. Gupta⁹², R. Haake³⁵, Ø. Haaland²², C. Hadjidakis⁵², M. Haiduc⁵⁹, H. Hamagaki¹³⁰, G. Hamar¹³⁹, J.C. Hamon⁶⁵, J.W. Harris¹⁴⁰, A. Harton¹³, D. Hatzifotiadou¹⁰⁶, S. Hayashi¹³⁰, S.T. Heckel⁶¹, E. Hellbär⁶¹, H. Helstrup³⁷, A. Herghelegiu⁷⁹, G. Herrera Corral¹¹, B.A. Hess⁹⁴, K.F. Hetland³⁷, H. Hillemanns³⁵, B. Hippolyte⁶⁵, D. Horak³⁹, R. Hosokawa¹³¹,

P. Hristov³⁵, C. Hughes¹²⁸, T.J. Humanic¹⁹, N. Hussain⁴⁴, T. Hussain¹⁸, D. Hutter⁴², D.S. Hwang²⁰, R. Ilkaev¹⁰¹, M. Inaba¹³¹, E. Incani²⁴, M. Ippolitov^{81,76}, M. Irfan¹⁸, M. Ivanov⁹⁹, V. Ivanov⁸⁷, V. Izucheev¹¹³, B. Jacak⁷⁵, N. Jacazio²⁷, P.M. Jacobs⁷⁵, M.B. Jadhav⁴⁸, S. Jadlovská¹¹⁷, J. Jadlovsky^{56,117}, C. Jahnke¹²², M.J. Jakubowska¹³⁷, H.J. Jang⁶⁹, M.A. Janik¹³⁷, P.H.S.Y. Jayarathna¹²⁵, C. Jena²⁹, S. Jena¹²⁵, R.T. Jimenez Bustamante⁹⁹, P.G. Jones¹⁰³, A. Jusko¹⁰³, P. Kalinak⁵⁶, A. Kalweit³⁵, J. Kamin⁶¹, J.H. Kang¹⁴¹, V. Kaplin⁷⁶, S. Kar¹³⁶, A. Karasu Uysal⁷⁰, O. Karavichev⁵³, T. Karavicheva⁵³, L. Karayan^{99,95}, E. Karpechev⁵³, U. Kebschull⁶⁰, R. Keidel¹⁴², D.L.D. Keijdener⁵⁴, M. Keil³⁵, M. Mohisin Khan^{18,iii}, P. Khan¹⁰², S.A. Khan¹³⁶, A. Khanzadeev⁸⁷, Y. Kharlov¹¹³, B. Kileng³⁷, D.W. Kim⁴³, D.J. Kim¹²⁶, D. Kim¹⁴¹, H. Kim¹⁴¹, J.S. Kim⁴³, J. Kim⁹⁵, M. Kim⁵¹, M. Kim¹⁴¹, S. Kim²⁰, T. Kim¹⁴¹, S. Kirsch⁴², I. Kisel⁴², S. Kiselev⁵⁵, A. Kisiel¹³⁷, G. Kiss¹³⁹, J.L. Klay⁶, C. Klein⁶¹, J. Klein³⁵, C. Klein-Bösing⁶², S. Klewin⁹⁵, A. Kluge³⁵, M.L. Knichel⁹⁵, A.G. Knospe^{125,120}, C. Kobdaj¹¹⁶, M. Kofarago³⁵, T. Kollegger⁹⁹, A. Kolojvari¹³⁵, V. Kondratiev¹³⁵, N. Kondratyeva⁷⁶, E. Kondratyuk¹¹³, A. Konevskikh⁵³, M. Kopicik¹¹⁷, M. Kour⁹², C. Kouzinopoulos³⁵, O. Kovalenko⁷⁸, V. Kovalenko¹³⁵, M. Kowalski¹¹⁹, G. Koyithatta