Investigations of Anisotropic Flow Using Multiparticle Azimuthal Correlations in pp, p-Pb, Xe-Xe, and Pb-Pb Collisions at the LHC

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Investigations of Anisotropic Flow Using Multiparticle Azimuthal Correlations in *pp*, *p*-Pb, Xe-Xe, and Pb-Pb Collisions at the LHC

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Measurements of anisotropic flow coefficients (v_n) and their cross-correlations using two- and multiparticle cumulant methods are reported in collisions of pp at $\sqrt{s} = 13$ TeV, p-Pb at a center-of-mass energy per nucleon pair $\sqrt{s_{\rm NN}} = 5.02$ 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. The multiplicity dependence of v_n is studied in a very wide range from 20 to 3000 particles produced in the midrapidity region $|\eta| < 0.8$ for the transverse momentum range $0.2 < p_T < 3.0$ 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 a novel subevent method, v_2 measured with four-particle cumulants is found to be compatible with that from six-particle cumulants in pp and p-Pb collisions. The magnitude of the correlation between v_n^2 and v_m^2, evaluated with the symmetric cumulants SC(m, n) is observed to be positive at all multiplicities for v_2 and v_4, while for v_2 and v_3 it is negative and changes sign for multiplicities below 100, which may indicate a different v_n fluctuation pattern in this multiplicity range. The observed long-range multiparticle azimuthal correlations in high multiplicity pp and p-Pb collisions can neither be described by PYTHIA 8 nor by impact-parameter-Glasma, MUSIC, and ultrarelativistic quantum molecular dynamics model calculations, and hence, provide new insights into the understanding of collective effects in small collision systems.

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Experiments investigating ultrarelativistic collisions of heavy ions intend to explore a deconfined state of quarks and gluons, the quark-gluon plasma (QGP). Azimuthal correlations of final state particles over a wide range in pseudorapidity relative to the collision symmetry plane Ψ_n ($n \geq 1$), whose magnitudes are quantified by flow coefficients v_n, provide important information into the matter created in these collisions [1–3]. Extensive measurements of v_n for inclusive [4–9] and identified hadrons [10] were performed for Xe-Xe and Pb-Pb collisions at the Large Hadron Collider (LHC). These studies, together with quantitative descriptions by hydrodynamic calculations, have enabled an extraction of the properties of the QGP [11], revealing that it 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]. Recently, significant progress has also been achieved by measuring correlations between different flow coefficients and symmetry planes [6,7,13–18]. In particular, the correlation strength between different flow coefficients v_m^2 and v_n^2, quantified by symmetric cumulants SC(m, n) [19], was found to be sensitive to the temperature dependence of η/s and 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 observed across different collision systems at both RHIC and LHC energies, when compared at similar multiplicity of produced particles within a specific phase space [20–22]. The "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-A and pp collisions [23]. In addition, measurements of azimuthal correlations using multiparticle cumulants revealed signatures' collective effects in small systems, such as a negative four-particle cumulant $c_2\{4\}$ [24–28].

Whether the observed similarities between small (pp and p-A) and large (A-A) collision systems arise from the same physics mechanism is under intense debate. Besides hydrodynamic descriptions [29–33], calculations

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from transport models [34–36], hadronic rescattering [37,38], a string rope and shoving mechanism [39], as well as initial stage effects [40–42] have been investigated.

We report measurements of v_n and $\mathrm{SC}(m,n)$ as a function of produced particle multiplicity across small and large collision systems. These measurements provide information on the collective effects observed in all systems, which can be studied via long-range multiparticle correlations. A significant extension of recent studies [28,43,44] is achieved by adding new results of v_2 and $\mathrm{SC}(m,n)$ for all available collision systems at the LHC, together with a comprehensive comparison to the available models ranging from nonflow dominated (PYTHIA 8) to the state of the art hydrodynamic model calculations. They rely on a new technique of performing multiparticle long range correlations named the subevent method [45,46], which further minimizes biases from few particle correlations such as resonances and jets, usually called nonflow, 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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, Xe-Xe at $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV, and Pb-Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. They were recorded with the ALICE detector [47,48] 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 [49]. 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 corresponding average multiplicity is at least 4 times larger than in minimum bias collisions. In comparison to minimum-bias collisions, the selection of high-multiplicity events based on forward multiplicity suppresses the nonflow contribution to v_n at midrapidity by suppressing jet correlations.

