EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP-2019-033
22 February 2019

Investigations of anisotropic flow using multi-particle azimuthal correlations in pp, p–Pb, Xe–Xe, and Pb–Pb collisions at the LHC

ALICE Collaboration*

Abstract

Measurements of anisotropic flow coefficients (v_n) and their cross-correlations using two- and multi-particle cumulant methods are reported in collisions of pp at $\sqrt{s} = 13$ TeV, p–Pb at $\sqrt{s_{\rm NN}} = 5.02$ TeV, Xe–Xe at $\sqrt{s_{\rm NN}} = 5.44$ TeV, and Pb–Pb at $\sqrt{s_{\rm NN}} = 5.02$ TeV recorded with the ALICE detector. These measurements are performed as a function of multiplicity in the mid-rapidity region $|\eta| < 0.8$ for the transverse momentum range $0.2 < p_{\rm T} < 3.0$ GeV/c. An ordering of the coefficients $v_2 > v_3 > v_4$ is found in pp and p–Pb collisions, similar to that seen in large collision systems, while a weak v_2 multiplicity dependence is observed relative to nucleus–nucleus collisions in the same multiplicity range. Using the novel subevent method, v_2 measured in pp and p–Pb collisions with four-particle cumulants is found to be compatible with that from six-particle cumulants. The symmetric cumulants $SC(m,n)$ calculated with the subevent method which evaluate the correlation strength between v_n^2 and v_m^2 are also presented. The presented data, which add further support to the existence of long-range multi-particle azimuthal correlations in high multiplicity pp and p–Pb collisions, can neither be described by PYTHIA8 nor by IP-Glasma+MUSIC+UrQMD model calculations, and hence provide new insights into the understanding of collective effects in small collision systems.

*See Appendix B for the list of collaboration members

Experiments investigating ultra-relativistic collisions of heavy ions intend to recreate and explore the state of matter known as Quark–Gluon Plasma (QGP), a deconfined state of quarks and gluons, which prevailed in the early universe. Investigations of azimuthal correlations of final state particles over a wide range in pseudorapidity relative to the collision symmetry plane Ψ_n ($n \geq 1$), whose magnitude is usually quantified by flow coefficients v_n, provide important insights into the nature of the hot and dense matter created in these collisions [1–3]. Extensive measurements of v_n for inclusive [4–9] and identified hadrons [10] were performed at the Large Hadron Collider (LHC). These studies, together with quantitative predictions by hydrodynamic calculations, have enabled an extraction of the properties of the created matter [11], revealing in particular that the QGP behaves as a nearly-perfect fluid with a shear viscosity over entropy density ratio η/s close to the universal lower limit $1/4\pi$ from Ads/CFT [12]. Over the past few years, significant progress was achieved in measuring v_n distributions, as well as correlations between different flow coefficients and symmetry planes [6, 7, 13–18]. In particular, the correlation strength between different orders of flow coefficients (m and n), quantified by symmetric cumulants $SC(m,n)$ [19], was found to be sensitive to the temperature dependence of η/s and the details of the initial conditions [14]. The experimental measurements of $SC(m,n)$, together with v_n, thus provide tighter constraints on theoretical models than the individual flow coefficients alone [14, 17].

Striking similarities between numerous observables, thought to indicate the emergence of a QGP, were revealed across the pp, p–Pb and Pb–Pb collision systems at LHC energies, when compared at similar multiplicity of produced particles within a specific phase space [20]. The so-called "ridge" structure measured using two-particle correlations as a function of the pseudorapidity difference $\Delta\eta$ and the azimuthal angle difference $\Delta\varphi$, which in heavy-ion collisions results from anisotropic flow, was also observed in high multiplicity p–Pb and pp collisions [21]. In addition, reported measurements of azimuthal correlations using multi-particle cumulants revealed signatures believed to be associated with the presence of collective effects in heavy-ion collisions, such as a negative four-particle cumulant $c_2\{4\}$ [22–26]. These results have indicated the presence of collective behaviour also in pp and p–Pb collisions.

Whether the observed similarities between small (pp and p–Pb) and large (Xe–Xe and Pb–Pb) collision systems arise from the same physics mechanism is under intense debate. Besides hydrodynamic descriptions [27–31], calculations from transport models [32–34], hadronic rescattering [35, 36], a string rope and shoving mechanism [37], as well as initial stage effects [38–40], can also reproduce qualitatively or even quantitatively the multiplicity dependence observed in data. No consensus on a single scenario which consistently explains all measurements across collision systems was reached so far. A better understanding of the initial conditions in small collision systems is needed, in particular in pp collisions where sub-nucleon degrees of freedom are relevant [29, 41].

In this letter, we report measurements of v_n and $SC(m,n)$ as a function of produced particle multiplicity across small and large collision systems. These measurements are expected to provide information on collective effects for all systems, which can be revealed via long-range multi-particle correlations. They rely on a new technique of performing multi-particle correlations in ranges of pseudorapidity named the *subevent method* [42, 43], where the produced particles are grouped into two or more subevents, separated by a pseudorapidity gap, to achieve a long range separation between particles that are correlated. The subevent approach minimises biases from few particle correlations such as resonances and jets, usually called non-flow, which are not associated with a collision symmetry plane.

The analyzed data are from collisions of pp at $\sqrt{s}$ = 13 TeV, p–Pb at $\sqrt{s_{\rm NN}}$ = 5.02 TeV, Xe–Xe at $\sqrt{s_{\rm NN}}$ = 5.44 TeV and Pb–Pb at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. They were recorded with the ALICE detector [44, 45] in Run 2 of the LHC during the years 2015, 2016 and 2017. Minimum bias events were triggered using a coincidence signal in the two scintillator arrays of the V0 detector, V0A and V0C, which cover the pseudorapidity ranges $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively [46]. A dedicated trigger was used in pp collisions to select high-multiplicity events based on the amplitude in both arrays of the V0 detector. The trigger selected approximately 0.1% of events with the largest multiplicity in the V0 acceptance. The average multiplicity is about 4 times larger than the one in minimum bias collisions. In comparison to minimum-bias collisions, the selection of high-multiplicity events based on forward multiplicity decreases the measurement performed at mid-rapidity, which is due to a suppression of non-flow correlations at mid-rapidity.

Only events with a reconstructed primary vertex $Z_{\rm vtx}$ within ± 10 cm from the nominal interaction point were selected. Removal of background events from e.g. beam interaction with the residual gas molecules in the beam pipe and pileup events was performed based on the information from the Silicon Pixel Detector (SPD) and V0 detectors. A sample of 310×10^6 high-multiplicity pp, 230×10^6 minimum bias p–Pb, 1.3×10^6 Xe–Xe and 55×10^6 Pb–Pb collisions that passed the event selection criteria was used for the analysis.

The charged tracks were reconstructed using the Inner Tracking System (ITS) [47] and the Time Projection Chamber (TPC) [48]. Only tracks with more than 70 clusters in the TPC (out of a maximum of 159) were selected. A selection on pseudorapidity to be within $-0.8 < \eta < 0.8$ ensured a high track reconstruction efficiency. Tracks with a transverse momentum $p_{\rm T} < 0.2$ GeV/c were rejected due to low tracking efficiency and tracks with $p_{\rm T} > 3.0$ GeV/c were removed in order to reduce the contribution from jets. A criterion on the maximum distance of closest approach (DCA) of the track to the collision point of less than 2 cm in longitudinal direction and a $p_{\rm T}$-dependent selection in the transverse direction, ranging from 0.2 cm at $p_{\rm T} = 0.2$ GeV/c down to 0.02 cm at $p_{\rm T} = 3.0$ GeV/c, was applied to ensure an optimum rejection of contamination from secondary particles.

The multi-particle cumulants and symmetric cumulants were calculated from two- and multi-particle azimuthal correlations using the framework introduced in [19], which was recently extended to include the subevent method. The ranges of the subevents were chosen to be $\eta^A = (-0.8, 0)$ and $\eta^B = (0, 0.8)$ for the 2-subevent, and $\eta^A = (-0.8, -0.4)$, $\eta^B = (-0.4, 0.4)$ and $\eta^C = (0.4, 0.8)$ for 3-subevent measurements.

A correction dependent on pseudorapidity η and $Z_{\rm vtx}$ was applied within the generic framework to account for azimuthal non-uniformity . The correction for tracking inefficiencies was obtained from Monte Carlo simulations as a function of $p_{\rm T}$, η and $Z_{\rm vtx}$ from generated particles and from tracks reconstructed after particle propagation through the detector description based on a GEANT3 simulation [49]. The systematic uncertainty was estimated by varying the event and track selection criteria, and by evaluating the analysis performance using Monte Carlo simulations with the so-called closure test. The contribution to the systematic uncertainty from the event selection was examined by narrowing the selection on $Z_{\rm vtx}$ to ± 5 cm. The track reconstruction biases were evaluated by tightening the selection criteria on the DCA in both the longitudinal and transverse directions, by increasing the required minimum number of TPC clusters in the track reconstruction, and by comparing the results to those obtained with other types of tracks, which have different requirements regarding the role of the ITS. The uncertainty from the Monte Carlo closure test was estimated by comparing calculations at the event generator level (i.e. invoking neither the detector geometry, nor the reconstruction algorithm) with simulation output after the full reconstruction. The individual contributions were summed in quadrature to form the systematic uncertainties. Results were obtained as a function of the number of tracks with the same selection as was applied to the measurements, which were corrected for losses due to detector inefficiencies with Monte Carlo simulations to obtain the true number of created charged particles $N_{\rm ch}(|\eta| < 0.8)$.