Meethalevedu⁴⁸, I. Králik⁵⁶, A. Kravčáková⁴⁰, M. Krivda^{103,56}, F. Krizek⁸⁵, E. Kryshen^{35,87}, M. Krzewicki⁴², A.M. Kubera¹⁹, V. Kučera⁸⁵, C. Kuhn⁶⁵, P.G. Kuijjer⁸³, A. Kumar⁹², J. Kumar⁴⁸, L. Kumar⁸⁹, S. Kumar⁴⁸, P. Kurashvili⁷⁸, A. Kurepin⁵³, A.B. Kurepin⁵³, A. Kuryakin¹⁰¹, M.J. Kweon⁵¹, Y. Kwon¹⁴¹, S.L. La Pointe¹¹², P. La Rocca²⁸, P. Ladron de Guevara¹¹, C. Lagana Fernandes¹²², I. Lakomov³⁵, R. Langoy⁴¹, K. Lapidus^{96,36}, C. Lara⁶⁰, A. Lardeux¹⁵, A. Lattuca²⁶, E. Laudi³⁵, R. Lea²⁵, L. Leardini⁹⁵, G.R. Lee¹⁰³, S. Lee¹⁴¹, F. Lehas⁸³, S. Lehner¹¹⁴, R.C. Lemmon⁸⁴, V. Lenti¹⁰⁵, E. Leogrande⁵⁴, I. León Monzón¹²¹, H. León Vargas⁶⁴, M. Leoncino²⁶, P. Lévai¹³⁹, S. Li^{71,7}, X. Li¹⁴, J. Lien⁴¹, R. Lietava¹⁰³, S. Lindal²¹, V. Lindenstruth⁴², C. Lippmann⁹⁹, M.A. Lisa¹⁹, H.M. Ljunggren³⁴, D.F. Lodato⁵⁴, P.I. Loenne²², V. Loginov⁷⁶, C. Loizides⁷⁵, X. Lopez⁷¹, E. López Torres⁹, A. Lowe¹³⁹, P. Luettig⁶¹, M. Lunardon²⁹, G. Luparello²⁵, T.H. Lutz¹⁴⁰, A. Maevskaya⁵³, M. Mager³⁵, S. Mahajan⁹², S.M. Mahmood²¹, A. Maire⁶⁵, R.D. Majka¹⁴⁰, M. Malaev⁸⁷, I. Maldonado Cervantes⁶³, L. Malinina^{67,iv}, D. Mal'Kevich⁵⁵, P. Malzacher⁹⁹, A. Mamonov¹⁰¹, V. Manko⁸¹, F. Manso⁷¹, V. Manzari^{105,35}, M. Marchisone^{26,129,66}, J. Mareš⁵⁷, G.V. Margagliotti²⁵, A. Margotti¹⁰⁶, J. Margutti⁵⁴, A. Marín⁹⁹, C. Markert¹²⁰, M. Marquard⁶¹, N.A. Martin⁹⁹, J. Martin Blanco¹¹⁵, P. Martinengo³⁵, M.I. Martínez², G. Martínez García¹¹⁵, M. Martinez