Longitudinal Flow Decorrelations in Xe + Xe Collisions at $\sqrt{s_{NN}} = 5.44$ TeV with the ATLAS Detector

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The first measurement of longitudinal decorrelations of harmonic flow amplitudes v_n for $n = 2$–4 in Xe + Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV is obtained using 3 μb^{-1} of data with the ATLAS detector at the LHC. The decorrelation signal for v_3 and v_4 is found to be nearly independent of collision centrality and transverse momentum (p_T) requirements on final-state particles, but for v_2 a strong centrality and p_T dependence is seen. When compared with the results from Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, the longitudinal decorrelation signal in midcentral Xe + Xe collisions is found to be larger for v_2, but smaller for v_3. Current hydrodynamic models reproduce the ratios of the v_n measured in Xe + Xe collisions to those in Pb + Pb collisions but fail to describe the magnitudes and trends of the ratios of longitudinal flow decorrelations between Xe + Xe and Pb + Pb. The results on the system-size dependence provide new insights and an important lever arm to separate effects of the longitudinal structure of the initial state from other early and late time effects in heavy-ion collisions.

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High-energy heavy-ion collisions create a new state of matter known as a quark-gluon plasma (QGP), whose space-time dynamics is well described by relativistic viscous hydrodynamic models [1–3]. During its expansion, the large pressure gradients of the QGP convert the spatial anisotropies in the initial-state geometry into momentum anisotropies of the final-state particles. Such momentum anisotropies are often characterized by a Fourier expansion of particle density in the azimuthal angle ϕ, $dN/d\phi \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$, where v_n and Φ_n are the magnitude and phase of the nth-order flow vector $V_n = v_n e^{-in\Phi_n}$. The V_n reflects the hydrodynamic response of the QGP to the shape of the overlap region in the transverse plane, described by eccentricity vector $\mathcal{E}_n = \varepsilon_n e^{-in\Psi_n}$ [4]. Extensive studies of V_n and their event-by-event fluctuations in a broad range of beam energy and collision systems [5–15] have provided strong constraints on the $\mathcal{E}_n$ and the properties of the QGP [4,16–20].

Most previous efforts assume that the shape of the initial overlap and dynamic evolution of the QGP are boost invariant. Recently, LHC experiments made the first observation of "flow decorrelations" in Pb + Pb collisions [21,22], which show that, even in a single event, v_n and Φ_n can fluctuate along the longitudinal direction. This can be attributed to the fact that the distribution of particle production sources, and the associated eccentricity vectors, fluctuates along pseudorapidity (η). For example, the number of forward- and backward-going nucleon participants, and the corresponding eccentricity vectors $\mathcal{E}_n^F$ and $\mathcal{E}_n^B$, are not the same in a given event. While the harmonic flow V_n are driven by the average of the two eccentricity vectors $V_n \propto \mathcal{E}_n \approx (\mathcal{E}_n^F + \mathcal{E}_n^B)/2$, the flow decorrelation is related to the difference between them, $\mathcal{E}_{n-} = (\mathcal{E}_n^F - \mathcal{E}_n^B)/2$ [23]. Indeed, hydrodynamic model and transport model calculations [24–29] show that the flow decorrelations are driven mostly by longitudinal fluctuation of $\mathcal{E}_n$ in the initial-state geometry. They are also influenced by other early time effects, such as initial-state momentum anisotropy [30] and hydrodynamic fluctuations [31], but are insensitive to late time dynamics, including shear viscosity [27]. These different early time contributions compete with each other, and current measurements [21,22] from a single system (Pb + Pb) in a limited energy range ($\sqrt{s_{NN}} = 2.76$–5.02 TeV) do not disentangle these effects. To improve our understanding of the longitudinal structure of the QGP, it is crucial to extend the measurements to a broad range in the beam energy and size of the collision systems [27,32].