Only events with a reconstructed primary vertex Z_{vtx} within ± 10 cm from the nominal interaction point were selected. A 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 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) [50] and the time projection chamber (TPC) [51]. Only tracks with more than 70 clusters in the TPC (out of a maximum of 159) were selected. A selection requiring the pseudorapidity to be within $-0.8 < \eta < 0.8$ ensured a high track reconstruction efficiency of 80%. Tracks with a transverse momentum $p_T < 0.2$ GeV/c and $p_T > 3.0$ GeV/c were rejected due to low tracking efficiency and to reduce the contribution from jets, respectively. 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_T-dependent selection in the transverse direction, ranging from 0.2 cm at $p_T = 0.2$ GeV/c down to 0.02 cm at $p_T = 3.0$ GeV/c, was applied leading to a residual contamination from secondaries between 1% and 3%.

The results were calculated from two- and multiparticle azimuthal correlations using the generic framework [19], recently extended to include the subevent method [46]. The ranges of the subevents were chosen to be $(-0.8, 0)$ and (0,0.8) for the two-subevent, and $(-0.8, -0.4)$, $(-0.4, 0.4)$, and (0.4,0.8) for three-subevent measurements.

A correction dependent on η and Z_{vtx} was applied to account for azimuthal nonuniformity. The correction for tracking inefficiencies was obtained from Monte Carlo simulations as a function of p_T, η, and Z_{vtx} from generated particles and from tracks reconstructed from a GEANT3 simulation [52]. The systematic uncertainties were estimated as follows. The contribution from the event selection was examined by narrowing the selection on Z_{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 tracks having 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 with the simulation output after the full reconstruction. The individual contributions were summed in quadrature to form the systematic uncertainties, ranging between 1%–6% for the two-particle cumulant, and 10%–17% for the multiparticle cumulant results. The results are reported as a function of the number of produced charged particles $N_{\mathrm{ch}}(|\eta| < 0.8, 0.2 < p_T < 3.0$ GeV/c).

Figure 1 presents the measurements of anisotropic flow coefficients $v_n\{k\}$ of order 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 no collision energy dependence of the integrated v_n is expected [27].

Figures 1(a)–1(c) show v_2, v_3, and v_4 measured using two-particle ($k = 2$) cumulants with a pseudorapidity separation $|\Delta\eta| > 1.4$, 1.0, and 1.0, respectively, chosen to suppress nonflow contributions. Because of the limited statistics of the pp data sample, the $|\Delta\eta|$ separation in the cases of v_3 and v_4 was reduced to 1.0, consistently across all collision systems. A pronounced multiplicity dependence of v_2 is observed in the flow dominated collision systems (Pb-Pb and Xe-Xe) as a result of the medium response to the eccentricity of the initial overlap region of the colliding nuclei. The Pb-Pb data exhibit larger v_2 values