Pedreira³⁵, A. Mas¹²², S. Masciocchi⁹⁹, M. Maserà²⁶, A. Masoni¹⁰⁷, A. Mastroserio³³, A. Matyja¹¹⁹, C. Mayer¹¹⁹, J. Mazer¹²⁸, M.A. Mazzoni¹¹⁰, D. McDonald¹²⁵, F. Meddi²³, Y. Melikyan⁷⁶, A. Menchaca-Rocha⁶⁴, E. Meninno³⁰, J. Mercado Pérez⁹⁵, M. Meres³⁸, Y. Miake¹³¹, M.M. Mieskolainen⁴⁶, K. Mikhaylov^{55,67}, L. Milano^{75,35}, J. Milosevic²¹, A. Mischke⁵⁴, A.N. Mishra⁴⁹, D. Miśkowiec⁹⁹, J. Mitra¹³⁶, C.M. Mitu⁵⁹, N. Mohammadi⁵⁴, B. Mohanty⁸⁰, L. Molnar⁶⁵, L. Montaño Zetina¹¹, E. Montes¹⁰, D.A. Moreira De Godoy⁶², L.A.P. Moreno², S. Moretto²⁹, A. Morreale¹¹⁵, A. Morsch³⁵, V. Muccifora⁷³, E. Mudnic¹¹⁸, D. Mühlheim⁶², S. Muhuri¹³⁶, M. Mukherjee¹³⁶, J.D. Mulligan¹⁴⁰, M.G. Munhoz¹²², K. Munning⁴⁵, R.H. Munzer^{96,36,61}, H. Murakami¹³⁰, S. Murray⁶⁶, L. Musa³⁵, J. Musinsky⁵⁶, B. Naik⁴⁸, R. Nair⁷⁸, B.K. Nandi⁴⁸, R. Nania¹⁰⁶, E. Nappi¹⁰⁵, M.U. Naru¹⁶, H. Natal da Luz¹²², C. Natrass¹²⁸, S.R. Navarro², K. Nayak⁸⁰, R. Nayak⁴⁸, T.K. Nayak¹³⁶, S. Nazarenko¹⁰¹, A. Nedosekin⁵⁵, L. Nellen⁶³, F. Ng¹²⁵, M. Nicassio⁹⁹, M. Niculescu⁵⁹, J. Niedziela³⁵, B.S. Nielsen⁸², S. Nikolaev⁸¹, S. Nikulin⁸¹, V. Nikulin⁸⁷, F. Noferini^{12,106}, P. Nomokonov⁶⁷, G. Nooren⁵⁴, J.C.C. Noris², J. Norman¹²⁷, A. Nyanin⁸¹, J. Nystrand²², H. Oeschler⁹⁵, S. Oh¹⁴⁰, S.K. Oh⁶⁸, A. Ohlson³⁵, A. Okatan⁷⁰, T. Okubo⁴⁷, L. Olah¹³⁹, J. Oleniacz¹³⁷, A.C. Oliveira Da Silva¹²², M.H. Oliver¹⁴⁰, J. Onderwaater⁹⁹, C. Oppedisano¹¹², R. Orava⁴⁶, M. Oravec¹¹⁷, A. Ortiz