This Letter investigates the system-size dependence of longitudinal decorrelations of v_2, v_3, and v_4 by performing measurements in ^{129}Xe + ^{129}Xe collisions and comparing them with ^{208}Pb + ^{208}Pb collisions. Recent measurements show that the inclusive v_n exhibit modest differences (< 10%–20%) between these two systems as a function of centrality, except in the central collisions where the difference for v_2 is significantly larger [33–35]. These are

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sensitive to the differences in the initial eccentricities and viscous effects in the two systems [36,37]. Similarly, comparison of v_n decorrelation between Xe + Xe and Pb + Pb, together with the comparison of inclusive v_n, could improve our understanding of the longitudinal structures of the QGP and, in particular, answer the question whether the decorrelation is controlled by the overall system size or the shape of the overlap region.

The measurement is performed using the ATLAS inner detector (ID) and forward calorimeters (FCals) along with the trigger and data acquisition system [38,39]. The ID measures charged particles over a pseudorapidity range $|\eta| < 2.5$ using a combination of silicon pixel detectors, silicon microstrip detectors, and a straw-tube transition radiation tracker, all immersed in a 2 T axial magnetic field [40–42]. [ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.] The FCal measures the sum of the transverse energy $\sum E_T$ over $3.2 < |\eta| < 4.9$ to determine the event centrality and uses copper and tungsten absorbers with liquid argon as the active medium. The ATLAS trigger system [39] consists of a level-one (L1) trigger based on electronics and a software-based high-level trigger.

This analysis uses 3 μb^{-1} of $\sqrt{s_{NN}} = 5.44$ TeV Xe + Xe data collected in 2017. The events are selected by requiring the total transverse energy deposited in the calorimeters over $|\eta| < 4.9$ at L1 to be larger than 4 GeV. In the off-line analysis, the z position of the primary vertex [43] of each event is required to be within 100 mm of the IP. Events containing more than one inelastic interaction are suppressed by exploiting the correlation between the $\sum E_T$ measured in the FCal and the number of tracks associated with a primary vertex. The event centrality classification is based on the $\sum E_T$ in the FCal [44]. A Glauber model [45,46] is used to determine the mapping between $\sum E_T$ in the FCal and the centrality percentiles, as well as to estimate the average number of participating nucleons N_{part} for each centrality interval.

Charged-particle tracks are reconstructed from ionization hits in the ID using a reconstruction procedure optimized for heavy-ion collisions [47]. Tracks used in this analysis are required to have $|\eta| < 2.4$ and transverse momentum in the range $0.5 < p_T < 3$ GeV. In addition, the point of closest approach of the track to the primary vertex is required to be within 1 mm in both the transverse and longitudinal directions. More details of the track selection can be found in Ref. [35].

The efficiency $\epsilon(p_T, \eta)$ of the track reconstruction and track selection requirements is evaluated using minimum-bias Xe + Xe Monte Carlo (MC) events produced with the HIJING [48] event generator with the effect of flow added via Ref. [49]. The response of the detector was simulated [50] using GEANT4 [51], and the resulting events are reconstructed with the same algorithms as applied to the data. The efficiency varies from 40% to 73% depending on η and p_T, with an uncertainty of 1%–4% arising mainly from the uncertainty in the detector material budget. The rate of falsely reconstructed (fake) tracks $f(p_T, \eta)$ is significant only for $p_T < 0.8$ GeV in central collisions, where it ranges from 2% for η near zero to 6% for $|\eta| > 2$.

The method and analysis procedure closely follow those established in Ref. [22] and are described briefly below. The nth-order azimuthal anisotropy in an event is estimated using the observed flow vectors

$$\boldsymbol{q}_n \equiv \Sigma_j w_j e^{in\phi_j} / (\Sigma_j w_j), \tag{1}$$

where the sum runs over charged particles (for the ID) or calorimeter towers (for the FCal) in a specified η interval, and ϕ_j and w_j are the azimuthal angle and the weight assigned to each track or tower, respectively. The weight for the FCal is the E_T of each tower, and the weight for the ID is calculated as $d(\eta, \phi)(1 - f(p_T, \eta))/\epsilon(p_T, \eta)$ to correct for tracking performance [52]. The additional factor $d(\eta, \phi)$, derived from the data, corrects for azimuthal nonuniformity of the detector performance in each η interval.