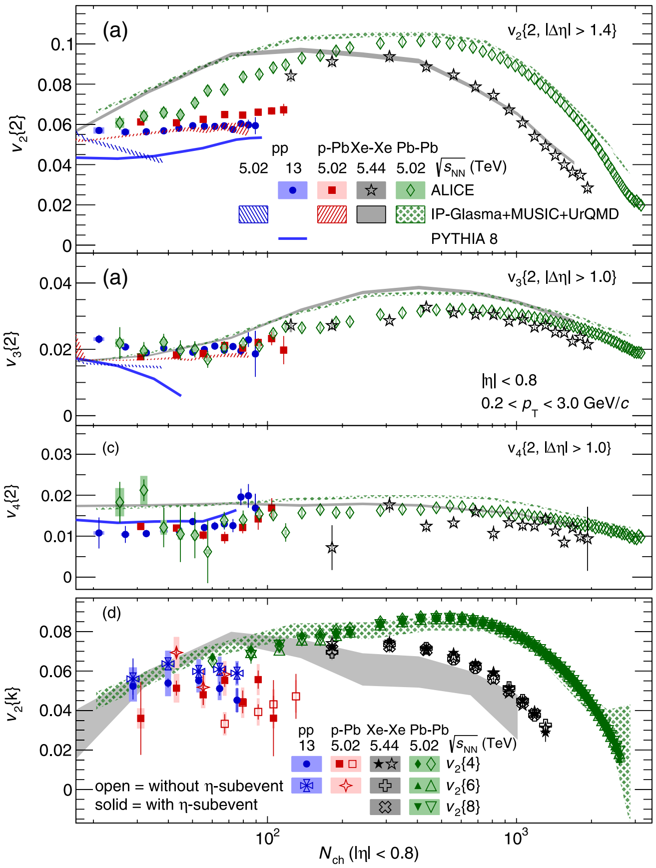

FIG. 1. Multiplicity dependence of $v_n\{k\}$ for pp, p-Pb, Xe-Xe, and Pb-Pb collisions. Statistical uncertainties are shown as vertical lines and systematic uncertainties as filled boxes. Data are compared with PYTHIA 8.210 Monash 2013 [53] simulations (solid lines) of pp collisions at $\sqrt{s} = 13$ TeV and impact-parameter-Glasma, MUSIC, and ultrarelativistic quantum molecular dynamics (IP-Glasma+MUSIC+UrQMD) [31,54] 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). The width of the band represents the statistical uncertainty of the model. (a), (b), and (c): v_2, v_3, and v_4 measured using two-particle cumulants with a pseudorapidity separation $|\Delta\eta| > 1.4$, 1.0 and 1.0, respectively. (d) v_2 measured using multiparticle cumulants, with the three-subevent method for the four-particle cumulant, and two-subevent method for higher order cumulants in Pb-Pb collisions.

than the Xe-Xe data, but they are compatible for $N_{ch} < 200$. An ordering of $v_2 > v_3 > v_4$ is observed in large systems except for the very high 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 large systems are compared with calculations using impact-parameter Glasma (IP-Glasma) initial conditions, MUSIC hydrodynamic model, and the ultrarelativistic quantum molecular dynamics (UrQMD) model for hadronic rescatterings [31,54]. The calculations qualitatively describe all the v_n measurements except for $N_{ch} < 200$ where they overestimate the v_2.

In small collision systems, all the v_n coefficients exhibit a weak dependence on multiplicity. The trend and magnitudes, particularly for v_2, cannot be explained solely by model calculations without collective effects. This can be demonstrated by the comparison with predictions from PYTHIA 8 [53], computed with a similar multiplicity definition as the experimental results from pp collisions. The ordering of v_n in pp collisions for all multiplicities is the same as in large collision systems ($v_2 > v_3 > v_4$) and is not described by PYTHIA 8 where $v_2 > v_4 > v_3$ for $N_{ch} > 30$. These observations suggest the presence of effects other than just nonflow correlations at multiplicities larger than about 2–3 times the minimum bias value of $\langle N_{ch}\rangle \approx 10$ in pp and $\langle N_{ch}\rangle \approx 24$ in p-Pb collisions. In p-Pb collisions, these conclusions are further supported by the qualitative agreement with the IP-Glasma+MUSIC +UrQMD calculations. Nevertheless, the hydrodynamic model reveals a strong decrease of v_2 with multiplicity in pp collisions, which is in stark contrast with the data. A further nonflow suppression with a larger $|\Delta\eta|$ separation in the experimental results of p-Pb collisions, or improvements in the phenomenological description, might help to reach a quantitative agreement.

Figure 1(d) shows measurements of $v_2\{k\}$ using cumulants with a number $k = 4$, 6 and 8 particles. Measurements of $v_2\{4\}$ with the three-subevent method, and of $v_2\{6\}$ and $v_2\{8\}$ in Pb-Pb collisions with the two-subevent method, are also presented. Compared to $v_2\{2\}$, multiparticle cumulants are less influenced by nonflow effects, since the latter usually involve only a few particles. No further nonflow suppression was observed by increasing the $|\Delta\eta|$ separation between the subevents in the multiparticle cumulant measurements. In Xe-Xe and Pb-Pb collisions, characteristic patterns of long-range multiparticle 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 multiparticle cumulants ($v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$) are found, signaling a negligible contribution from nonflow correlations and the dominance of collective effects. Moreover, a good agreement of $v_2\{4\}$ between data and calculations from the IP-Glasma+MUSIC+UrQMD [31,54] model is found for Pb-Pb collisions down to $N_{ch} \approx 200$. The same 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 p-Pb collisions, a further nonflow suppression with the three-subevent method leads to a decrease of the cumulant $c_2\{4\} > c_2\{4\}_{3-\mathrm{sub}}$, which, due to the relation $v_2\{4\} = \sqrt[4]{-c_2\{4\}}$, corresponds up to a 2σ increase $v_2\{4\} < v_2\{4\}_{3-\mathrm{sub}}$. The three-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.