Velasquez⁶³, A. Oskarsson³⁴, J. Otwinowski¹¹⁹, K. Oyama^{95,77}, M. Ozdemir⁶¹, Y. Pachmayer⁹⁵, D. Pagano¹³⁴, P. Pagano³⁰, G. Paić⁶³, S.K. Pal¹³⁶, J. Pan¹³⁸, A.K. Pandey⁴⁸, V. Papikyan¹, G.S. Pappalardo¹⁰⁸, P. Pareek⁴⁹, J. Park⁵¹, W.J. Park⁹⁹, S. Parmar⁸⁹, A. Passfeld⁶², V. Paticchio¹⁰⁵, R.N. Patra¹³⁶, B. Paul^{112,102}, H. Pei⁷, T. Peitzmann⁵⁴, X. Peng⁷, H. Pereira Da Costa¹⁵, D. Peresunko^{76,81}, E. Perez Lezama⁶¹, V. Peskov⁶¹, Y. Pestov⁵, V. Petráček³⁹, V. Petrov¹¹³, M. Petrovici⁷⁹, C. Petta²⁸, S. Piano¹¹¹, M. Pikna³⁸, P. Pillot¹¹⁵, L.O.D.L. Pimentel⁸², O. Pinazza^{106,35}, L. Pinsky¹²⁵, D.B. Piyarathna¹²⁵, M. Płoskon⁷⁵, M. Planinic¹³², J. Pluta¹³⁷, S. Pochybova¹³⁹, P.L.M. Podesta-Lerma¹²¹, M.G. Poghossyan^{88,86}, B. Polichtchouk¹¹³, N. Poljak¹³², W. Poonsawat¹¹⁶, A. Pop⁷⁹, H. Poppenborg⁶², S. Porteboeuf-Houssais⁷¹, J. Porter⁷⁵, J. Pospisil⁸⁵, S.K. Prasad⁴, R. Preghenella^{35,106}, F. Prino¹¹², C.A. Pruneau¹³⁸, I. Pshenichnov⁵³, M. Puccio²⁶, G. Puddu²⁴, P. Pujahari¹³⁸, V. Punin¹⁰¹, J. Putschke¹³⁸, H. Qvigstad²¹, A. Rachevski¹¹¹, S. Raha⁴, S. Rajput⁹², J. Rak¹²⁶, A. Rakotozafindrabe¹⁵, L. Ramello³², F. Rami⁶⁵, R. Raniwala⁹³, S. Raniwala⁹³, S.S. Räsänen⁴⁶, B.T. Rascanu⁶¹, D. Rathee⁸⁹, K.F. Read^{128,86}, K. Redlich⁷⁸, R.J. Reed¹³⁸, A. Rehman²², P. Reichelt⁶¹, F. Reidt^{95,35}, X. Ren⁷, R. Renfordt⁶¹, A.R. Reolon⁷³, A. Reshetin⁵³, K. Reygers⁹⁵, V. Riabov⁸⁷, R.A. Ricci⁷⁴, T. Richert³⁴, M. Richter²¹, P. Riedler³⁵, W. Riegler³⁵, F. Riggi²⁸, C. Ristea⁵⁹, E. Rocco⁵⁴, M. Rodríguez Cahuantzi², A. Rodríguez Manso⁸³, K. Røed²¹, E. Rogochaya⁶⁷, D. Rohr⁴², D. Röhrich²², F. Ronchetti^{73,35}, L. Ronflette¹¹⁵, P. Rosnet⁷¹, A. Rossi²⁹, F. Roukoutakis⁹⁰, A. Roy⁴⁹, C. Roy⁶⁵, P. Roy¹⁰², A.J. Rubio Montero¹⁰, R. Rui²⁵,