The flow decorrelations are studied using product of flow vectors $\boldsymbol{q}_n(\eta)$ in the ID and $\boldsymbol{q}_n(\eta_{\text{ref}})$ in the FCal [21] averaged over events in a given centrality interval,

$$\begin{aligned} r_{n|n}(\eta) &= \frac{\langle \boldsymbol{q}_n(-\eta)\boldsymbol{q}_n^*(\eta_{\text{ref}})\rangle}{\langle \boldsymbol{q}_n(\eta)\boldsymbol{q}_n^*(\eta_{\text{ref}})\rangle} \\ &= \frac{\langle v_n(-\eta)v_n(\eta_{\text{ref}})\cos n[\Phi_n(-\eta) - \Phi_n(\eta_{\text{ref}})]\rangle}{\langle v_n(\eta)v_n(\eta_{\text{ref}})\cos n[\Phi_n(\eta) - \Phi_n(\eta_{\text{ref}})]\rangle}, \end{aligned} \tag{2}$$

where η_{ref} is a reference pseudorapidity range in the FCal, common to both the numerator and the denominator. The $r_{n|n}$ correlator defined this way quantifies the decorrelation between η and $-\eta$ [21,23]. Three reference η ranges, $3.2 < |\eta_{\text{ref}}| < 4.0$, $4.0 < |\eta_{\text{ref}}| < 4.9$, and $3.2 < |\eta_{\text{ref}}| < 4.9$ are used. Since $\langle \boldsymbol{q}_n(-\eta)\boldsymbol{q}_n^*(\eta_{\text{ref}})\rangle = \langle \boldsymbol{q}_n(\eta)\boldsymbol{q}_n^*(-\eta_{\text{ref}})\rangle$ for a symmetric system, the correlator is further symmetrized to enhance the statistics and reduce detector effects: $r_{n|n}(\eta) = [\langle \boldsymbol{q}_n(-\eta)\boldsymbol{q}_n^*(\eta_{\text{ref}}) + \boldsymbol{q}_n(\eta)\boldsymbol{q}_n^*(-\eta_{\text{ref}})\rangle]/[\langle \boldsymbol{q}_n(\eta)\boldsymbol{q}_n^*(\eta_{\text{ref}}) + \boldsymbol{q}_n(-\eta)\boldsymbol{q}_n^*(-\eta_{\text{ref}})\rangle]$.

If flow harmonics for two-particle correlation from two different η factorize into single-particle harmonics, then it is expected that $r_{n|n}(\eta) = 1$. Therefore, a value of $r_{n|n}(\eta)$ incompatible with unity implies a factorization-breaking effect due to longitudinal flow decorrelations. The deviation of $r_{n|n}$ from unity can be parametrized with a linear function $r_{n|n}(\eta) = 1–2F_n\eta$. The slope parameter F_n is obtained via a simple linear regression of the $r_{n|n}(\eta)$ data [22]. Using a Glauber model with a parametrized longitudinal structure, it was shown that $F_n \propto A_{\varepsilon_n} = \langle \varepsilon_{n-}^2 \rangle / \langle \varepsilon_n^2 \rangle$ with $\varepsilon_{n-} = |\mathcal{E}_{n-}|$ [32]; i.e., F_n is sensitive to the difference between the eccentricity for forward- and backward-going participants. Since effects of viscosity partially cancels in the ratio, F_n is less sensitive to late time effects.

Systematic uncertainties in $r_{n|n}$ and the slope parameter F_n arise from the uncertainties in the reconstruction and track selection efficiency, acceptance reweighting procedure, and centrality definition. The systematic uncertainties are estimated by varying different aspects of the analysis, recalculating $r_{n|n}$ and F_n, and comparing them with the nominal values. The systematic uncertainty associated with fake tracks is estimated by loosening the requirements on the transverse and longitudinal impact parameters [35]; the resulting changes are 1%–2% for F_2, 1%–4% for F_3, and 1%–9% for F_4. The uncertainty associated with $\epsilon(p_T, \eta)$ is evaluated to be less than 1% for F_n. The effect of reweighting is studied by setting $d(\eta, \phi) = 1$ and repeating the analysis. The change is found to be 0.6%–2% for F_2 and F_3, and 2%–7% for F_4. The uncertainty due to the centrality definition is estimated by varying the mapping between $\sum E_T$ and centrality percentiles; the influence is 0.5%–4% for F_2 and F_3, and 0.5%–8% for F_4.