Genuine multiparticle correlations in p-Pb collisions are indicated by consistent results of $v_2\{4\}$ and $v_2\{6\}$. In pp collisions, significant nonflow contributions 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 three-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. These results confirm the existence of long-range multiparticle correlations in pp and p-Pb collisions at multiplicities $N_{\mathrm{ch}} \geq 30$. PYTHIA 8 calculations, which do not contain genuine long-range multiparticle correlations, do not give a real valued $v_2\{4\}$ even with the subevent method [45]. The superSONIC [32] and iEBE-VISHNU [33] hydrodynamic models, which can quantitatively describe all available two-particle correlation measurements in pp, p-Pb, and Pb-Pb collisions, cannot reproduce the four-particle cumulants with the currently used initial state model, not even on a qualitative level. Another model with initial-state calculations predicts the multiparticle cumulants with correct signs and a weak dependence on the saturation scale Q_s^2, but the predictions are 10 times larger than what is observed in the data, and there is no direct connection of the Q_s^2 to the experimentally measured number of produced charged particles [41]. 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 obtained from symmetric cumulants $\mathrm{SC}(m,n)$, which quantify the correlation between v_m^2 and v_n^2. Figures 2(a) and 2(c) present the multiplicity dependence of $\mathrm{SC}(m,n)$ measured with the three-subevent method. In Fig. 2(a), a positive $\mathrm{SC}(4,2)_{3-\mathrm{sub}}$ is observed in large 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 [31,54] calculations. A similar positive $\mathrm{SC}(4,2)_{3-\mathrm{sub}}$ is observed both in pp and p-Pb collisions, as was also found in [44]. The measurements in pp collisions are compared with PYTHIA 8 [53], which shows a decrease of $\mathrm{SC}(4,2)_{3-\mathrm{sub}}$ with decreasing multiplicity, different from what is seen in data. Calculations [41,55] with initial state correlations or parton-escape mechanism can qualitatively or even semi-quantitatively describe the p-Pb data. We note that the results from the initial state model [41] were calculated as a function of variables that cannot be directly computed from experimental data.

An anticorrelation 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 for $N_{\mathrm{ch}} > 100$ in Fig. 2(c), similar to that in [14,17]. There is a hint of a change to a positive sign of $\mathrm{SC}(3,2)_{3-\mathrm{sub}}$ in Pb-Pb collisions below multiplicities of $N_{\mathrm{ch}} \approx 100$. This tendency is observed at even 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 behavior is not observed for small collision systems with a larger η acceptance [44], where $\mathrm{SC}(3,2)_{3-\mathrm{sub}}$ remains negative in the whole multiplicity range. One possible explanation is the different contributions from nonflow effects. The IP-Glasma+MUSIC+UrQMD [31,54] 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 [53] fails to quantitatively describe the results from pp collisions, but it does qualitatively reproduce the trend of the data.

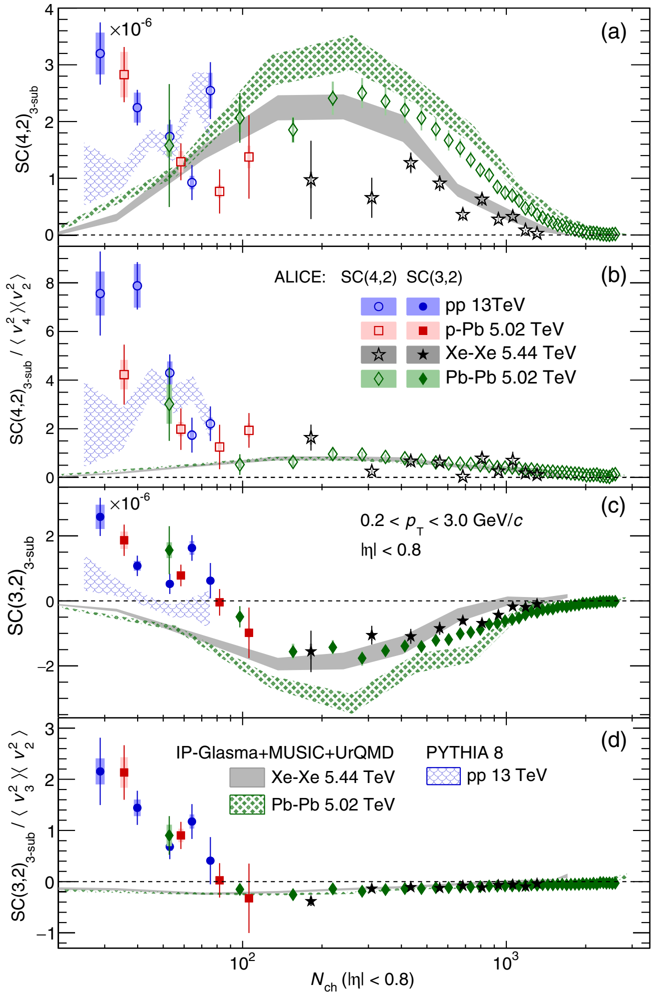

FIG. 2. Multiplicity dependence of the (a) and (c) symmetric cumulant $\mathrm{SC}(m,n)_{3-\mathrm{sub}}$ and (b) and (d) normalized ratio $\mathrm{SC}(m,n)_{3-\mathrm{sub}}/\langle v_m^2\rangle\langle v_n^2\rangle$ for pp, p-Pb, Xe-Xe and Pb-Pb collisions. Observables in the denominator are obtained from the $v_2\{2, |\Delta\eta| > 1.4\}$ and $v_n\{2, |\Delta\eta| > 1.0\}$ for higher harmonics. Statistical uncertainties are shown as vertical lines and systematic uncertainties as filled boxes. The measurements in large collision systems are compared with the IP-Glasma+MUSIC+UrQMD [31,54] calculations and results in pp collisions are compared with the PYTHIA 8 model [53].

No hydrodynamic calculations of $\mathrm{SC}(m,n)$ in small systems are currently available. Nevertheless, calculations based on initial state correlations in [40,41] reflect the crossing from negative to positive SC(3,2) in p-Pb collisions, whereas a positive correlation is predicted in pp collisions [40].

While $\mathrm{SC}(m,n)$ encodes information on both the magnitude of and correlation between the flow coefficients, in the absence of nonflow, the latter can be accessed directly by dividing $\mathrm{SC}(m,n)_{3-\mathrm{sub}}$ by the corresponding flow coefficients $\langle v_m^2\rangle\langle v_n^2\rangle$. The normalized ratios, shown in Figs. 2(b) and 2(d), indicate that the correlation between flow coefficients is possibly the same between different collision systems at the same N_{ch}, and reveals a large increase in magnitude in the correlation strength for collisions with $N_{\mathrm{ch}} < 100$ compared to higher multiplicities. While this may be indicative of a different fluctuation pattern at low multiplicity, nonflow effects likely persist in this region based on the observed finite values of PYTHIA 8 calculations. Such effects make the interpretation of an increase of the normalized ratio significantly less straightforward and requires further study.

In summary, we have presented the measurements of flow coefficients $v_n\{k\}$ and symmetric cumulants $\mathrm{SC}(m,n)$ as a function of the produced particle multiplicity in small (pp, p-Pb) and large (Xe-Xe, Pb-Pb) collision systems. In pp and p-Pb collisions, an 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 multiplicities. These first ALICE measurements of v_2 using multiparticle cumulants in small collision systems are found to be compatible with each other after a suppression of nonflow 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 anticorrelation 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 also indicated 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 nonflow. 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 about the origin of the observed collectivity and provides key constraints to the various approaches for modeling collectivity in small systems.

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