R. Russo²⁶, E. Ryabinkin⁸¹, Y. Ryabov⁸⁷, A. Rybicki¹¹⁹, S. Saarinen⁴⁶, S. Sadhu¹³⁶, S. Sadovsky¹¹³, K. Šafařík³⁵, B. Sahlmuller⁶¹, P. Sahoo⁴⁹, R. Sahoo⁴⁹, S. Sahoo⁵⁸, P.K. Sahu⁵⁸, J. Saini¹³⁶, S. Sakai⁷³, M.A. Saleh¹³⁸, J. Salzwedel¹⁹, S. Sambyal⁹², V. Samsonov^{87,76}, L. Šándor⁵⁶, A. Sandoval⁶⁴, M. Sano¹³¹, D. Sarkar¹³⁶, N. Sarkar¹³⁶, P. Sarma⁴⁴, E. Scapparone¹⁰⁶, F. Scarlassara²⁹, C. Schiaua⁷⁹, R. Schicker⁹⁵, C. Schmidt⁹⁹, H.R. Schmidt⁹⁴, M. Schmidt⁹⁴, S. Schuchmann⁶¹, J. Schukraft³⁵, M. Schulc³⁹, Y. Schutz^{35,115}, K. Schwarz⁹⁹, K. Schweda⁹⁹, G. Scioli²⁷, E. Scomparin¹¹², R. Scott¹²⁸, M. Šefčík⁴⁰, J.E. Seger⁸⁸, Y. Sekiguchi¹³⁰, D. Sekihata⁴⁷, I. Selyuzhenkov⁹⁹, K. Senosi⁶⁶, S. Senyukov^{35,3}, E. Serradilla^{64,10}, A. Sevcenco⁵⁹, A. Shabanov⁵³, A. Shabetai¹¹⁵, O. Shadura³, R. Shahoyan³⁵, A. Shangaraev¹¹³, A. Sharma⁹², M. Sharma⁹², M. Sharma⁹², N. Sharma¹²⁸, A.I. Sheikh¹³⁶, K. Shigaki⁴⁷, Q. Shou⁷, K. Shtejer^{26,9}, Y. Sibiriak⁸¹, S. Siddhanta¹⁰⁷, K.M. Sielewicz³⁵, T. Siemiarczuk⁷⁸, D. Silvermyr³⁴, C. Silvestre⁷², G. Simatovic¹³², G. Simonetti³⁵, R. Singaraju¹³⁶, R. Singh⁸⁰, V. Singhal¹³⁶, T. Sinha¹⁰², B. Sitar³⁸, M. Sitta³², T.B. Skaali²¹, M. Slupecki¹²⁶, N. Smirnov¹⁴⁰, R.J.M. Snellings⁵⁴, T.W. Snellman¹²⁶, J. Song⁹⁸, M. Song¹⁴¹, Z. Song⁷, F. Soramel²⁹, S. Sorensen¹²⁸, F. Sozzi⁹⁹, M. Spacek³⁹, E. Spiriti⁷³, I. Sputowska¹¹⁹, M. Spyropoulou-Stassinaki⁹⁰, J. Stachel⁹⁵, I. Stan⁵⁹, P. Stankus⁸⁶, E. Stenlund³⁴, G. Steyn⁶⁶, J.H. Stiller⁹⁵, D. Stocco¹¹⁵, P. Strmen³⁸, A.A.P. Suaide¹²², T. Sugitate⁴⁷, C. Suire⁵², M. Suleymanov¹⁶, M. Suljic²⁵, R. Sultanov⁵⁵, M. Šumbera⁸⁵, S. Sumowidagdo⁵⁰, A. Szabo³⁸, I. Szarka³⁸, A. Szczepankiewicz¹³⁷, M. Szymanski¹³⁷, U. Tabassam¹⁶, J. Takahashi¹²³, G.J. Tambave²², N. Tanaka¹³¹, M. Tarhini⁵², M. Tariq¹⁸, M.G. Tarzila⁷⁹, A. Tauro³⁵, G. Tejeda