Figure 1 shows the measured $r_{n|n}(\eta)$ for $n = 2$–4 in two centrality intervals, quantifying the flow decorrelation between η and $-\eta$ according to Eq. (2). The $r_{n|n}$ values show an approximately linear decrease with η, implying stronger flow decorrelation at large η. The magnitudes of decorrelation for $r_{3|3}$ and $r_{4|4}$ are significantly larger than that for $r_{2|2}$. The range $4.0 < |\eta_{\mathrm{ref}}| < 4.9$ chosen for $r_{2|2}$ is different from the range $3.2 < |\eta_{\mathrm{ref}}| < 4.9$ used for $r_{3|3}$ and $r_{4|4}$ in order to reduce sensitivity to nonflow correlations; this is further discussed below.

The slope parameters F_n for $r_{n|n}$ are summarized in Fig. 2 as a function of centrality percentile with smaller percentile corresponding to more-central collisions. The left panels show the F_n for three $|\eta_{\mathrm{ref}}|$ ranges and right panels show the F_n for three p_T ranges. Within uncertainties, F_3 and F_4 show very weak dependence on centrality. The F_2 values, on the other hand, show a strong centrality dependence: they are smallest in the 20%–30% centrality interval and larger toward more-central or more-peripheral collisions. This strong centrality dependence is related to the fact that v_2 is dominated by the average elliptic geometry in midcentral collisions and therefore is less affected by decorrelations, while it is dominated by fluctuation-driven collision geometries in central and peripheral collisions [26,27].

Figure 2 also shows that F_2 has sizable variation between choices of $|\eta_{\mathrm{ref}}|$ or p_T in central and midcentral collisions. The contribution from nonflow correlations associated with back-to-back dijets are expected to contribute to the denominator more than the numerator due to a small gap between η and η_{ref}, and therefore tend to increase the F_n values [22,53]. Such nonflow contributions are expected to be larger for smaller $|\eta_{\mathrm{ref}}|$ or larger p_T. However, although the data show a larger F_2 for smaller $|\eta_{\mathrm{ref}}|$ compatible with nonflow, they show a smaller F_2 for larger p_T, opposite to the expectation from nonflow contributions. Such p_T and η_{ref} dependences are most significant in ultracentral collisions, suggesting a nonlinear behavior of v_2 decorrelation due to disappearance of average elliptic geometry in these collisions. Within uncertainties, the F_3 and F_4, as well as the original $r_{3|3}$

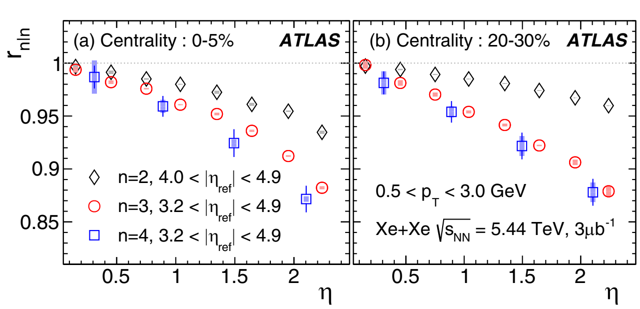

FIG. 1. The η dependence of $r_{2|2}$, $r_{3|3}$, and $r_{4|4}$ in Xe + Xe collisions for two centrality intervals: (a) 0%–5%, (b) 20%–30%. The $|\eta_{\mathrm{ref}}|$ is chosen to be $4.0 < |\eta_{\mathrm{ref}}| < 4.9$ for $r_{2|2}$ and $3.2 < |\eta_{\mathrm{ref}}| < 4.9$ for $r_{3|3}$ and $r_{4|4}$. The error bars and shaded boxes represent statistical and systematic uncertainties, respectively.