Figure 1 presents the measurements of anisotropic flow coefficients $v_n\{k\}$ of harmonic n, obtained from k-particle correlations, in pp, p–Pb, Xe–Xe and Pb–Pb collisions. The collision energies are similar except for pp collisions where, however, no collision energy dependence of the integrated v_n is expected, as was shown in [25]. Figure 1 (a) shows v_2, v_3 and v_4 measured using two-particle ($k = 2$) cumulants with a pseudorapidity gap $|\Delta\eta|$ greater than 1.4 or 1.0 units, chosen to suppress non-flow contributions. Due to the limited statistics of the pp data sample, the $|\Delta\eta|$ gap in case of v_3 and v_4 was reduced to 1 unit, consistently across all collision systems. A pronounced multiplicity dependence of v_2 is ob-

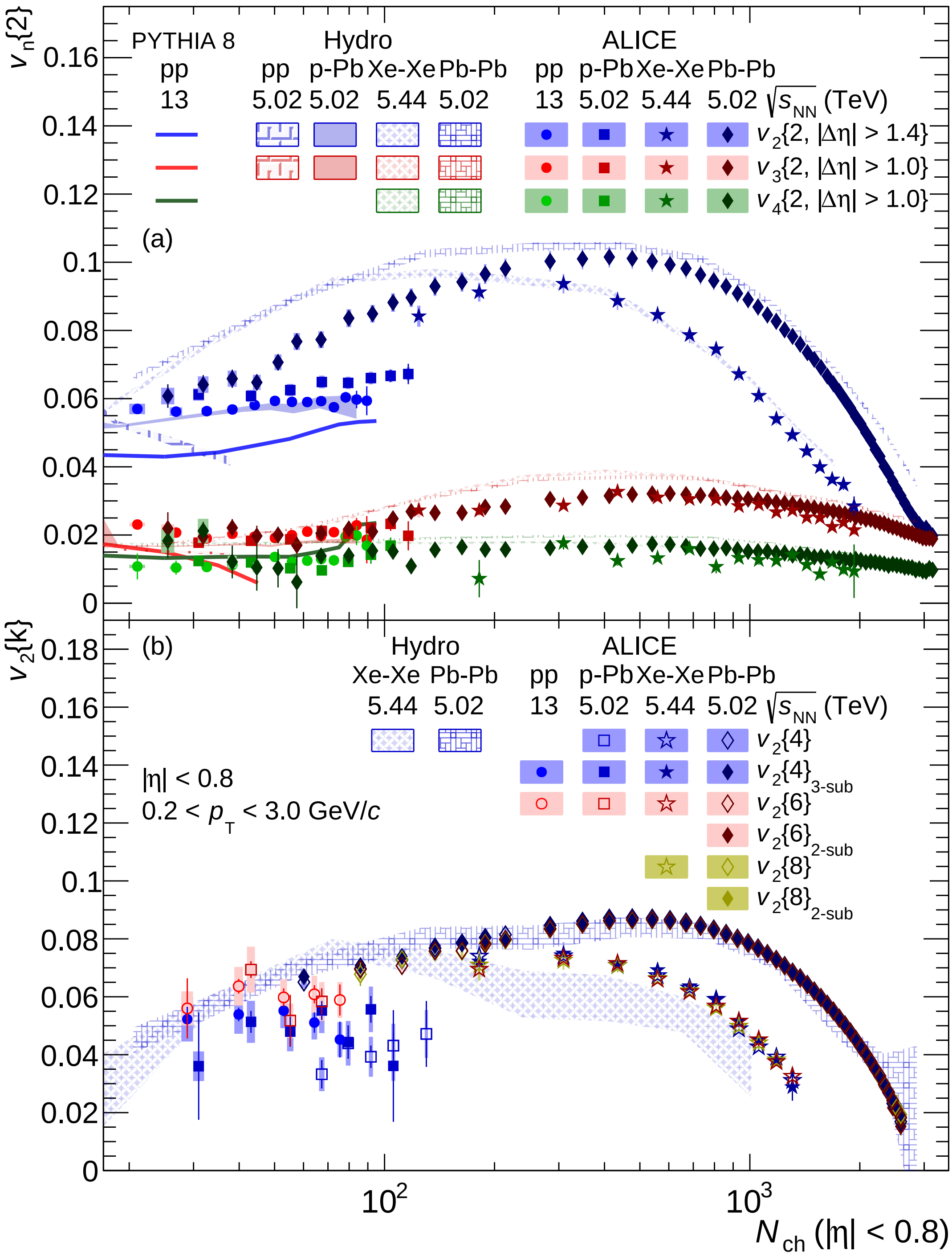

Fig. 1: Multiplicity dependence of $v_n\{k\}$ for pp, p–Pb, Xe–Xe and Pb–Pb collisions. Statistical uncertainties are shown as vertical lines and systematic uncertainties as filled boxes (coloured online). Data are compared with PYTHIA 8 [50] simulations (solid lines) of pp collisions at $\sqrt{s} = 13$ TeV and IP-Glasma+MUSIC+UrQMD [29, 51] calculations of pp, p–Pb, Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV (filled bands - coloured online). (a) v_2, v_3 and v_4 measured using two-particle cumulants with a pseudorapidity gap greater than 1.4 or 1.0 units. (b) v_2 measured using multi-particle cumulants, with the 3-subevent method for the four-particle cumulant, and 2-subevent method for higher order cumulants in Pb–Pb collisions.

served in the flow dominated collision systems (Pb–Pb and Xe–Xe) as a result of the medium response to the anisotropic shape of the initial overlap region of the colliding nuclei and the effectivity to transform the initial eccentricities to final flow coefficients, which decreases at low multiplicities. The Pb–Pb data exhibit larger values of v_2 than the Xe–Xe data, except at low multiplicity ($N_{\mathrm{ch}}(|\eta| < 0.8) < 200$) where the two measurements become compatible. An ordering of $v_2 > v_3 > v_4$ is observed in large collision systems except for the region with the largest multiplicities, where $v_2 \approx v_3$. At low multiplicity, the magnitudes of v_n are similar to those measured in pp and p–Pb collisions. The measurements from Xe–Xe and Pb–Pb collisions are compared with recent calculations containing IP-Glasma initial conditions, a MUSIC hydrodynamic model, and the UrQMD model for hadronic rescatterings [29, 51], shown with filled bands, where the width of the band represents the statistical uncertainty of the model. The calculations qualitatively describe all the v_n measurements at large and intermediate multiplicities, while they tend to overestimate the v_2 in the low multiplicity region. In small collision systems, all the v_n coefficients exhibit a weak dependence on multiplicity. This trend cannot be explained solely by model calculations without collective effects, as demonstrated by the comparison with predictions from PYTHIA 8.210 Monash 2013 with colour reconnection [50], computed with a similar multiplicity definition as the experimental results from pp collisions. The qualitatively similar ordering of v_n in pp and p–Pb collisions with the one observed in large collision systems is not described by PYTHIA either. These observations suggest the presence of effects other than just non-flow correlations at multiplicities larger than about 2–3 times the minimum bias value of $\langle N_{\mathrm{ch}} \rangle \approx 10$ in pp and $\langle N_{\mathrm{ch}} \rangle \approx 24$ in p–Pb collisions within $|\eta| < 0.8$ and $0.2 < p_{\mathrm{T}} < 3.0$ GeV/c. Such conclusions are supported in p–Pb collisions by the comparison with the IP-Glasma+MUSIC+UrQMD model calculations, which qualitatively describes the measurements, noting that further non-flow suppression with a larger $|\Delta\eta|$ separation in the experimental results or improvements in the phenomenological description could help to reach a quantitative agreement. Nevertheless, the model reveals a strong decrease of v_n with multiplicity in pp collisions, which is in stark contrast with the weak dependence in data. However, a simultaneous description of pp, p–Pb and Pb–Pb collision measurements was achieved in [30] with the hydrodynamic superSONIC model with hadronic rescatterings from UrQMD, which suggests that hydrodynamic collectivity prevails in both small and large collision systems.

Figure 1 (b) shows measurements of elliptic flow $v_2\{k\}$ using multi-particle cumulants with $k = 4, 6$ and 8. Measurements of $v_2\{4\}$ calculated with the 3-subevent method are also presented, and in Pb–Pb collisions the v_2 from six- and eight-particle cumulants with the 2-subevent method is shown in addition. Compared to two-particle correlations, multi-particle cumulants are less influenced by non-flow effects, since the latter usually only involve a few particles. No further non-flow suppression was observed by increasing an $|\Delta\eta|$ gap between the subevents up to 0.2 in the multi-particle cumulant measurements. Characteristic patterns of long-range multi-particle correlations, such as consistent results from the standard and subevent methods ($v_2\{4\} \approx v_2\{4\}_{3-\mathrm{sub}}$, $v_2\{6\} \approx v_2\{6\}_{2-\mathrm{sub}}$ and $v_2\{8\} \approx v_2\{8\}_{2-\mathrm{sub}}$), and compatible measurements of v_2 with multi-particle cumulants ($v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$) are found in both Xe–Xe and Pb–Pb collisions, signalling a negligible contribution from non-flow correlations and the dominance of collective effects. Moreover, a good agreement of $v_2\{4\}$ calculated with the IP-Glasma+MUSIC+UrQMD [29, 51] model is found for Pb–Pb collisions down to $N_{\mathrm{ch}} \approx 200$, below which $v_2\{2\}$ measurements are overestimated by the model. The hydrodynamic model prediction, which does not include any tuning of its parameters to other collision systems, underestimates the $v_2\{4\}$ from Xe–Xe collisions by about 15–20% in the presented multiplicity range. In p–Pb collisions, further non-flow suppression with the 3-subevent method leads to a decrease of the cumulant $c_2\{4\} > c_2\{4\}_{3-\mathrm{sub}}$, which due to the relation $v_2\{4\} = \sqrt[4]{-c_2\{4\}}$ leads to an increase $v_2\{4\} < v_2\{4\}_{3-\mathrm{sub}}$. The 3-subevent method allows for a measurement of a real-valued $v_2\{4\}_{3-\mathrm{sub}}$ at a lower N_{ch} than the standard $v_2\{4\}$ measurement, making it possible to study collectivity at even lower multiplicities. An indication of multi-particle correlations in p–Pb collisions is unveiled with consistent results of v_2 measured with four- and six-particle cumulants. In pp collisions, significant contributions from non-flow effects to the four-particle cumulant ($c_2\{4\} > 0$) prevent the extraction of a real-valued $v_2\{4\}$. However, a measurement of the real-valued

$v_2\{4\}_{3-\mathrm{sub}}$ is possible with the 3-subevent method. Similarly as for $v_2\{2,|\Delta\eta|>1.4\}$, the $v_2\{4\}_{3-\mathrm{sub}}$ exhibits only a weak dependence on multiplicity. Our results confirm the existence of long-range multi-particle correlations in pp and p–Pb collisions at multiplicities $N_{\mathrm{ch}}(|\eta|<0.8) \geq 30$. PYTHIA calculations, which do not contain genuine long-range multi-particle correlations, do not allow real values of $v_2\{4\}$ to be measured even with the subevent method [42]. The iEBE-VISHNU hydrodynamic calculations [31] can quantitatively describe all available two-particle correlation measurements in pp collisions. However, they cannot reproduce the four-particle cumulants with the currently used initial state model parameters, not even on a qualitative level. Another model with initial-state calculations predicts the measured multi-particle cumulants without involving final-state interactions [39]. Therefore, with v_n measurements alone it is not completely clear whether the origin of the apparent collectivity observed in small collision systems is the same as in large collision systems.