Muñoz², A. Telesca³⁵, K. Terasaki¹³⁰, C. Terrevoli²⁹, B. Teyssier¹³³, J. Thäder⁷⁵, D. Thakur⁴⁹, D. Thomas¹²⁰, R. Tieulent¹³³, A. Tikhonov⁵³, A.R. Timmins¹²⁵, A. Toia⁶¹, S. Trogolo²⁶, G. Trombetta³³, V. Trubnikov³, W.H. Trzaska¹²⁶, T. Tsuji¹³⁰, A. Tumkin¹⁰¹, R. Turrisi¹⁰⁹, T.S. Tveter²¹, K. Ullaland²², A. Uras¹³³, G.L. Usai²⁴, A. Utrobicic¹³², M. Vala⁵⁶, L. Valencia Palomo⁷¹, S. Vallero²⁶, J. Van Der Maarel⁵⁴, J.W. Van Hoorne^{114,35}, M. van Leeuwen⁵⁴, T. Vanat⁸⁵, P. Vande Vyvre³⁵, D. Varga¹³⁹, A. Vargas², M. Vargyas¹²⁶, R. Varma⁴⁸, M. Vasileiou⁹⁰, A. Vasiliev⁸¹, A. Vauthier⁷², O. Vázquez Doce^{96,36}, V. Vechernin¹³⁵, A.M. Veen⁵⁴, A. Velure²², E. Vercellin²⁶, S. Vergara Limón², R. Vernet⁸, M. Verweij¹³⁸, L. Vickovic¹¹⁸, J. Viinikainen¹²⁶, Z. Vilakazi¹²⁹, O. Villalobos Baillie¹⁰³, A. Villatoro Tello², A. Vinogradov⁸¹, L. Vinogradov¹³⁵, Y. Vinogradov^{101,i}, T. Virgili³⁰, V. Vislavicius³⁴, Y.P. Viyogi¹³⁶, A. Vodopyanov⁶⁷, M.A. Völkl⁹⁵, K. Voloshin⁵⁵, S.A. Voloshin¹³⁸, G. Volpe^{33,139}, B. von Haller³⁵, I. Vorobyev^{36,96}, D. Vranic^{35,99}, J. Vrláková⁴⁰, B. Vulpescu⁷¹, B. Wagner²², J. Wagner⁹⁹, H. Wang⁵⁴, M. Wang⁷, D. Watanabe¹³¹, Y. Watanabe¹³⁰, M. Weber^{35,114}, S.G. Weber⁹⁹, D.F. Weiser⁹⁵, J.P. Wessels⁶², U. Westerhoff⁶², A.M. Whitehead⁹¹, J. Wiechula^{94,61}, J. Wikne²¹, G. Wilk⁷⁸, J. Wilkinson⁹⁵, M.C.S. Williams¹⁰⁶, B. Windelband⁹⁵, M. Winn⁹⁵, P. Yang⁷, S. Yano⁴⁷, Z. Yin⁷, H. Yokoyama^{131,72}, I.-K. Yoo⁹⁸, J.H. Yoon⁵¹, V. Yurchenko³, A. Zaborowska¹³⁷, V. Zaccolo⁸², A. Zaman¹⁶, C. Zampolli^{106,35}, H.J.C. Zanoli¹²², S. Zaporozhets⁶⁷, N. Zardoshti¹⁰³, A. Zarochentsev¹³⁵, P. Závada⁵⁷, N. Zaviyalov¹⁰¹, H. Zbroszczyk¹³⁷, I.S. Zgura⁵⁹, M. Zhalov⁸⁷, H. Zhang^{22,7}, X. Zhang^{7,75}, Y. Zhang⁷, C. Zhang⁵⁴, Z. Zhang⁷, C. Zhao²¹, N. Zhigareva⁵⁵, D. Zhou⁷, Y. Zhou⁸², Z. Zhou²², H. Zhu^{22,7}, J. Zhu^{115,7}, A. Zichichi^{27,12}, A. Zimmermann⁹⁵, M.B. Zimmermann^{62,35}, G. Zinovjev³, M. Zyzak⁴²