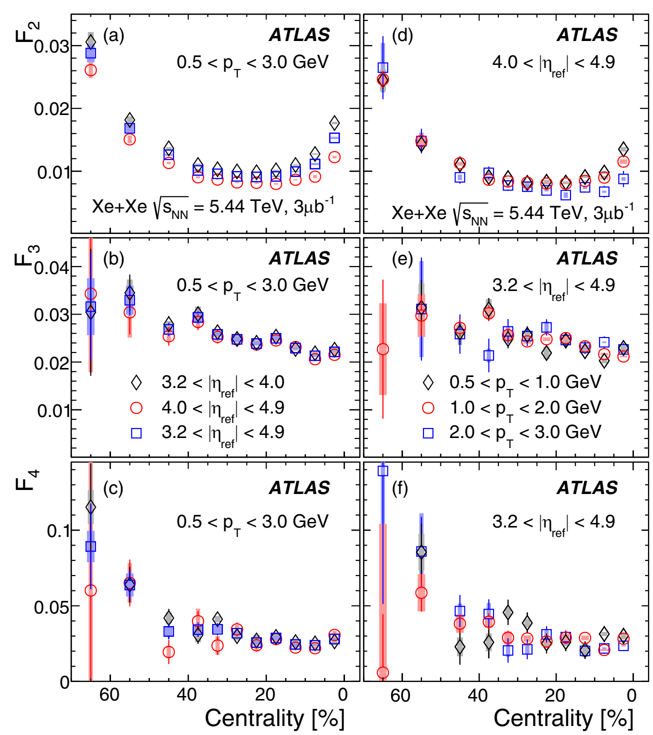

FIG. 2. The centrality dependence of F_n calculated for three $|\eta_{\mathrm{ref}}|$ ranges (left) and three p_T ranges (right) for (a),(d) $n = 2$, (b),(e) $n = 3$, and (c),(f) $n = 4$. The error bars and shaded boxes represent statistical and systematic uncertainties, respectively.

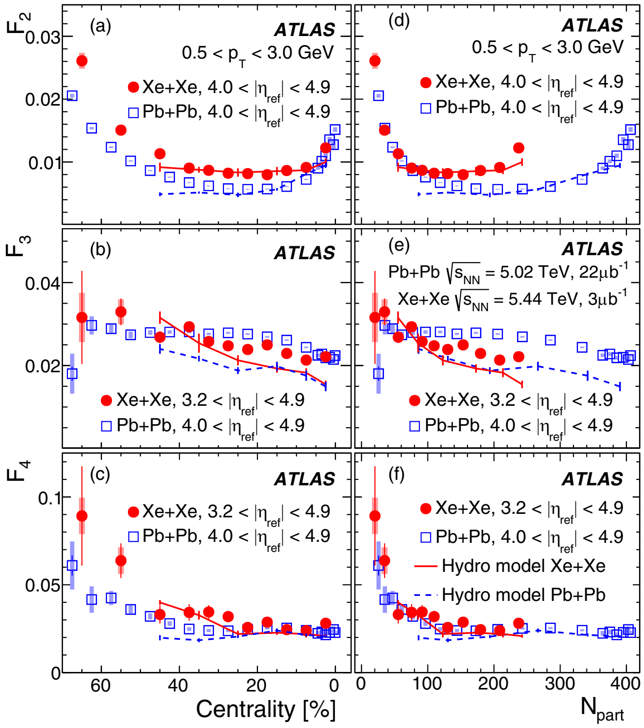

FIG. 3. The F_n compared between Xe + Xe and Pb + Pb [22] collisions as a function of centrality percentiles (left) and N_{part} (right) for (a),(d) $n = 2$, (b),(e) $n = 3$, and (c),(f) $n = 4$. The error bars and shaded boxes on the data represent statistical and systematic uncertainties, respectively. The results from a hydrodynamic model [30,54] are shown as solid lines (Xe + Xe) and dashed lines (Pb + Pb) with the vertical error bars denoting statistical uncertainty of the model predictions.

and $r_{4|4}$, show no differences between various p_T or $|\eta_{\mathrm{ref}}|$ ranges, suggesting that they are not affected by nonflow. Based on results in Fig. 2, $4.0 < |\eta_{\mathrm{ref}}| < 4.9$ is chosen for F_2 to reduce nonflow, but a wider range $3.2 < |\eta_{\mathrm{ref}}| < 4.9$ is chosen for F_3 and F_4 to improve the precision of the measurement.

To gain insights into the system-size dependence of the longitudinal fluctuations, Fig. 3 compares the F_n from the Xe + Xe system with those obtained from the Pb + Pb system at $\sqrt{s_{NN}} = 5.02$ TeV from Ref. [22] as a function of centrality percentile (left column) or N_{part} (right column). For both systems, F_2 shows a strong dependence on centrality percentile and N_{part}, while the F_3 and F_4 each show rather weak dependence. The F_4 values depend weakly on both centrality percentile and N_{part}, and they agree between the two systems. In the noncentral collisions (centrality percentiles $\gtrsim 30\%$ or $N_{\mathrm{part}} \lesssim 80$), the F_2 for the two systems agree only as a function of N_{part}, while the F_3 agree as a function of either centrality percentiles or N_{part}. In the midcentral collisions, F_2 is much larger in Xe + Xe collisions than in Pb + Pb collisions, while an opposite trend is observed for F_3. This reverse system-size ordering between F_2 and F_3 is also observed for A_{ε_2} and A_{ε_3} from Ref. [32], which strongly suggests that the flow decorrelations are driven by longitudinal fluctuations of the eccentricity vector in the initial state. The data are also compared with results from a hydrodynamic model with longitudinal fluctuations included [30,54]. The model quantitatively describes the behavior of F_2 and F_4 in midcentral collisions, but fails to describe the magnitude of F_3 and the splitting between the two systems, pointing to an inadequate description of the initial state and its system-size dependence implemented in this model.

To help further understand the relationship between the transverse harmonic flow and its longitudinal fluctuations, Fig. 4 compares the ratios of flow decorrelation $F_n^{\mathrm{XeXe}}/F_n^{\mathrm{PbPb}}$ (F_n ratios) with ratios of flow harmonics $v_n^{\mathrm{XeXe}}/v_n^{\mathrm{PbPb}}$ (v_n ratios) from Ref. [35] as a function of centrality percentile. While the v_n ratios all decrease with centrality percentile, the F_n ratios increase with centrality percentile; this opposite trend implies that, when the ratio of average flow is larger, the ratio of its relative fluctuations in the longitudinal direction is smaller and vice versa. Beyond this overall opposite trend, there are other contrasting features between the two types of ratios. The F_2 ratio is always above 1, while the v_2 ratio decreases to below 1 around 10%–20% centrality; the F_2 ratio is larger than the v_2 ratio except in the 0%–5% centrality interval, where the v_2 ratio is enhanced due to the deformation of the Xe nucleus [36]. The differences between the F_3 ratio and the v_3 ratio are smaller, but with different centrality dependencies: while the v_3 ratio decreases nearly linearly with centrality percentile, the F_3 ratio first decreases and then increases as a function of centrality percentile. The F_4 ratio has larger uncertainties, but shows much stronger centrality dependence compared with the v_4 ratio.

Figure 4 compares these ratios with hydrodynamic model calculations [30,36,54]. The advantage of comparison in terms of ratios is that the model uncertainties in the initial-state geometry as well as final-state dynamics are expected to partially cancel out. While the calculations from Ref. [36] quantitatively describe the trend of the v_n ratios, they agree less well with the F_n ratios and, in particular, the model [30,54] overestimates the F_2 and F_3 ratios for centrality percentiles beyond 20%–30%. Therefore, these hydrodynamic models fail to describe the longitudinal flow fluctuations and their system-size dependence trends, even though they have been tuned to describe the overall transverse collective dynamics. This failure is likely due to an inadequate description of the longitudinal structure of the initial state in these models. In fact, a recent calculation [32] based on a simple Glauber model with the parametrized longitudinal structure was able to describe simultaneously the system-size dependence of the v_n decorrelation and inclusive v_n, supporting this conjecture. One future direction is to develop a framework based on the three-dimensional initial condition dynamically generated from gluon saturation physics,

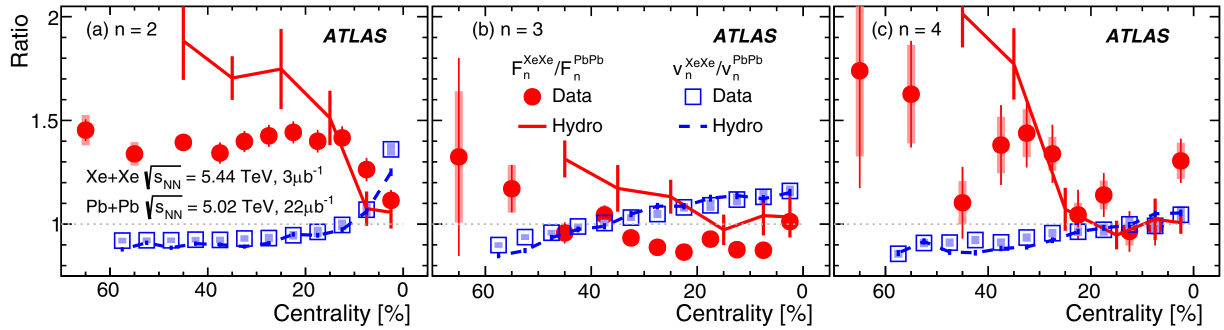

FIG. 4. The ratios $F_n^{\rm XeXe}/F_n^{\rm PbPb}$ from data [22] (solid symbols) and model [30,54] (solid lines) and $v_n^{\rm XeXe}/v_n^{\rm PbPb}$ from data [35] (open symbols) and model [36] (dashed lines) as a function of centrality for (a) $n = 2$, (b) $n = 3$, and (c) $n = 4$, respectively. The error bars and shaded boxes on the data represent statistical and systematic uncertainties, respectively. The vertical error bars on the theory calculations represent the statistical uncertainties.

coupled with a hydrodynamic model [55,56]. The part of $\mathcal{E}_{n-}$ arising from gluon saturation is related to the saturation scale (Q_s) controlled by the overall system size, while that arising from the forward-backward asymmetry is related to the shape of the overlap controlled by the centrality. Therefore, one could fix the Q_s evolution in the Pb + Pb and make predictions in the Xe + Xe system, which will help to separate different initial-state effects. The system-size dependence of the v_n and v_n decorrelation data provides important input to stimulate further theoretical efforts along this direction.

In summary, ATLAS presents the first measurement of longitudinal decorrelations for harmonic flow v_n in Xe + Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV, based on 3 μb^{-1} of data collected at the LHC. The v_n decorrelations are nearly independent of centrality percentile and p_T for $n = 3$ and 4. For $n = 2$, the v_n decorrelations are smallest in midcentral collisions and increases for more-central or more-peripheral collisions, and also depends on p_T. A comparison with Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV shows that the v_2 decorrelation is larger in Xe + Xe collisions than in Pb + Pb collisions in most of the centrality range, while the opposite trend is observed for v_3 decorrelation. This reverse ordering is consistent with the expected behavior of eccentricity decorrelations in the two systems and is not observed for the ratios of v_2 and v_3 between the two systems. Hydrodynamic models are found to describe the ratios of v_n between Xe + Xe and Pb + Pb, but fail to describe most of the magnitudes and trends of the ratios of the v_n decorrelations between Xe + Xe and Pb + Pb. This suggests that current models tuned to describe the transverse dynamics do not describe the longitudinal structure of the initial-state geometry.

Understanding the initial conditions and early time effects is vital for adequate modeling of heavy-ion collisions [57]. System-size dependence of flow decorrelations, together with measurements of the inclusive flow harmonics, provide new insights and an important lever arm to separate effects of the longitudinal structure of the initial state from other early time and late time effects. This measurement gives important input for complete modeling of the three-dimensional initial conditions and space-time dynamics of heavy-ion collisions used in hydrodynamic models.

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