Further information about the origin of the observed collectivity can be extracted from the correlations between different orders of v_n^2 and v_m^2 represented by symmetric cumulants $\mathrm{SC}(m,n)$. Figure 2 presents the multiplicity dependence of $\mathrm{SC}(m,n)$ measured with the 3-subevent method. A positive $\mathrm{SC}(4,2)_{3-\mathrm{sub}}$ is observed in large collision systems over the entire multiplicity range, similar to what was measured previously in Pb–Pb collisions at 2.76 TeV [14, 17] without the subevent method. The trend is reproduced by the IP-Glasma+MUSIC+UrQMD [29, 51] calculations. A positive $\mathrm{SC}(4,2)_{3-\mathrm{sub}}$ is similarly observed both in pp and p–Pb collisions, as was found in [52]. The measurements in pp collisions are compared with PYTHIA 8 [50], which indicates a decrease of $\mathrm{SC}(4,2)_{3-\mathrm{sub}}$ with decreasing multiplicity different from what is seen in data. Calculations [39, 53] with initial state correlations or parton-escape mechanism can qualitatively, or even semi-quantitatively, describe the p–Pb data. It should be noted that the results from the initial state model [39] were calculated with respect to variables that cannot be directly compared to experimental data.

An anti-correlation between v_2^2 and v_3^2 is implied by the negative $\mathrm{SC}(3,2)_{3-\mathrm{sub}}$ observed in Xe–Xe and Pb–Pb collisions, similarly as in [14, 17]. Considering the linear response of v_n to initial state eccentricities ε_n (for $n=2,3$), the negative $\mathrm{SC}(3,2)_{3-\mathrm{sub}}$ also implies an anti-correlation between initial state ε_2 and ε_3, and thus provides tight constraints on the initial conditions in Xe–Xe and Pb–Pb collisions. There is a hint of a change to a positive sign of $\mathrm{SC}(3,2)_{3-\mathrm{sub}}$ in Pb–Pb collisions at $N_{\mathrm{ch}} \approx 100$. This tendency seems to be maintained and extended to lower multiplicities in small collision systems, suggesting a common positive correlation between v_2^2 and v_3^2 among collision systems of different sizes. Such a behaviour is not observed in the measurements from small collision systems with a larger η acceptance [52], where $\mathrm{SC}(3,2)_{3-\mathrm{sub}}$ remains negative in the whole multiplicity range. Among possible reasons for this can be different contributions from non-flow effects. The IP-Glasma+MUSIC+UrQMD [29, 51] calculations for Xe–Xe and Pb–Pb collisions reproduce the negative correlation at large multiplicities. This negative sign persists in simulations down to the lowest multiplicities. PYTHIA 8 [50] fails to describe the results from pp collisions quantitatively, but it does reproduce the trend of the data. No hydrodynamic computation of $\mathrm{SC}(m,n)$ in small systems is currently available. Nevertheless, calculations based on initial state correlations in [38, 39] reflect the crossing from negative to positive $\mathrm{SC}(3,2)$ in p–Pb collisions, whereas a positive correlation is observed in pp collisions [38].

While the $\mathrm{SC}(m,n)$ encodes information on both the magnitude of and correlation between the flow coefficients, in the absence of non-flow the latter can be accessed directly by dividing $\mathrm{SC}(m,n)_{3-\mathrm{sub}}$ by the corresponding flow coefficients $\langle v_m^2\rangle\langle v_n^2\rangle$ from Figs. 2 and 1, respectively. The normalised ratio indicates that the correlation between flow coefficients is similar between different collision systems at the same N_{ch}, and reveals a large increase in magnitude in the correlation strength for collisions with N_{ch} below ≈ 100 compared to higher multiplicities. While this may be indicative of a different fluctuation pattern in low multiplicity interactions, it has to be noted that non-flow effects likely persist in this region based on the observed finite values of PYTHIA calculations in Figs. 1 and 2. Such effects make the interpretation of an increase of the normalised ratio significantly less straightforward and requires further

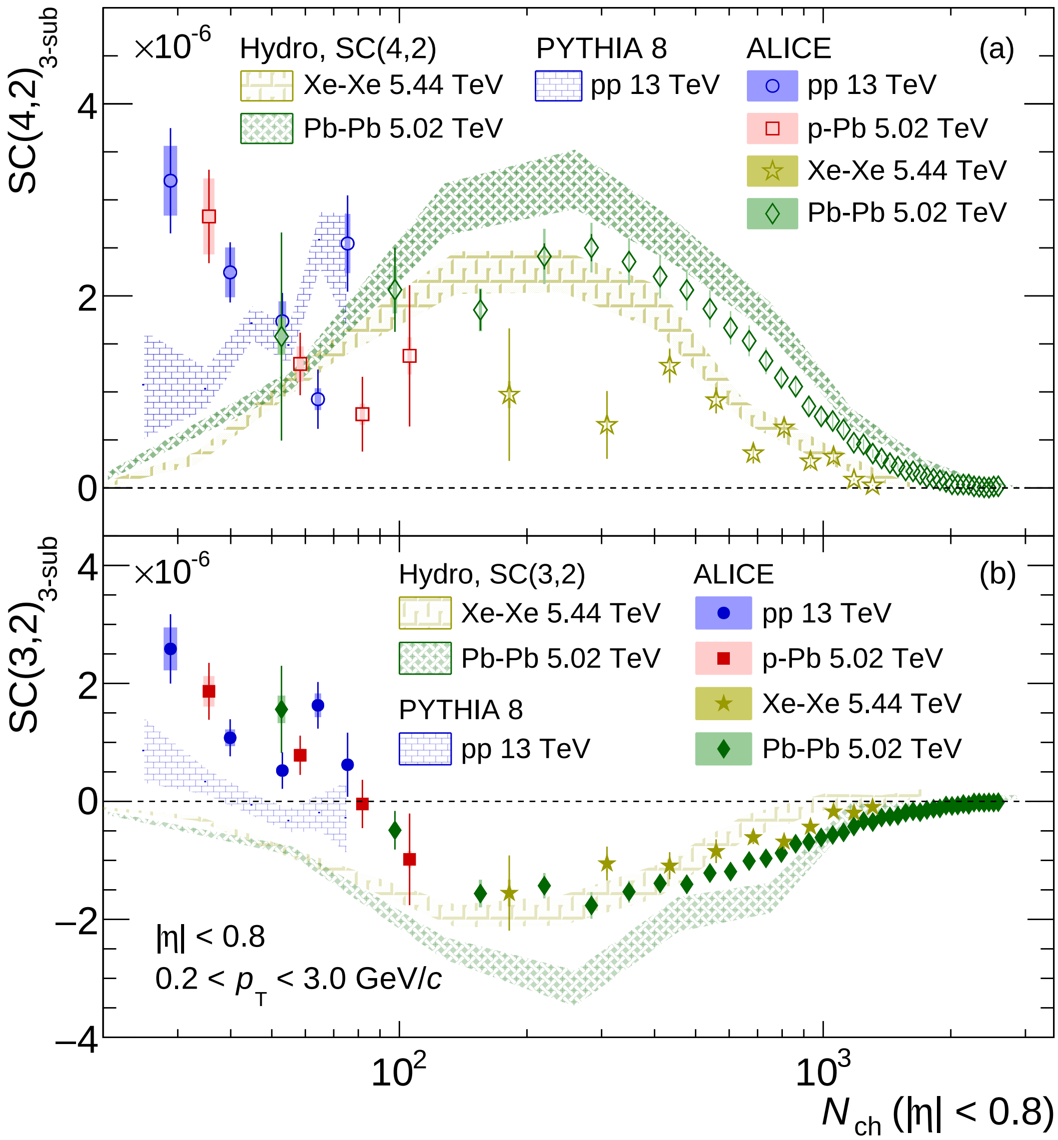

Fig. 2: Multiplicity dependence of the symmetric cumulant (a) $SC(3,2)_{3-\mathrm{sub}}$ and (b) $SC(4,2)_{3-\mathrm{sub}}$ for pp, p–Pb, Xe–Xe and Pb–Pb collisions. Statistical uncertainties are shown as vertical lines and systematic uncertainties as filled boxes (coloured online). The measurements in large collision systems are compared with the IP-Glasma+MUSIC+UrQMD [29, 51] calculations and results in pp collisions are compared with the PYTHIA 8 model [50].

studies. The normalised ratio $\mathrm{SC}(m,n)_{3-\mathrm{sub}}/\langle v_m^2\rangle\langle v_n^2\rangle$ is shown in Fig. A.1 of supplemental materials where it is accompanied with more discussion.

In summary, we have presented the measurements of flow coefficients $v_n\{k\}$ and symmetric cumulants $\mathrm{SC}(m,n)_{3-\mathrm{sub}}$ as a function of produced particle multiplicity in small (pp, p–Pb) and large (Xe–Xe, Pb–Pb) collision systems. In pp and p–Pb collisions, a non-trivial ordering $v_2 > v_3 > v_4$ and a weak dependence of v_n on the multiplicity, is observed. The values of v_n from pp and p–Pb collisions are compatible with heavy-ion collisions at low multiplicity. These first ALICE measurements of v_2 using multi-particle cumulants in small collision systems are found to be compatible with each other after suppression of non-flow contributions with the subevent method. Positive values of $\mathrm{SC}(4,2)_{3-\mathrm{sub}}$ are seen in all four collision systems (pp, p–Pb, Xe–Xe and Pb–Pb). The observed anti-correlation between v_2^2 and v_3^2 measured with $\mathrm{SC}(3,2)_{3-\mathrm{sub}}$ in large collision systems seems to evolve into a positive correlation at low multiplicity. A similar sign change is indicated also in pp and p–Pb collisions. Thus, the different systems exhibit a similar $\mathrm{SC}(m,n)$ at the same N_{ch}, and below $N_{\mathrm{ch}} < 100$ reveal a large variation of the correlation strength and/or an increasing contribution of non-flow. The measurements in pp collisions can not be reproduced by the PYTHIA 8 model. The hydrodynamic description with the IP-Glasma+MUSIC+UrQMD calculations shows rather good agreement with data in Pb–Pb, Xe–Xe and p–Pb collisions, but fails to describe the measurements in pp collisions, where applicable. The presented data provide new information to help us understand the origin of the observed collectivity, and by future comparisons with phenomenological calculations with various mechanisms will disentangle the correct approach to modelling of small systems.

Acknowledgements

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: 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), Universidade Federal do Rio Grande do Sul (UFRGS), Financiadora de Estudos e Projetos (Finep) and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Brazil; Ministry of Science & Technology of China (MSTC), National Natural Science Foundation of China (NSFC) and Ministry of Education of China (MOEC) , China; Croatian Science Foundation and Ministry of Science and Education, 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 Carlsberg Foundation and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l'Energie Atomique (CEA), Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS) and Rlégion des Pays de la Loire, France; Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (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; Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi and Istituto Nazionale di Fisica Nucleare (INFN), Italy; Institute for Innovative Science and Technology , Nagasaki Institute of Applied Science (IIST), Japan Society for the Promotion of Science (JSPS) KAKENHI and Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT), 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 Academico (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 and National Science Centre, 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 & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; National Science and Technology Development Agency (NSDTA), Suranaree University of Technology (SUT) 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.

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] U. Heinz and R. Snellings, "Collective flow and viscosity in relativistic heavy-ion collisions," *Ann. Rev. Nucl. Part. Sci.* **63** (2013) 123–151, `arXiv:1301.2826 [nucl-th]`.

[4] **ALICE** Collaboration, J. Adam *et al.*, "Pseudorapidity dependence of the anisotropic flow of charged particles in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV," *Phys. Lett.* **B762** (2016) 376–388, `arXiv:1605.02035 [nucl-ex]`.

[5] **ALICE** Collaboration, J. Adam *et al.*, "Anisotropic flow of charged particles in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV," *Phys. Rev. Lett.* **116** no. 13, (2016) 132302, `arXiv:1602.01119 [nucl-ex]`.

[6] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Non-Gaussian elliptic-flow fluctuations in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV," *Phys. Lett.* **B789** (2019) 643–665, `arXiv:1711.05594 [nucl-ex]`.

[7] **ALICE** Collaboration, S. Acharya *et al.*, "Energy dependence and fluctuations of anisotropic flow in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ and 2.76 TeV," *JHEP* **07** (2018) 103, `arXiv:1804.02944 [nucl-ex]`.

[8] **ALICE** Collaboration, S. Acharya *et al.*, "Anisotropic flow in Xe-Xe collisions at $\sqrt{\mathbf{s}_{\rm NN}} = \mathbf{5.44}$ TeV," *Phys. Lett.* **B784** (2018) 82–95, `arXiv:1805.01832 [nucl-ex]`.

[9] **ATLAS** Collaboration, M. Aaboud *et al.*, "Measurement of the azimuthal anisotropy of charged particles produced in $\sqrt{s_{\rm NN}}$ = 5.02 TeV Pb+Pb collisions with the ATLAS detector," *Eur. Phys. J.* **C78** no. 12, (2018) 997, `arXiv:1808.03951 [nucl-ex]`.

[10] **ALICE** Collaboration, S. Acharya *et al.*, "Anisotropic flow of identified particles in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV," *JHEP* **09** (2018) 006, `arXiv:1805.04390 [nucl-ex]`.

[11] H. Song, Y. Zhou, and K. Gajdosova, "Collective flow and hydrodynamics in large and small systems at the LHC," *Nucl. Sci. Tech.* **28** no. 7, (2017) 99, arXiv:1703.00670 [nucl-th].

[12] 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].

[13] **ALICE** Collaboration, J. Adam *et al.*, "Event shape engineering for inclusive spectra and elliptic flow in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV," *Phys. Rev.* **C93** no. 3, (2016) 034916, arXiv:1507.06194 [nucl-ex].

[14] **ALICE** Collaboration, J. Adam *et al.*, "Correlated event-by-event fluctuations of flow harmonics in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV," *Phys. Rev. Lett.* **117** (2016) 182301, arXiv:1604.07663 [nucl-ex].

[15] **ALICE** Collaboration, S. Acharya *et al.*, "Linear and non-linear flow modes in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV," *Phys. Lett.* **B773** (2017) 68–80, arXiv:1705.04377 [nucl-ex].

[16] **ALICE** Collaboration, S. Acharya *et al.*, "Searches for transverse momentum dependent flow vector fluctuations in Pb–Pb and p–Pb collisions at the LHC," *JHEP* **09** (2017) 032, arXiv:1707.05690 [nucl-ex].

[17] **ALICE** Collaboration, S. Acharya *et al.*, "Systematic studies of correlations between different order flow harmonics in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$=2.76 TeV," *Phys. Rev.* **C97** no. 2, (2018) 024906, arXiv:1709.01127 [nucl-ex].

[18] **ATLAS** Collaboration, M. Aaboud *et al.*, "Measurement of longitudinal flow decorrelations in Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ and 5.02 TeV with the ATLAS detector," *Eur. Phys. J.* **C78** no. 2, (2018) 142, arXiv:1709.02301 [nucl-ex].

[19] 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].

[20] C. Loizides, "Experimental overview on small collision systems at the LHC," *Nucl. Phys.* **A956** (2016) 200–207, arXiv:1602.09138 [nucl-ex].

[21] **ATLAS** Collaboration, M. Aaboud *et al.*, "Measurements of long-range azimuthal anisotropies and associated Fourier coefficients for pp collisions at $\sqrt{s} = 5.02$ and 13 TeV and p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the ATLAS detector," *Phys. Rev.* **C96** no. 2, (2017) 024908, arXiv:1609.06213 [nucl-ex].

[22] **ALICE** Collaboration, B. Abelev *et al.*, "Multiparticle azimuthal correlations in p–Pb and Pb–Pb collisions at the CERN Large Hadron Collider," *Phys.Rev.* **C90** no. 5, (2014) 054901, arXiv:1406.2474 [nucl-ex].

[23] **CMS** Collaboration, V. Khachatryan *et al.*, "Evidence for Collective Multiparticle Correlations in p-Pb Collisions," *Phys. Rev. Lett.* **115** no. 1, (2015) 012301, arXiv:1502.05382 [nucl-ex].

[24] **CMS** Collaboration, V. Khachatryan *et al.*, "Evidence for collectivity in pp collisions at the LHC," *Phys. Lett.* **B765** (2017) 193–220, arXiv:1606.06198 [nucl-ex].

[25] **ATLAS** Collaboration, M. Aaboud *et al.*, "Measurement of multi-particle azimuthal correlations in pp, p–Pb and low-multiplicity Pb–Pb collisions with the ATLAS detector," *Eur. Phys. J.* **C77** no. 6, (2017) 428, arXiv:1705.04176 [hep-ex].

[26] **ATLAS** Collaboration, M. Aaboud *et al.*, "Measurement of long-range multiparticle azimuthal correlations with the subevent cumulant method in pp and $p+Pb$ collisions with the ATLAS detector at the CERN Large Hadron Collider," *Phys. Rev.* **C97** no. 2, (2018) 024904, arXiv:1708.03559 [hep-ex].

[27] P. Bozek, "Collective flow in p–Pb and d–Pb collisions at TeV energies," *Phys.Rev.* **C85** (2012) 014911, arXiv:1112.0915 [hep-ph].

[28] A. Bzdak, B. Schenke, P. Tribedy, and R. Venugopalan, "Initial state geometry and the role of hydrodynamics in proton–proton, proton–nucleus and deuteron–nucleus collisions," *Phys.Rev.* **C87** (2013) 064906, arXiv:1304.3403 [nucl-th].

[29] H. Mäntysaari, B. Schenke, C. Shen, and P. Tribedy, "Imprints of fluctuating proton shapes on flow in proton-lead collisions at the LHC," *Phys. Lett.* **B772** (2017) 681–686, arXiv:1705.03177 [nucl-th]. The results from pp collisions are private communications based on this work.

[30] R. D. Weller and P. Romatschke, "One fluid to rule them all: viscous hydrodynamic description of event-by-event central pp, p–Pb and Pb–Pb collisions at $\sqrt{s} = 5.02$ TeV," *Phys. Lett.* **B774** (2017) 351–356, arXiv:1701.07145 [nucl-th].

[31] W. Zhao, Y. Zhou, H. Xu, W. Deng, and H. Song, "Hydrodynamic collectivity in proton?proton collisions at 13 TeV," *Phys. Lett.* **B780** (2018) 495–500, arXiv:1801.00271 [nucl-th].

[32] A. Bzdak and G.-L. Ma, "Elliptic and triangular flow in p–Pb and peripheral Pb–Pb collisions from parton scatterings," *Phys.Rev.Lett.* **113** (2014) 252301, arXiv:1406.2804 [hep-ph].

[33] A. Kurkela, U. A. Wiedemann, and B. Wu, "Nearly isentropic flow at sizeable η/s," *Phys. Lett.* **B783** (2018) 274–279, arXiv:1803.02072 [hep-ph].

[34] M.-W. Nie, P. Huo, J. Jia, and G.-L. Ma, "Multiparticle azimuthal cumulants in p+Pb collisions from a multiphase transport model," *Phys. Rev.* **C98** no. 3, (2018) 034903, arXiv:1802.00374 [hep-ph].

[35] Y. Zhou, X. Zhu, P. Li, and H. Song, "Investigation of possible hadronic flow in $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV p–Pb collisions," *Phys. Rev.* **C91** (2015) 064908, arXiv:1503.06986 [nucl-th].

[36] P. Romatschke, "Collective flow without hydrodynamics: simulation results for relativistic ion collisions," *Eur. Phys. J.* **C75** no. 9, (2015) 429, arXiv:1504.02529 [nucl-th].

[37] C. Bierlich, G. Gustafson, and L. Lönnblad, "Collectivity without plasma in hadronic collisions," *Phys. Lett.* **B779** (2018) 58–63, arXiv:1710.09725 [hep-ph].

[38] K. Welsh, J. Singer, and U. W. Heinz, "Initial state fluctuations in collisions between light and heavy ions," *Phys. Rev.* **C94** no. 2, (2016) 024919, arXiv:1605.09418 [nucl-th].

[39] K. Dusling, M. Mace, and R. Venugopalan, "Multiparticle collectivity from initial state correlations in high energy proton-nucleus collisions," *Phys. Rev. Lett.* **120** no. 4, (2018) 042002, arXiv:1705.00745 [hep-ph].

[40] B. Blok and U. A. Wiedemann, "Collectivity in pp from resummed interference effects?," arXiv:1812.04113 [hep-ph].

[41] M. Greif, C. Greiner, B. Schenke, S. Schlichting, and Z. Xu, "Importance of initial and final state effects for azimuthal correlations in p+Pb collisions," *Phys. Rev.* **D96** no. 9, (2017) 091504, arXiv:1708.02076 [hep-ph].

[42] J. Jia, M. Zhou, and A. Trzupek, "Revealing long-range multiparticle collectivity in small collision systems via subevent cumulants," *Phys. Rev.* **C96** no. 3, (2017) 034906, arXiv:1701.03830 [nucl-th].

[43] P. Huo, K. Gajdosová, J. Jia, and Y. Zhou, "Importance of non-flow in mixed-harmonic multi-particle correlations in small collision systems," *Phys. Lett.* **B777** (2018) 201–206, arXiv:1710.07567 [nucl-ex].

[44] **ALICE** Collaboration, K. Aamodt *et al.*, "The ALICE experiment at the CERN LHC," *JINST* **3** (2008) S08002.

[45] **ALICE** Collaboration, 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].

[46] **ALICE** Collaboration, E. Abbas *et al.*, "Performance of the ALICE VZERO system," *JINST* **8** (2013) P10016, arXiv:1306.3130 [nucl-ex].

[47] **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].

[48] 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].

[49] R. Brun, F. Carminati, and S. Giani, "GEANT Detector Description and Simulation Tool," *CERN Program Library Long Write-up, W5013* (1994) .

[50] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, "An Introduction to PYTHIA 8.2," *Comput. Phys. Commun.* **191** (2015) 159–177, arXiv:1410.3012 [hep-ph].

[51] B. Schenke, P. Tribedy, and R. Venugopalan, "Multiplicity distributions in p+p, p+A and A+A collisions from Yang-Mills dynamics," *Phys. Rev.* **C89** no. 2, (2014) 024901, arXiv:1311.3636 [hep-ph].

[52] **ATLAS** Collaboration, M. Aaboud *et al.*, "Correlated long-range mixed-harmonic fluctuations measured in *pp*, *p*+Pb and low-multiplicity Pb+Pb collisions with the ATLAS detector," *Phys. Lett.* **B789** (2019) 444–471, arXiv:1807.02012 [nucl-ex].

[53] L. He, T. Edmonds, Z.-W. Lin, F. Liu, D. Molnar, and F. Wang, "Anisotropic parton escape is the dominant source of azimuthal anisotropy in transport models," *Phys. Lett.* **B753** (2016) 506–510, arXiv:1502.05572 [nucl-th].

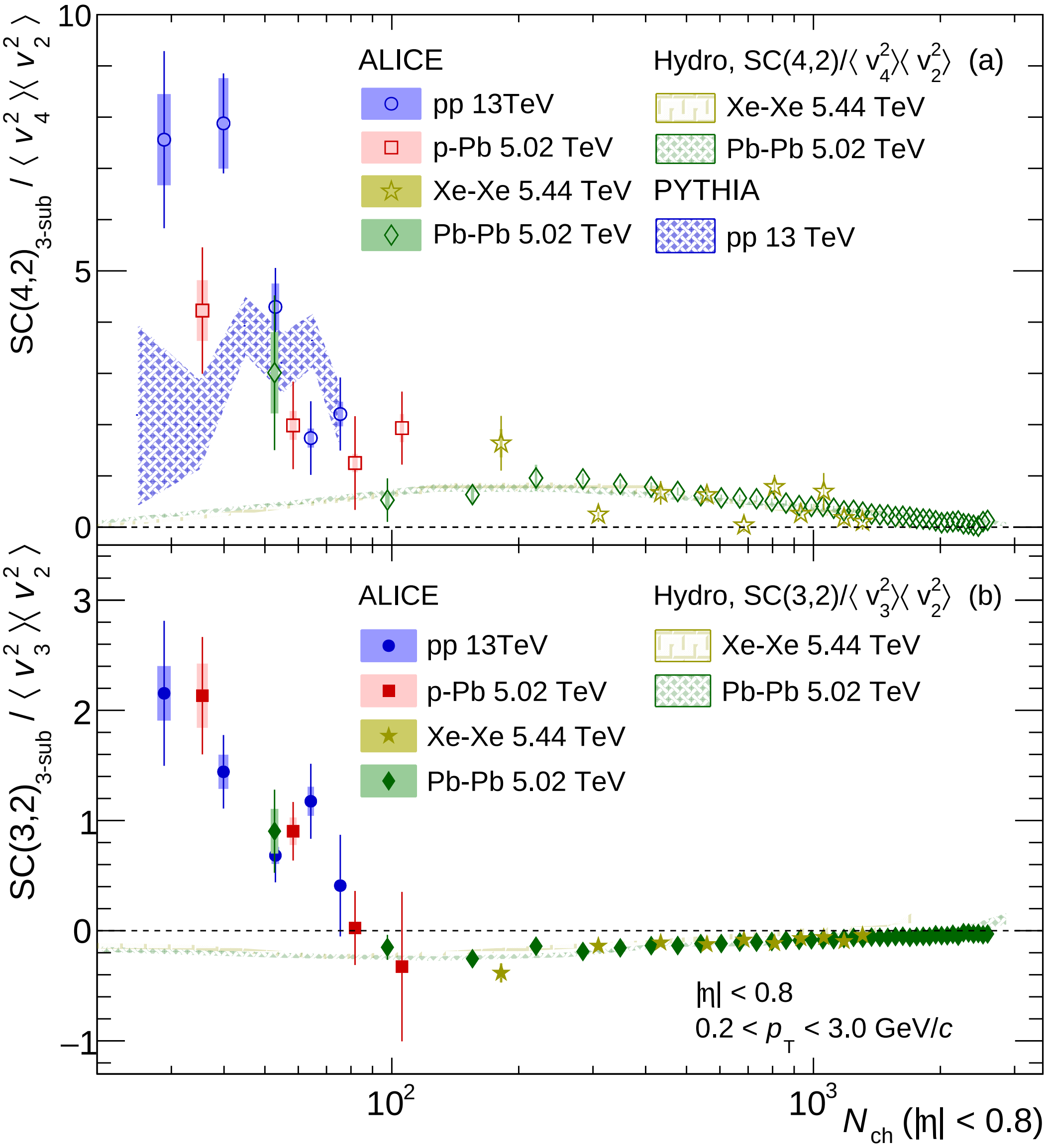

Fig. A.1: Multiplicity dependence of (a) $\mathrm{SC}(3,2)_{3-\mathrm{sub}}/\langle v_3^2\rangle\langle v_2^2\rangle$ and (b) $\mathrm{SC}(4,2)_{3-\mathrm{sub}}/\langle v_4^2\rangle\langle v_2^2\rangle$ for pp, p–Pb, Xe–Xe and Pb–Pb collisions. Observables in the denominator are obtained from the two-particle cumulants with a pseudorapidity gap $|\Delta\eta| > 1.4$ for v_2 and $|\Delta\eta| > 1.0$ for higher harmonics. Statistical uncertainties are shown as vertical lines and systematic uncertainties as filled boxes (coloured online). The results are compared with PYTHIA 8 [50] and the IP-Glasma+MUSIC+UrQMD [29, 51] calculations.

A Supplemental material

Figure A.1 shows the multiplicity dependence of the normalized ratio $\mathrm{SC}(m,n)_{3-\mathrm{sub}}/\langle v_n^2\rangle\langle v_m^2\rangle$, where the measurements in the denominator were obtained with a $|\Delta\eta|$ gap. In the absence of non-flow contamination, this observable directly reflects the correlation between v_n^2 and v_m^2, independent of the magnitude of the individual flow coefficients v_n and v_m.

The ratio $\mathrm{SC}(m,n)_{3-\mathrm{sub}}/\langle v_m^2\rangle\langle v_n^2\rangle$ complements observations made in Fig. 2 and reveals a strong increase of the correlation strength at $N_{\mathrm{ch}} < 100$ compared to (mid)central Pb-Pb and Xe-Xe collisions. This increase may be either due to different patterns of fluctuations or an increasing non-flow contribution towards small multiplicities, as suggested by the finite correlation strength seen in PYTHIA [50] simulations in both Fig. 1 and Fig. 2.

The data in Fig. A.1 are compared with PYTHIA 8 [50] and the IP-Glasma+MUSIC+UrQMD [29, 51] model calculations. The PYTHIA 8 calculations seem to underestimate the $\mathrm{SC}(4,2)_{3-\mathrm{sub}}/\langle v_4^2\rangle\langle v_2^2\rangle$ observed in pp collisions for $N_{\mathrm{ch}} < 30$. The $\mathrm{SC}(3,2)_{3-\mathrm{sub}}/\langle v_2^2\rangle\langle v_3^2\rangle$ value cannot be extracted from PYTHIA calculations due to small values of v_3. The IP-Glasma+MUSIC+UrQMD calculation describes the data at high $N_{\mathrm{ch}} > 100$, while for $N_{\mathrm{ch}} < 100$ the correlations seen in data are much stronger, and in case of $\mathrm{SC}(3,2)_{3-\mathrm{sub}}/\langle v_2^2\rangle\langle v_3^2\rangle$ are of an opposite sign.

B The ALICE Collaboration

S. Acharya[141] , D. Adamová[93] , S.P. Adhya[141] , A. Adler[74] , J. Adolfsson[80] , M.M. Aggarwal[98] , G. Aglieri Rinella[34] , M. Agnello[31] , N. Agrawal[10] , Z. Ahammed[141] , S. Ahmad[17] , S.U. Ahn[76] , S. Aiola[146] , A. Akindinov[64] , M. Al-Turany[105] , S.N. Alam[141] , D.S.D. Albuquerque[122] , D. Aleksandrov[87] , B. Alessandro[58] , H.M. Alfanda[6] , R. Alfaro Molina[72] , B. Ali[17] , Y. Ali[15] , A. Alici[10,53,27] , A. Alkin[2] , J. Alme[22] , T. Alt[69] , L. Altenkamper[22] , I. Altsybeev[112] , M.N. Anaam[6] , C. Andrei[47] , D. Andreou[34] , H.A. Andrews[109] , A. Andronic[105,144] , M. Angeletti[34] , V. Anguelov[102] , C. Anson[16] , T. Antičić[106] , F. Antinori[56] , P. Antonioli[53] , R. Anwar[126] , N. Apadula[79] , L. Aphecetche[114] , H. Appelshäuser[69] , S. Arcelli[27] , R. Arnaldi[58] , M. Arratia[79] , I.C. Arsene[21] , M. Arslandok[102] , A. Augustinus[34] , R. Averbeck[105] , S. Aziz[61] , M.D. Azmi[17] , A. Badalà[55] , Y.W. Baek[40,60] , S. Bagnasco[58] , R. Bailhache[69] , R. Bala[99] , A. Baldisseri[137] , M. Ball[42] , R.C. Baral[85] , R. Barbera[28] , L. Barioglio[26] , G.G. Barnaföldi[145] , L.S. Barnby[92] , V. Barret[134] , P. Bartalini[6] , K. Barth[34] , E. Bartsch[69] , N. Bastid[134] , S. Basu[143] , G. Batigne[114] , B. Batyunya[75] , P.C. Batzing[21] , D. Bauri[48] , J.L. Bazo Alba[110] , I.G. Bearden[88] , C. Bedda[63] , N.K. Behera[60] , I. Belikov[136] , F. Bellini[34] , R. Bellwied[126] , L.G.E. Beltran[120] , V. Belyaev[91] , G. Bencedi[145] , S. Beole[26] , A. Bercuci[47] , Y. Berdnikov[96] , D. Berenyi[145] , R.A. Bertens[130] , D. Berzano[58] , L. Betev[34] , A. Bhasin[99] , I.R. Bhat[99] , H. Bhatt[48] , B. Bhattacharjee[41] , A. Bianchi[26] , L. Bianchi[126,26] , N. Bianchi[51] , J. Bielčík[37] , J. Bielčíková[93] , A. Bilandzic[117,103] , G. Biro[145] , R. Biswas[3] , S. Biswas[3] , J.T. Blair[119] , D. Blau[87] , C. Blume[69] , G. Boca[139] , F. Bock[34] , A. Bogdanov[91] , L. Boldizsár[145] , A. Bolozdynya[91] , M. Bombara[38] , G. Bonomi[140] , M. Bonora[34] , H. Borel[137] , A. Borissov[91,144] , M. Borri[128] , E. Botta[26] , C. Bourjau[88] , L. Bratrud[69] , P. Braun-Munzinger[105] , M. Bregant[121] , T.A. Broker[69] , M. Broz[37] , E.J. Brucken[43] , E. Bruna[58] , G.E. Bruno[33,104] , M.D. Buckland[128] , D. Budnikov[107] , H. Buesching[69] , S. Bufalino[31] , P. Buhler[113] , P. Buncic[34] , O. Busch[133,i] , Z. Buthelezi[73] , J.B. Butt[15] , J.T. Buxton[95] , D. Caffarri[89] , H. Caines[146] , A. Caliva[105] , E. Calvo Villar[110] , R.S. Camacho[44] , P. Camerini[25] , A.A. Capon[113] , F. Carnesecchi[10] , J. Castillo Castellanos[137] , A.J. Castro[130] , E.A.R. Casula[54] , F. Catalano[31] , C. Ceballos Sanchez[52] , P. Chakraborty[48] , S. Chandra[141] , B. Chang[127] , W. Chang[6] , S. Chapeland[34] , M. Chartier[128] , S. Chattopadhyay[141] , S. Chattopadhyay[108] , A. Chauvin[24] , C. Cheshkov[135] , B. Cheynis[135] , V. Chibante Barroso[34] , D.D. Chinellato[122] , S. Cho[60] , P. Chochula[34] , T. Chowdhury[134] , P. Christakoglou[89] , C.H. Christensen[88] , P. Christiansen[80] , T. Chujo[133] , C. Cicalo[54] , L. Cifarelli[10,27] , F. Cindolo[53] , J. Cleymans[125] , F. Colamaria[52] , D. Colella[52] , A. Collu[79] , M. Colocci[27] , M. Concas[58,ii] , G. Conesa Balbastre[78] , Z. Conesa del Valle[61] , G. Contin[128] , J.G. Contreras[37] , T.M. Cormier[94] , Y. Corrales Morales[58,26] , P. Cortese[32] , M.R. Cosentino[123] , F. Costa[34] , S. Costanza[139] , J. Crkovská[61] , P. Crochet[134] , E. Cuautle[70] , L. Cunqueiro[94] , D. Dabrowski[142] , T. Dahms[117,103] , A. Dainese[56] , F.P.A. Damas[114,137] , S. Dani[66] , M.C. Danisch[102] , A. Danu[68] , D. Das[108] , I. Das[108] , S. Das[3] , A. Dash[85] , S. Dash[48] , A. Dashi[103] , S. De[85,49] , A. De Caro[30] , G. de Cataldo[52] , C. de Conti[121] , J. de Cuveland[39] , A. De Falco[24] , D. De Gruttola[10] , N. De Marco[58] , S. De Pasquale[30] , R.D. De Souza[122] , S. Deb[49] , H.F. Degenhardt[121] , A. Deisting[105,102] , K.R. Deja[142] , A. Deloff[84] , S. Delsanto[26,131] , P. Dhankher[48] , D. Di Bari[33] , A. Di Mauro[34] , R.A. Diaz[8] , T. Dietel[125] , P. Dillenseger[69] , Y. Ding[6] , R. Divià[34] , Ø. Djuvsland[22] , U. Dmitrieva[62] , A. Dobrin[68,34] , D. Domenicis Gimenez[121] , B. Dönigus[69] , O. Dordic[21] , A.K. Dubey[141] , A. Dubla[105] , S. Dudi[98] , A.K. Duggal[98] , M. Dukhishyam[85] , P. Dupieux[134] , R.J. Ehlers[146] , D. Elia[52] , H. Engel[74] , E. Epple[146] , B. Erazmus[114] , F. Erhardt[97] , A. Erokhin[112] , M.R. Ersdal[22] , B. Espagnon[61] , G. Eulisse[34] , J. Eum[18] , D. Evans[109] , S. Evdokimov[90] , L. Fabbietti[117,103] , M. Faggin[29] , J. Faivre[78] , A. Fantoni[51] , M. Fasel[94] , P. Fecchio[31] , L. Feldkamp[144] , A. Feliciello[58] , G. Feofilov[112] , A. Fernández Téllez[44] , A. Ferrero[137] , A. Ferretti[26] , A. Festanti[34] , V.J.G. Feuillard[102] , J. Figiel[118] , S. Filchagin[107] , D. Finogeev[62] , F.M. Fionda[22] , G. Fiorenza[52] , F. Flor[126] , S. Foertsch[73] , P. Foka[105] , S. Fokin[87] , E. Fragiacomo[59] , A. Francisco[114] , U. Frankenfeld[105] , G.G. Fronze[26] , U. Fuchs[34] , C. Furget[78] , A. Furs[62] , M. Fusco Girard[30] , J.J. Gaardhøje[88] , M. Gagliardi[26] , A.M. Gago[110] , A. Gal[136] , C.D. Galvan[120] , P. Ganoti[83] , C. Garabatos[105] , E. Garcia-Solis[11] , K. Garg[28] , C. Gargiulo[34] , K. Garner[144] , P. Gasik[103,117] , E.F. Gauger[119] , M.B. Gay Ducati[71] , M. Germain[114] , J. Ghosh[108] , P. Ghosh[141] , S.K. Ghosh[3] , P. Gianotti[51] , P. Giubellino[105,58] , P. Giubilato[29] , P. Glässel[102] , D.M. Goméz Coral[72] , A. Gomez Ramirez[74] , V. Gonzalez[105] , P. González-Zamora[44] , S. Gorbunov[39] , L. Görlich[118] , S. Gotovac[35] , V. Grabski[72] , L.K. Graczykowski[142] , K.L. Graham[109] , L. Greiner[79] , A. Grelli[63] , C. Grigoras[34] , V. Grigoriev[91] , A. Grigoryan[1] , S. Grigoryan[75] , O.S. Groettvik[22] , J.M. Gronefeld[105] , F. Grosa[31] , J.F. Grosse-Oetringhaus[34] , R. Grosso[105] , R. Guernane[78] , B. Guerzoni[27] , M. Guittiere[114] , K. Gulbrandsen[88] , T. Gunji[132] , A. Gupta[99] , R. Gupta[99] , I.B. Guzman[44] , R. Haake[34,146] , M.K. Habib[105] , C. Hadjidakis[61] , H. Hamagaki[81] , G. Hamar[145] , M. Hamid[6] , J.C. Hamon[136] , R. Hannigan[119] , M.R. Haque[63] , A. Harlenderova[105] , J.W. Harris[146] , A. Harton[11] , H. Hassan[78] , D. Hatzifotiadou[53,10] , P. Hauer[42] , S. Hayashi[132] , S.T. Heckel[69] , E. Hellbär[69] , H. Helstrup[36] , A. Herghelegiu[47] , E.G. Hernandez[44] , G. Herrera Corral[9] , F. Herrmann[144] , K.F. Hetland[36] , T.E. Hilden[43] , H. Hillemanns[34] , C. Hills[128] , B. Hippolyte[136] , B. Hohlweger[103] , D. Horak[37] , S. Hornung[105] , R. Hosokawa[133] ,

P. Hristov[34] , C. Huang[61] , C. Hughes[130] , P. Huhn[69] , T.J. Humanic[95] , H. Hushnud[108] , L.A. Husova[144] , N. Hussain[41] , S.A. Hussain[15] , T. Hussain[17] , D. Hutter[39] , D.S. Hwang[19] , J.P. Iddon[128] , R. Ilkaev[107] , M. Inaba[133] , M. Ippolitov[87] , M.S. Islam[108] , M. Ivanov[105] , V. Ivanov[96] , V. Izucheev[90] , B. Jacak[79] , N. Jacazio[27] , P.M. Jacobs[79] , M.B. Jadhav[48] , S. Jadlovska[116] , J. Jadlovsky[116] , S. Jaelani[63] , C. Jahnke[121] , M.J. Jakubowska[142] , M.A. Janik[142] , M. Jercic[97] , O. Jevons[109] , R.T. Jimenez Bustamante[105] , M. Jin[126] , F. Jonas[144,94] , P.G. Jones[109] , A. Jusko[109] , P. Kalinak[65] , A. Kalweit[34] , J.H. Kang[147] , V. Kaplin[91] , S. Kar[6] , A. Karasu Uysal[77] , O. Karavichev[62] , T. Karavicheva[62] , P. Karczmarczyk[34] , E. Karpechev[62] , U. Kebschull[74] , R. Keidel[46] , M. Keil[34] , B. Ketzer[42] , Z. Khabanova[89] , A.M. Khan[6] , S. Khan[17] , S.A. Khan[141] , A. Khanzadeev[96] , Y. Kharlov[90] , A. Khatun[17] , A. Khuntia[118,49] , B. Kileng[36] , B. Kim[60] , B. Kim[133] , D. Kim[147] , D.J. Kim[127] , E.J. Kim[13] , H. Kim[147] , J.S. Kim[40] , J. Kim[102] , J. Kim[147] , J. Kim[13] , M. Kim[102,60] , S. Kim[19] , T. Kim[147] , T. Kim[147] , K. Kindra[98] , S. Kirsch[39] , I. Kisel[39] , S. Kiselev[64] , A. Kisiel[142] , J.L. Klay[5] , C. Klein[69] , J. Klein[58] , S. Klein[79] , C. Klein-Bösing[144] , S. Klewin[102] , A. Kluge[34] , M.L. Knichel[34] , A.G. Knospe[126] , C. Kobdaj[115] , M. Kofarago[145] , M.K. Köhler[102] , T. Kollegger[105] , A. Kondratyev[75] , N. Kondratyeva[91] , E. Kondratyuk[90] , P.J. Konopka[34] , M. Konyushikhin[143] , L. Koska[116] , O. Kovalenko[84] , V. Kovalenko[112] , M. Kowalski[118] , I. Králik[65] , A. Kravčáková[38] , L. Kreis[105] , M. Krivda[65,109] , F. Krizek[93] , K. Krizkova Gajdosova[37,88] , M. Krüger[69] , E. Kryshen[96] , M. Krzewicki[39] , A.M. Kubera[95] , V. Kučera[60] , C. Kuhn[136] , P.G. Kuijer[89] , L. Kumar[98] , S. Kumar[48] , S. Kundu[85] , P. Kurashvili[84] , A. Kurepin[62] , A.B. Kurepin[62] , S. Kushpil[93] , J. Kvapil[109] , M.J. Kweon[60] , Y. Kwon[147] , S.L. La Pointe[39] , P. La Rocca[28] , Y.S. Lai[79] , R. Langoy[124] , K. Lapidus[34,146] , A. Lardeux[21] , P. Larionov[51] , E. Laudi[34] , R. Lavicka[37] , T. Lazareva[112] , R. Lea[25] , L. Leardini[102] , S. Lee[147] , F. Lehas[89] , S. Lehner[113] , J. Lehrbach[39] , R.C. Lemmon[92] , I. León Monzón[120] , M. Lettrich[34] , P. Lévai[145] , X. Li[12] , X.L. Li[6] , J. Lien[124] , R. Lietava[109] , B. Lim[18] , S. Lindal[21] , V. Lindenstruth[39] , S.W. Lindsay[128] , C. Lippmann[105] , M.A. Lisa[95] , V. Litichevskyi[43] , A. Liu[79] , S. Liu[95] , H.M. Ljunggren[80] , W.J. Llope[143] , D.F. Lodato[63] , V. Loginov[91] , C. Loizides[94] , P. Loncar[35] , X. Lopez[134] , E. López Torres[8] , P. Luettig[69] , J.R. Luhder[144] , M. Lunardon[29] , G. Luparello[59] , M. Lupi[34] , A. Maevskaya[62] , M. Mager[34] , S.M. Mahmood[21] , T. Mahmoud[42] , A. Maire[136] , R.D. Majka[146] , M. Malaev[96] , Q.W. Malik[21] , L. Malinina[75,iii], D. Mal'Kevich[64] , P. Malzacher[105] , A. Mamonov[107] , V. Manko[87] , F. Manso[134] , V. Manzari[52] , Y. Mao[6] , M. Marchisone[135] , J. Mareš[67] , G.V. Margagliotti[25] , A. Margotti[53] , J. Margutti[63] , A. Marín[105] , C. Markert[119] , M. Marquard[69] , N.A. Martin[102] , P. Martinengo[34] , J.L. Martinez[126] , M.I. Martínez[44] , G. Martínez García[114] , M. Martinez Pedreira[34] , S. Masciocchi[105] , M. Masera[26] , A. Masoni[54] , L. Massacrier[61] , E. Masson[114] , A. Mastroserio[138,52] , A.M. Mathis[103,117] , P.F.T. Matuoka[121] , A. Matyja[118] , C. Mayer[118] , M. Mazzilli[33] , M.A. Mazzoni[57] , A.F. Mechler[69] , F. Meddi[23] , Y. Melikyan[91] , A. Menchaca-Rocha[72] , E. Meninno[30] , M. Meres[14] , S. Mhlanga[125] , Y. Miake[133] , L. Micheletti[26] , M.M. Mieskolainen[43] , D.L. Mihaylov[103] , K. Mikhaylov[75,64] , A. Mischke[63,i], A.N. Mishra[70] , D. Miśkowiec[105] , C.M. Mitu[68] , N. Mohammadi[34] , A.P. Mohanty[63] , B. Mohanty[85] , M. Mohisin Khan[17,iv], M.M. Mondal[66] , C. Mordasini[103] , D.A. Moreira De Godoy[144] , L.A.P. Moreno[44] , S. Moretto[29] , A. Morreale[114] , A. Morsch[34] , T. Mrnjavac[34] , V. Muccifora[51] , E. Mudnic[35] , D. Mühlheim[144] , S. Muhuri[141] , J.D. Mulligan[79,146] , M.G. Munhoz[121] , K. Münning[42] , R.H. Munzer[69] , H. Murakami[132] , S. Murray[73] , L. Musa[34] , J. Musinsky[65] , C.J. Myers[126] , J.W. Myrcha[142] , B. Naik[48] , R. Nair[84] , B.K. Nandi[48] , R. Nania[10,53] , E. Nappi[52] , M.U. Naru[15] , A.F. Nassirpour[80] , H. Natal da Luz[121] , C. Nattrass[130] , K. Nayak[85] , R. Nayak[48] , T.K. Nayak[141,85] , S. Nazarenko[107] , R.A. Negrao De Oliveira[69] , L. Nellen[70] , S.V. Nesbo[36] , G. Neskovic[39] , F. Ng[126] , B.S. Nielsen[88] , S. Nikolaev[87] , S. Nikulin[87] , V. Nikulin[96] , F. Noferini[53,10] , P. Nomokonov[75] , G. Nooren[63] , J.C.C. Noris[44] , J. Norman[78] , P. Nowakowski[142] , A. Nyanin[87] , J. Nystrand[22] , M. Ogino[81] , A. Ohlson[102] , J. Oleniacz[142] , A.C. Oliveira Da Silva[121] , M.H. Oliver[146] , J. Onderwaater[105] , C. Oppedisano[58] , R. Orava[43] , A. Ortiz Velasquez[70] , A. Oskarsson[80] , J. Otwinowski[118] , K. Oyama[81] , Y. Pachmayer[102] , V. Pacik[88] , D. Pagano[140] , G. Paić[70] , P. Palni[6] , J. Pan[143] , A.K. Pandey[48] , S. Panebianco[137] , V. Papikyan[1] , P. Pareek[49] , J. Park[60] , J.E. Parkkila[127] , S. Parmar[98] , A. Passfeld[144] , S.P. Pathak[126] , R.N. Patra[141] , B. Paul[58] , H. Pei[6] , T. Peitzmann[63] , X. Peng[6] , L.G. Pereira[71] , H. Pereira Da Costa[137] , D. Peresunko[87] , G.M. Perez[8] , E. Perez Lezama[69] , V. Peskov[69] , Y. Pestov[4] , V. Petráček[37] , M. Petrovici[47] , R.P. Pezzi[71] , S. Piano[59] , M. Pikna[14] , P. Pillot[114] , L.O.D.L. Pimentel[88] , O. Pinazza[53,34] , L. Pinsky[126] , S. Pisano[51] , D.B. Piyarathna[126] , M. Płoskoń[79] , M. Planinic[97] , F. Pliquett[69] , J. Pluta[142] , S. Pochybova[145] , M.G. Poghosyan[94] , B. Polichtchouk[90] , N. Poljak[97] , W. Poonsawat[115] , A. Pop[47] , H. Poppenborg[144] , S. Porteboeuf-Houssais[134] , V. Pozdniakov[75] , S.K. Prasad[3] , R. Preghenella[53] , F. Prino[58] , C.A. Pruneau[143] , I. Pshenichnov[62] , M. Puccio[26,34] , V. Punin[107] , K. Puranapanda[141] , J. Putschke[143] , R.E. Quishpe[126] , S. Ragoni[109] , S. Raha[3] , S. Rajput[99] , J. Rak[127] , A. Rakotozafindrabe[137] , L. Ramello[32] , F. Rami[136] , R. Raniwala[100] , S. Raniwala[100] , S.S. Räsänen[43] , B.T. Rascanu[69] , R. Rath[49] , V. Ratza[42] , I. Ravasenga[31] , K.F. Read[94,130] , K. Redlich[84,v], A. Rehman[22] , P. Reichelt[69] , F. Reidt[34] , X. Ren[6] , R. Renfordt[69] , A. Reshetin[62] , J.-P. Revol[10] , K. Reygers[102] , V. Riabov[96] ,

T. Richert[88,80], M. Richter[21], P. Riedler[34], W. Riegler[34], F. Riggi[28], C. Ristea[68], S.P. Rode[49], M. Rodríguez Cahuantzi[44], K. Røed[21], R. Rogalev[90], E. Rogochaya[75], D. Rohr[34], D. Röhrich[22], P.S. Rokita[142], F. Ronchetti[51], E.D. Rosas[70], K. Roslon[142], P. Rosnet[134], A. Rossi[56,29], A. Rotondi[139], F. Roukoutakis[83], A. Roy[49], P. Roy[108], O.V. Rueda[80], R. Rui[25], B. Rumyantsev[75], A. Rustamov[86], E. Ryabinkin[87], Y. Ryabov[96], A. Rybicki[118], H. Rytkonen[127], S. Saarinen[43], S. Sadhu[141], S. Sadovsky[90], K. Šafařík[37,34], S.K. Saha[141], B. Sahoo[48], P. Sahoo[49], R. Sahoo[49], S. Sahoo[66], P.K. Sahu[66], J. Saini[141], S. Sakai[133], S. Sambyal[99], V. Samsonov[91,96], A. Sandoval[72], A. Sarkar[73], D. Sarkar[143,141], N. Sarkar[141], P. Sarma[41], V.M. Sarti[103], M.H.P. Sas[63], E. Scapparone[53], B. Schaefer[94], J. Schambach[119], H.S. Scheid[69], C. Schiaua[47], R. Schicker[102], A. Schmah[102], C. Schmidt[105], H.R. Schmidt[101], M.O. Schmidt[102], M. Schmidt[101], N.V. Schmidt[94,69], A.R. Schmier[130], J. Schukraft[34,88], Y. Schutz[136,34], K. Schwarz[105], K. Schweda[105], G. Scioli[27], E. Scomparin[58], M. Šefčík[38], J.E. Seger[16], Y. Sekiguchi[132], D. Sekihata[45], I. Selyuzhenkov[105,91], S. Senyukov[136], E. Serradilla[72], P. Sett[48], A. Sevcenco[68], A. Shabanov[62], A. Shabetai[114], R. Shahoyan[34], W. Shaikh[108], A. Shangaraev[90], A. Sharma[98], A. Sharma[99], M. Sharma[99], N. Sharma[98], A.I. Sheikh[141], K. Shigaki[45], M. Shimomura[82], S. Shirinkin[64], Q. Shou[111], Y. Sibiriak[87], S. Siddhanta[54], T. Siemiarczuk[84], D. Silvermyr[80], G. Simatovic[89], G. Simonetti[103,34], R. Singh[85], R. Singh[99], V.K. Singh[141], V. Singhal[141], T. Sinha[108], B. Sitar[14], M. Sitta[32], T.B. Skaali[21], M. Slupecki[127], N. Smirnov[146], R.J.M. Snellings[63], T.W. Snellman[127], J. Sochan[116], C. Soncco[110], J. Song[60], A. Songmoolnak[115], F. Soramel[29], S. Sorensen[130], I. Sputowska[118], J. Stachel[102], I. Stan[68], P. Stankus[94], P.J. Steffanic[130], E. Stenlund[80], D. Stocco[114], M.M. Storetvedt[36], P. Strmen[14], A.A.P. Suaide[121], T. Sugitate[45], C. Suire[61], M. Suleymanov[15], M. Suljic[34], R. Sultanov[64], M. Šumbera[93], S. Sumowidagdo[50], K. Suzuki[113], S. Swain[66], A. Szabo[14], I. Szarka[14], U. Tabassam[15], G. Taillepied[134], J. Takahashi[122], G.J. Tambave[22], S. Tang[6], M. Tarhini[114], M.G. Tarzila[47], A. Tauro[34], G. Tejeda Muñoz[44], A. Telesca[34], C. Terrevoli[29,126], D. Thakur[49], S. Thakur[141], D. Thomas[119], F. Thoresen[88], R. Tieulent[135], A. Tikhonov[62], A.R. Timmins[126], A. Toia[69], N. Topilskaya[62], M. Toppi[51], F. Torales-Acosta[20], S.R. Torres[120], S. Tripathy[49], T. Tripathy[48], S. Trogolo[26,29], G. Trombetta[33], L. Tropp[38], V. Trubnikov[2], W.H. Trzaska[127], T.P. Trzcinski[142], B.A. Trzeciak[63], T. Tsuji[132], A. Tumkin[107], R. Turrisi[56], T.S. Tveter[21], K. Ullaland[22], E.N. Umaka[126], A. Uras[135], G.L. Usai[24], A. Utrobicic[97], M. Vala[38,116], N. Valle[139], N. van der Kolk[63], L.V.R. van Doremalen[63], M. van Leeuwen[63], P. Vande Vyvre[34], D. Varga[145], A. Vargas[44], M. Vargyas[127], R. Varma[48], M. Vasileiou[83], A. Vasiliev[87], O. Vázquez Doce[117,103], V. Vechernin[112], A.M. Veen[63], E. Vercellin[26], S. Vergara Limón[44], L. Vermunt[63], R. Vernet[7], R. Vértesi[145], L. Vickovic[35], J. Viinikainen[127], Z. Vilakazi[131], O. Villalobos Baillie[109], A. Villatoro Tello[44], G. Vino[52], A. Vinogradov[87], T. Virgili[30], V. Vislavicius[88], A. Vodopyanov[75], B. Volkel[34], M.A. Völkl[101], K. Voloshin[64], S.A. Voloshin[143], G. Volpe[33], B. von Haller[34], I. Vorobyev[103,117], D. Voscek[116], J. Vrláková[38], B. Wagner[22], M. Wang[6], Y. Watanabe[133], M. Weber[113], S.G. Weber[105], A. Wegrzynek[34], D.F. Weiser[102], S.C. Wenzel[34], J.P. Wessels[144], U. Westerhoff[144], A.M. Whitehead[125], E. Widmann[113], J. Wiechula[69], J. Wikne[21], G. Wilk[84], J. Wilkinson[53], G.A. Willems[144,34], E. Willsher[109], B. Windelband[102], W.E. Witt[130], Y. Wu[129], R. Xu[6], S. Yalcin[77], K. Yamakawa[45], S. Yang[22], S. Yano[137], Z. Yin[6], H. Yokoyama[63], I.-K. Yoo[18], J.H. Yoon[60], S. Yuan[22], A. Yuncu[102], V. Yurchenko[2], V. Zaccolo[25,58], A. Zaman[15], C. Zampolli[34], H.J.C. Zanoli[121], N. Zardoshti[109,34], A. Zarochentsev[112], P. Závada[67], N. Zaviyalov[107], H. Zbroszczyk[142], M. Zhalov[96], X. Zhang[6], Y. Zhang[6], Z. Zhang[6,134], C. Zhao[21], V. Zherebchevskii[112], N. Zhigareva[64], D. Zhou[6], Y. Zhou[88], Z. Zhou[22], H. Zhu[6], J. Zhu[6], Y. Zhu[6], A. Zichichi[27,10], M.B. Zimmermann[34], G. Zinovjev[2], N. Zurlo[140],

Affiliation notes

[i] Deceased
[ii] Dipartimento DET del Politecnico di Torino, Turin, Italy
[iii] M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear, Physics, Moscow, Russia
[iv] Department of Applied Physics, Aligarh Muslim University, Aligarh, India
[v] Institute of Theoretical Physics, University of Wroclaw, Poland

Collaboration Institutes

[1] A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
[2] Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine
[3] Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
[4] Budker Institute for Nuclear Physics, Novosibirsk, Russia
[5] California Polytechnic State University, San Luis Obispo, California, United States

[6] Central China Normal University, Wuhan, China
[7] Centre de Calcul de l'IN2P3, Villeurbanne, Lyon, France
[8] Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
[9] Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
[10] Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi', Rome, Italy
[11] Chicago State University, Chicago, Illinois, United States
[12] China Institute of Atomic Energy, Beijing, China
[13] Chonbuk National University, Jeonju, Republic of Korea
[14] Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovakia
[15] COMSATS University Islamabad, Islamabad, Pakistan
[16] Creighton University, Omaha, Nebraska, United States
[17] Department of Physics, Aligarh Muslim University, Aligarh, India
[18] Department of Physics, Pusan National University, Pusan, Republic of Korea
[19] Department of Physics, Sejong University, Seoul, Republic of Korea
[20] Department of Physics, University of California, Berkeley, California, United States
[21] Department of Physics, University of Oslo, Oslo, Norway
[22] Department of Physics and Technology, University of Bergen, Bergen, Norway
[23] Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, Italy
[24] Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
[25] Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
[26] Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
[27] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
[28] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
[29] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
[30] Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
[31] Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
[32] Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy
[33] Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
[34] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[35] Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
[36] Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway
[37] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[38] Faculty of Science, P.J. Šafárik University, Košice, Slovakia
[39] Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[40] Gangneung-Wonju National University, Gangneung, Republic of Korea
[41] Gauhati University, Department of Physics, Guwahati, India
[42] Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
[43] Helsinki Institute of Physics (HIP), Helsinki, Finland
[44] High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
[45] Hiroshima University, Hiroshima, Japan
[46] Hochschule Worms, Zentrum für Technologietransfer und Telekommunikation (ZTT), Worms, Germany
[47] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[48] Indian Institute of Technology Bombay (IIT), Mumbai, India
[49] Indian Institute of Technology Indore, Indore, India
[50] Indonesian Institute of Sciences, Jakarta, Indonesia
[51] INFN, Laboratori Nazionali di Frascati, Frascati, Italy
[52] INFN, Sezione di Bari, Bari, Italy
[53] INFN, Sezione di Bologna, Bologna, Italy
[54] INFN, Sezione di Cagliari, Cagliari, Italy
[55] INFN, Sezione di Catania, Catania, Italy
[56] INFN, Sezione di Padova, Padova, Italy

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

[108] Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
[109] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[110] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[111] Shanghai Institute of Applied Physics, Shanghai, China
[112] St. Petersburg State University, St. Petersburg, Russia
[113] Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
[114] SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France
[115] Suranaree University of Technology, Nakhon Ratchasima, Thailand
[116] Technical University of Košice, Košice, Slovakia
[117] Technische Universität München, Excellence Cluster 'Universe', Munich, Germany
[118] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[119] The University of Texas at Austin, Austin, Texas, United States
[120] Universidad Autónoma de Sinaloa, Culiacán, Mexico
[121] Universidade de São Paulo (USP), São Paulo, Brazil
[122] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
[123] Universidade Federal do ABC, Santo Andre, Brazil
[124] University College of Southeast Norway, Tonsberg, Norway
[125] University of Cape Town, Cape Town, South Africa
[126] University of Houston, Houston, Texas, United States
[127] University of Jyväskylä, Jyväskylä, Finland
[128] University of Liverpool, Liverpool, United Kingdom
[129] University of Science and Techonology of China, Hefei, China
[130] University of Tennessee, Knoxville, Tennessee, United States
[131] University of the Witwatersrand, Johannesburg, South Africa
[132] University of Tokyo, Tokyo, Japan
[133] University of Tsukuba, Tsukuba, Japan
[134] Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
[135] Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, Lyon, France
[136] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France
[137] Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Départment de Physique Nucléaire (DPhN), Saclay, France
[138] Università degli Studi di Foggia, Foggia, Italy
[139] Università degli Studi di Pavia, Pavia, Italy
[140] Università di Brescia, Brescia, Italy
[141] Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India
[142] Warsaw University of Technology, Warsaw, Poland
[143] Wayne State University, Detroit, Michigan, United States
[144] Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany
[145] Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary
[146] Yale University, New Haven, Connecticut, United States
[147] Yonsei University, Seoul, Republic of Korea