Affiliation notes

ⁱ Deceased

ⁱⁱ Also at: Georgia State University, Atlanta, Georgia, United States

ⁱⁱⁱ Also at: Also at Department of Applied Physics, Aligarh Muslim University, Aligarh, India

^{iv} Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear, Physics, Moscow, Russia

Collaboration Institutes

¹A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia

²Benemérita Universidad Autónoma de Puebla, Puebla, Mexico

³Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine

⁴Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India

⁵Budker Institute for Nuclear Physics, Novosibirsk, Russia

⁶California Polytechnic State University, San Luis Obispo, California, United States

⁷Central China Normal University, Wuhan, China

⁸Centre de Calcul de l'IN2P3, Villeurbanne, Lyon, France

- ⁹Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
- ¹⁰Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
- ¹¹Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
- ¹²Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, Rome, Italy
- ¹³Chicago State University, Chicago, Illinois, United States
- ¹⁴China Institute of Atomic Energy, Beijing, China
- ¹⁵Commissariat à l’Energie Atomique, IRFU, Saclay, France
- ¹⁶COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan
- ¹⁷Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain
- ¹⁸Department of Physics, Aligarh Muslim University, Aligarh, India
- ¹⁹Department of Physics, Ohio State University, Columbus, Ohio, United States
- ²⁰Department of Physics, Sejong University, Seoul, South Korea
- ²¹Department of Physics, University of Oslo, Oslo, Norway
- ²²Department of Physics and Technology, University of Bergen, Bergen, Norway
- ²³Dipartimento di Fisica dell’Università ‘La Sapienza’ and Sezione INFN, Rome, Italy
- ²⁴Dipartimento di Fisica dell’Università and Sezione INFN, Cagliari, Italy
- ²⁵Dipartimento di Fisica dell’Università and Sezione INFN, Trieste, Italy
- ²⁶Dipartimento di Fisica dell’Università and Sezione INFN, Turin, Italy
- ²⁷Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Bologna, Italy
- ²⁸Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Catania, Italy
- ²⁹Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Padova, Italy
- ³⁰Dipartimento di Fisica ‘E.R. Caianiello’ dell’Università and Gruppo Collegato INFN, Salerno, Italy
- ³¹Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
- ³²Dipartimento di Scienze e Innovazione Tecnologica dell’Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy
- ³³Dipartimento Interateneo di Fisica ‘M. Merlin’ and Sezione INFN, Bari, Italy
- ³⁴Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
- ³⁵European Organization for Nuclear Research (CERN), Geneva, Switzerland
- ³⁶Excellence Cluster Universe, Technische Universität München, Munich, Germany
- ³⁷Faculty of Engineering, Bergen University College, Bergen, Norway
- ³⁸Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
- ³⁹Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
- ⁴⁰Faculty of Science, P.J. Šafárik University, Košice, Slovakia
- ⁴¹Faculty of Technology, Buskerud and Vestfold University College, Tonsberg, Norway
- ⁴²Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- ⁴³Gangneung-Wonju National University, Gangneung, South Korea
- ⁴⁴Gauhati University, Department of Physics, Guwahati, India
- ⁴⁵Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
- ⁴⁶Helsinki Institute of Physics (HIP), Helsinki, Finland
- ⁴⁷Hiroshima University, Hiroshima, Japan
- ⁴⁸Indian Institute of Technology Bombay (IIT), Mumbai, India
- ⁴⁹Indian Institute of Technology Indore, Indore, India
- ⁵⁰Indonesian Institute of Sciences, Jakarta, Indonesia
- ⁵¹Inha University, Incheon, South Korea
- ⁵²Institut de Physique Nucléaire d’Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France
- ⁵³Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
- ⁵⁴Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands
- ⁵⁵Institute for Theoretical and Experimental Physics, Moscow, Russia
- ⁵⁶Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
- ⁵⁷Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
- ⁵⁸Institute of Physics, Bhubaneswar, India
- ⁵⁹Institute of Space Science (ISS), Bucharest, Romania
- ⁶⁰Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany

- ⁶¹Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- ⁶²Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany
- ⁶³Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
- ⁶⁴Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
- ⁶⁵Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
- ⁶⁶iThemba LABS, National Research Foundation, Somerset West, South Africa
- ⁶⁷Joint Institute for Nuclear Research (JINR), Dubna, Russia
- ⁶⁸Konkuk University, Seoul, South Korea
- ⁶⁹Korea Institute of Science and Technology Information, Daejeon, South Korea
- ⁷⁰KTO Karatay University, Konya, Turkey
- ⁷¹Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS-IN2P3, Clermont-Ferrand, France
- ⁷²Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
- ⁷³Laboratori Nazionali di Frascati, INFN, Frascati, Italy
- ⁷⁴Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy
- ⁷⁵Lawrence Berkeley National Laboratory, Berkeley, California, United States
- ⁷⁶Moscow Engineering Physics Institute, Moscow, Russia
- ⁷⁷Nagasaki Institute of Applied Science, Nagasaki, Japan
- ⁷⁸National Centre for Nuclear Studies, Warsaw, Poland
- ⁷⁹National Institute for Physics and Nuclear Engineering, Bucharest, Romania
- ⁸⁰National Institute of Science Education and Research, Bhubaneswar, India
- ⁸¹National Research Centre Kurchatov Institute, Moscow, Russia
- ⁸²Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- ⁸³Nikhef, Nationaal instituut voor subatomaire fysica, Amsterdam, Netherlands
- ⁸⁴Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
- ⁸⁵Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic
- ⁸⁶Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
- ⁸⁷Petersburg Nuclear Physics Institute, Gatchina, Russia
- ⁸⁸Physics Department, Creighton University, Omaha, Nebraska, United States
- ⁸⁹Physics Department, Panjab University, Chandigarh, India
- ⁹⁰Physics Department, University of Athens, Athens, Greece
- ⁹¹Physics Department, University of Cape Town, Cape Town, South Africa
- ⁹²Physics Department, University of Jammu, Jammu, India
- ⁹³Physics Department, University of Rajasthan, Jaipur, India
- ⁹⁴Physikalisches Institut, Eberhard Karls Universität Tübingen, Tübingen, Germany
- ⁹⁵Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ⁹⁶Physik Department, Technische Universität München, Munich, Germany
- ⁹⁷Purdue University, West Lafayette, Indiana, United States
- ⁹⁸Pusan National University, Pusan, South Korea
- ⁹⁹Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
- ¹⁰⁰Rudjer Bošković Institute, Zagreb, Croatia
- ¹⁰¹Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
- ¹⁰²Saha Institute of Nuclear Physics, Kolkata, India
- ¹⁰³School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ¹⁰⁴Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
- ¹⁰⁵Sezione INFN, Bari, Italy
- ¹⁰⁶Sezione INFN, Bologna, Italy
- ¹⁰⁷Sezione INFN, Cagliari, Italy
- ¹⁰⁸Sezione INFN, Catania, Italy
- ¹⁰⁹Sezione INFN, Padova, Italy
- ¹¹⁰Sezione INFN, Rome, Italy
- ¹¹¹Sezione INFN, Trieste, Italy
- ¹¹²Sezione INFN, Turin, Italy
- ¹¹³SSC IHEP of NRC Kurchatov institute, Protvino, Russia

- ¹¹⁴Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
¹¹⁵SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France
¹¹⁶Suranaree University of Technology, Nakhon Ratchasima, Thailand
¹¹⁷Technical University of Košice, Košice, Slovakia
¹¹⁸Technical University of Split FESB, Split, Croatia
¹¹⁹The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
¹²⁰The University of Texas at Austin, Physics Department, Austin, Texas, United States
¹²¹Universidad Autónoma de Sinaloa, Culiacán, Mexico
¹²²Universidade de São Paulo (USP), São Paulo, Brazil
¹²³Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
¹²⁴Universidade Federal do ABC, Santo Andre, Brazil
¹²⁵University of Houston, Houston, Texas, United States
¹²⁶University of Jyväskylä, Jyväskylä, Finland
¹²⁷University of Liverpool, Liverpool, United Kingdom
¹²⁸University of Tennessee, Knoxville, Tennessee, United States
¹²⁹University of the Witwatersrand, Johannesburg, South Africa
¹³⁰University of Tokyo, Tokyo, Japan
¹³¹University of Tsukuba, Tsukuba, Japan
¹³²University of Zagreb, Zagreb, Croatia
¹³³Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, Lyon, France
¹³⁴Università di Brescia, Brescia, Italy
¹³⁵V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia
¹³⁶Variable Energy Cyclotron Centre, Kolkata, India
¹³⁷Warsaw University of Technology, Warsaw, Poland
¹³⁸Wayne State University, Detroit, Michigan, United States
¹³⁹Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary
¹⁴⁰Yale University, New Haven, Connecticut, United States
¹⁴¹Yonsei University, Seoul, South Korea
¹⁴²Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany