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Longitudinal flow decorrelations in Xe+Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV with the ATLAS detector

The ATLAS Collaboration

The first measurement of longitudinal decorrelations of harmonic flow amplitudes v_n for $n = 2, 3$ and 4 in Xe+Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV is obtained using $3 \mu\text{b}^{-1}$ 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 $\sqrt{s_{\text{NN}}} = 5.02$ TeV, the longitudinal decorrelation signal in mid-central 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. These results provide new insights into the longitudinal structure of the initial-state geometry in heavy-ion collisions.

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 n^{th} -order anisotropy. Extensive studies of v_n and their event-by-event fluctuations in the last decade [4–14] have provided strong constraints on the properties of the QGP and the initial-state geometry [15–20]. Most of these studies, however, assume that the initial condition and dynamic evolution of the QGP are boost-invariant in the longitudinal direction. Recently, LHC experiments made the first observation [21, 22] of “flow decorrelations” in Pb+Pb collisions, which show that, even in a given event, v_n and Φ_n can fluctuate along the longitudinal direction. Hydrodynamic model calculations [23–28] show that such flow decorrelations are driven mostly by primordial longitudinal structure in the initial-state geometry. Testing how flow decorrelations vary with the size of the collision system can improve our knowledge about the early-time dynamics of the QGP.

This Letter investigates the system-size dependence of longitudinal decorrelations of v_2 , v_3 , v_4 by performing measurements in $^{129}\text{Xe}+^{129}\text{Xe}$ collisions and comparing them with $^{208}\text{Pb}+^{208}\text{Pb}$ collisions. Recent measurements [29–31] show that the v_n exhibit modest differences ($< 10\text{--}20\%$) between these two systems as a function of centrality, except in the most central collisions where the difference for v_2 is significantly larger. Model calculations [32, 33] suggest that these differences are compatible with the expected ordering of the initial eccentricities and roles of viscous effects in the two systems. It is of great interest to study whether the relative strength of the v_n decorrelation between the two systems follows that of the inclusive v_n , which should provide insight into the nature of the initial sources responsible for both the transverse harmonic flow and its longitudinal fluctuations.

The measurement is performed using the ATLAS inner detector (ID) and forward calorimeters (FCal) along with the trigger and data acquisition system [34, 35]. The ID measures charged particles over a pseudorapidity¹ range $|\eta| < 2.5$ using a combination of silicon pixel detectors, silicon microstrip detectors (SCT), and a straw-tube transition radiation tracker, all immersed in a 2 T axial magnetic field [36–38]. 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 FCal towers consist of calorimeter cells grouped into regions in $\Delta\eta \times \Delta\phi$ of approximately 0.1×0.1 . The ATLAS trigger system [35] consists of a level-1 (L1) trigger implemented using a combination of dedicated electronics and programmable logic, and a software based high-level trigger.

This analysis uses $3 \mu\text{b}^{-1}$ of $\sqrt{s_{\text{NN}}} = 5.44 \text{ TeV}$ Xe+Xe data collected in 2017. The events are selected by requiring the total transverse energy deposited in the calorimeters over $|\eta| < 4.9$, as estimated in the L1 trigger system, to be larger than 4 GeV. In the offline analysis, the z -position of the primary vertex [39] of each event is required to be within 100 mm of the nominal IP. Events containing more than one inelastic interaction (pileup) 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 fraction of pileup after event selection is estimated to be less than 0.2%. The event centrality classification is based on the $\sum E_T$ in the FCal [40]. A Glauber model [41, 42] is used to determine the mapping between $\sum E_T$ in the FCal and the centrality

¹ 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 $\eta = -\ln \tan(\theta/2)$.

percentiles, as well as to provide an estimate of the average number of participating nucleons, N_{part} , for each centrality interval. This analysis is restricted to the 0–70% centrality percentiles where the L1 trigger is estimated to be fully efficient.

Charged-particle tracks are reconstructed from ionization hits in the ID using a reconstruction procedure developed for tracking in dense environments in proton–proton (pp) collisions, and optimized for heavy-ion collisions [43]. Tracks used in this analysis are required to have transverse momentum (p_T) $0.5 < p_T < 3$ GeV, $|\eta| < 2.4$, at least two pixel hits, a hit in the first pixel layer when one is expected, at least eight SCT hits, and no missing hit in the SCT. In addition, the point of closest approach of the track is required to be within 1 mm of the primary vertex in both the transverse and longitudinal directions. More details of the track selection can be found in Ref. [31]. The range of accepted track p_T is chosen to be the same as used in the previous analysis [22] of Pb+Pb collisions.

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 [44] event generator with the effect of flow added using the procedure described in Ref. [45]. The response of the detector was simulated [46] using GEANT4 [47], and the resulting events are reconstructed with the same algorithms as applied to the data. For $|\eta| < 1$, the efficiency is 60% at low p_T and increases to 73% at higher p_T . For $|\eta| > 1$, the efficiency ranges between 40% and 60% depending on the p_T . The efficiency depends only weakly on the centrality; a change of about 3% over the full centrality range is observed for $p_T < 1$ GeV. The uncertainty in $\epsilon(p_T, \eta)$, which arises mainly from the uncertainty in the detector material budget, varies from 1% to 4% depending on p_T and η . The rate of falsely reconstructed (fake) tracks $f(p_T, \eta)$ is found to be 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 fake rate decreases rapidly for higher p_T values.

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

$$\mathbf{q}_n \equiv \sum_j w_j e^{in\phi_j} / (\sum_j w_j) \quad (1)$$

where the sum runs over charged particles (for the ID) or 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 $d(\eta, \phi)(1 - f(p_T, \eta))/\epsilon(p_T, \eta)$ [48] to correct for tracking performance. The additional factor $d(\eta, \phi)$, derived from the data, corrects for azimuthal nonuniformity of the detector performance in each η interval. The flow vectors $\mathbf{q}_n$ are further corrected by an event-averaged offset, $\mathbf{q}_n - \langle \mathbf{q}_n \rangle$, to account for detector effects.

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

$$r_{n|n}(\eta) = \frac{\langle \mathbf{q}_n(-\eta) \mathbf{q}_n^*(\eta_{\text{ref}}) \rangle}{\langle \mathbf{q}_n(\eta) \mathbf{q}_n^*(\eta_{\text{ref}}) \rangle} = \frac{\langle v_n(-\eta) v_n(\eta_{\text{ref}}) \cos n[\Phi_n(-\eta) - \Phi_n(\eta_{\text{ref}})] \rangle}{\langle v_n(\eta) v_n(\eta_{\text{ref}}) \cos n[\Phi_n(\eta) - \Phi_n(\eta_{\text{ref}})] \rangle}, \quad (2)$$

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, 49]. 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 $\langle \mathbf{q}_n(-\eta) \mathbf{q}_n^*(\eta_{\text{ref}}) \rangle = \langle \mathbf{q}_n(\eta) \mathbf{q}_n^*(-\eta_{\text{ref}}) \rangle$ for a symmetric system, the correlator is further symmetrized to enhance the statistics,

$$r_{n|n}(\eta) = \frac{\langle \mathbf{q}_n(-\eta) \mathbf{q}_n^*(\eta_{\text{ref}}) + \mathbf{q}_n(\eta) \mathbf{q}_n^*(-\eta_{\text{ref}}) \rangle}{\langle \mathbf{q}_n(\eta) \mathbf{q}_n^*(\eta_{\text{ref}}) + \mathbf{q}_n(-\eta) \mathbf{q}_n^*(-\eta_{\text{ref}}) \rangle}.$$

The symmetrization procedure also allows further cancellation of any differences between η and $-\eta$ in the detector performance.

If flow harmonics for two-particle correlation from two different η factorize into single-particle harmonics, i.e. $\langle v_n(\eta_1)v_n(\eta_2) \rangle^2 = \langle v_n(\eta_1)^2 \rangle \langle v_n(\eta_2)^2 \rangle$, 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 parameterized with a linear function, $r_{n|n}(\eta) = 1 - 2F_n\eta$. The slope parameter F_n is obtained via a simple linear-regression [22],

$$F_n = \frac{\sum_i (1 - r_{n|n}(\eta_i))\eta_i}{2 \sum_i \eta_i^2}, \quad (3)$$

where the sum runs over all $r_{n|n}$ data points as a function of η . If $r_{n|n}$ is a linear function in η , the linear-regression is equivalent to a linear fit, but it is well defined even if $r_{n|n}$ has nonlinear behavior.

Systematic uncertainties in $r_{n|n}$ and the slope parameter F_n arise from the uncertainties in the reconstruction and track selection efficiency, the acceptance reweighting procedure and the centrality definition. Most of these enter the analysis through the particle weights in Eq. (1). 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 [31]; the resulting changes are 1–2% for F_2 , 1–4% for F_3 , and 1–9% for F_4 . The uncertainty associated with the efficiency $\epsilon(p_T, \eta)$ is evaluated by varying the tracking efficiency up and down within its uncertainties; the influence is less than 1% for F_n . The effect of reweighting to account for nonuniformity in the detector azimuthal acceptance 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 . In most of the cases, the total systematic uncertainties are smaller than the corresponding statistical uncertainties. Finally, HIJING events with azimuthal anisotropy imposed according to measured v_n but without decorrelations are used to cross-check the detector performance: the q_n are calculated using both the generated and reconstructed tracks, and the resulting correlators are compared and found to be consistent within their statistical uncertainties.

Figure 1 shows the measured $r_{n|n}(\eta)$ for $n = 2, 3$ and 4 in six 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 $4.0 < |\eta_{\text{ref}}| < 4.9$ chosen for $r_{2|2}$ is different from the range $3.2 < |\eta_{\text{ref}}| < 4.9$ used for $r_{3|3}$ and $r_{4|4}$ in order to reduce sensitivity to nonflow correlations; this is further discussed below.

The slope parameter F_n is calculated from $r_{n|n}$ via Eq. (3) and summarized in Figure 2 as a function of centrality percentile. The left panels show the F_n for three $|\eta_{\text{ref}}|$ 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 towards 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 mid-central collisions and therefore is less affected by decorrelations, while it is dominated by fluctuation-driven collision geometries in central and peripheral collisions [25, 26].

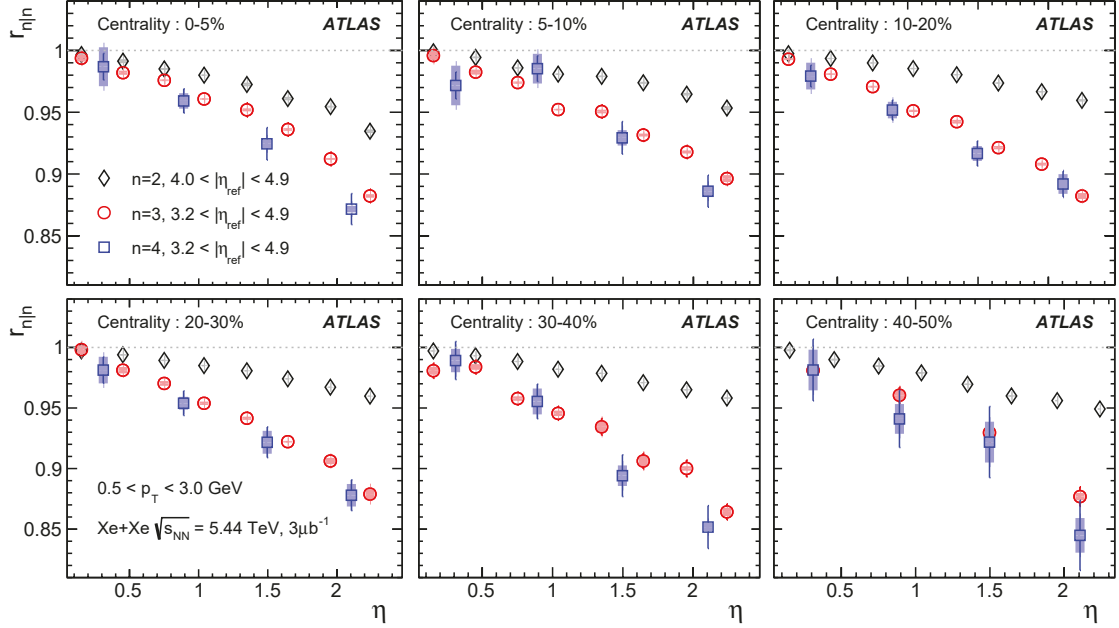


Figure 1: The η dependence of $r_{2|2}$, $r_{3|3}$ and $r_{4|4}$ in Xe+Xe collisions for six centrality intervals. The $|\eta_{\text{ref}}|$ is chosen to be $4.0 < |\eta_{\text{ref}}| < 4.9$ for $r_{2|2}$, and $3.2 < |\eta_{\text{ref}}| < 4.9$ for $r_{3|3}$ and $r_{4|4}$. The error bars and shaded boxes represent statistical and systematic uncertainties, respectively.

Figure 2 also shows that F_2 has sizable variation between various choices of $|\eta_{\text{ref}}|$ or p_T in central and mid-central collisions. The contribution from nonflow correlations associated with back-to-back dijets could bias the decorrelation signal [22, 50]. Since the gap between η and η_{ref} in the denominator of $r_{n|n}$ is smaller than the gap between $-\eta$ and η_{ref} in the numerator, the nonflow contributions from dijets are expected to contribute to the denominator more than the numerator and therefore tend to increase the F_n values. Such nonflow contributions are expected to be larger for smaller $|\eta_{\text{ref}}|$ or larger p_T . However, although the data show a larger F_2 for smaller $|\eta_{\text{ref}}|$ compatible with nonflow, they show a smaller F_2 for larger p_T , opposite to the expectation from nonflow contributions. Within uncertainties, the F_3 and F_4 , as well as the original $r_{3|3}$ and $r_{4|4}$, show no differences between various p_T or $|\eta_{\text{ref}}|$ ranges, suggesting that they are not affected by nonflow. All these trends are qualitatively similar to the previous observations in Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [22]. Based on results in Figure 2, $4.0 < |\eta_{\text{ref}}| < 4.9$ is chosen for F_2 to reduce nonflow, but a wider range $3.2 < |\eta_{\text{ref}}| < 4.9$ 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, Figure 3 compares the F_n from the Xe+Xe system with those obtained from the Pb+Pb system at $\sqrt{s_{\text{NN}}} = 5.02$ TeV from Ref. [22] as a function of centrality percentile (left column) or N_{part} (right column). Since F_n depends only very weakly on $\sqrt{s_{\text{NN}}}$ [22], the 8% difference in $\sqrt{s_{\text{NN}}}$ between the two systems is expected to play negligible role for this comparison. For both systems, F_2 shows a strong dependence on centrality percentile and N_{part} , while F_3 and F_4 each show rather weak dependence. In the noncentral collisions (centrality percentiles $\gtrsim 30\%$ or $N_{\text{part}} \lesssim 80$), the F_2 for the two systems agree only as a function of N_{part} , while F_3 agree as a function of either centrality percentiles or N_{part} . When compared as a function of centrality percentile, both F_2 and F_3 agree in the most central collisions, but they do not agree as a function of N_{part} in the large N_{part} region. In

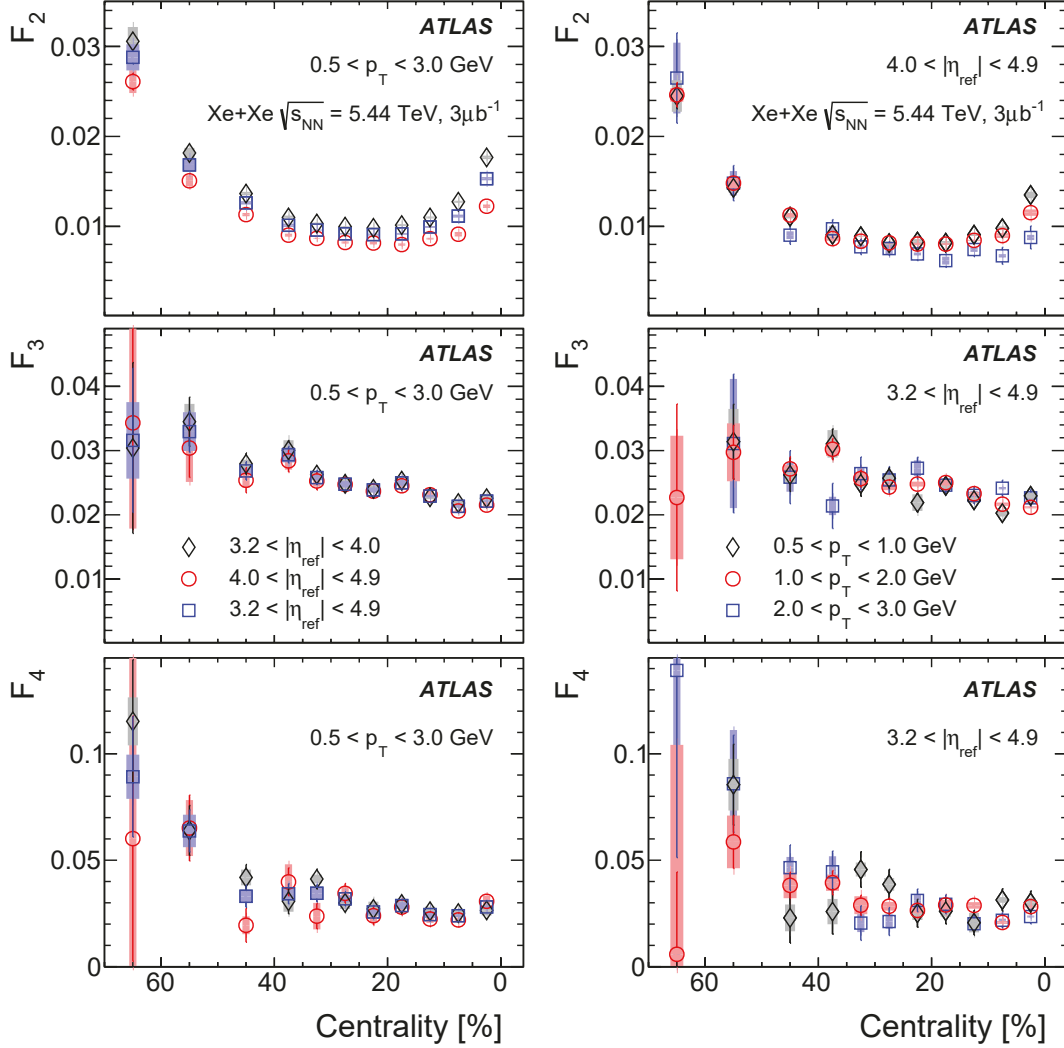


Figure 2: The centrality dependence of F_n calculated for three $|\eta_{\text{ref}}|$ ranges (left) and three p_T ranges (right) for $n = 2$ (top row), $n = 3$ (middle row) and $n = 4$ (bottom row). The error bars and shaded boxes represent statistical and systematic uncertainties, respectively.

the mid-central collisions, F_2 is much larger in Xe+Xe than Pb+Pb collisions, while an opposite trend is observed for F_3 . The F_4 values have rather weak dependence on both centrality percentile and N_{part} , and they agree between the two systems. The data are also compared with results from a hydrodynamic model with longitudinal fluctuations included [51, 52]. This model describes quantitatively the behavior of F_2 and F_4 in mid-central collisions, but fails to describe the magnitude of F_3 and the splitting between the two systems.

To help further understand the relationship between the transverse harmonic flow and its longitudinal fluctuations, Figure 4 compares the ratios of flow decorrelation $F_n^{\text{XeXe}}/F_n^{\text{PbPb}}$ (F_n -ratios) for $0.5 < p_T < 3$ GeV with ratios of flow harmonics $v_n^{\text{XeXe}}/v_n^{\text{PbPb}}$ (v_n -ratios) for $0.5 < p_T < 5$ GeV from Ref. [31] as a function of centrality percentile. While the v_n -ratios all decrease with centrality percentile, the F_n -ratios

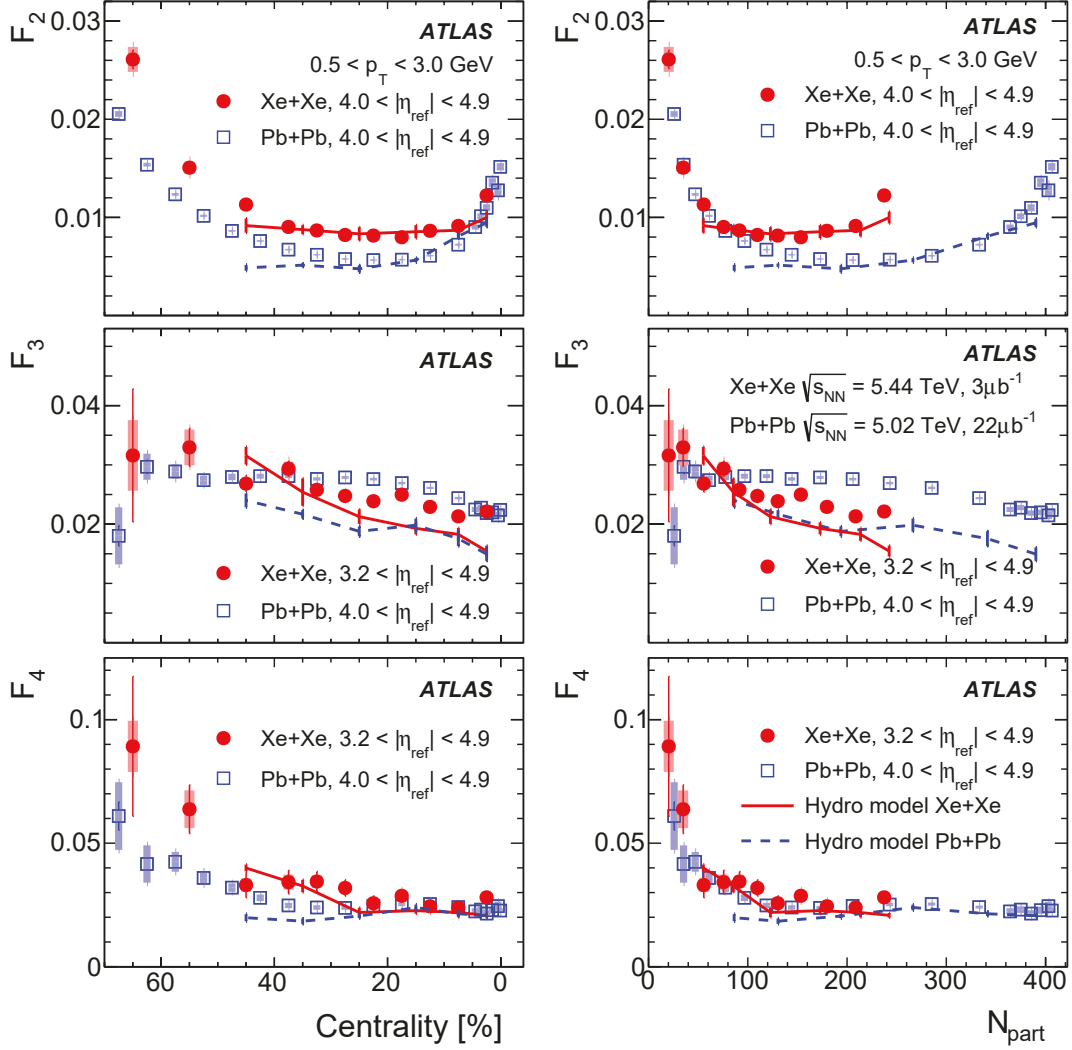


Figure 3: The F_n compared between Xe+Xe and Pb+Pb [22] collisions as a function of centrality percentiles (left) and N_{part} (right) for $n = 2$ (top row), $n = 3$ (middle row) and $n = 4$ (bottom row). The error bars and shaded boxes on the data represent statistical and systematic uncertainties, respectively. The results from a hydrodynamic model [51, 52] are shown as solid lines (Xe+Xe) and dashed lines (Pb+Pb) with the vertical error bars denoting statistical uncertainty of the model predictions.

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 one, while the v_2 -ratio decreases to below one 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 [32]. 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. While

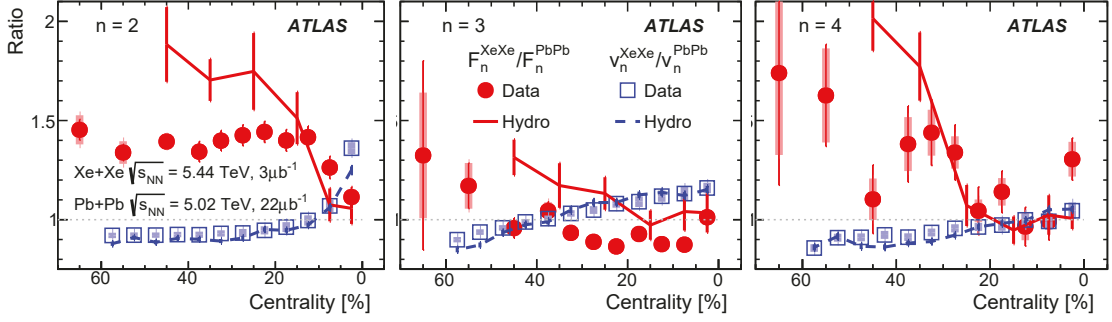


Figure 4: The ratios $F_n^{\text{XeXe}}/F_n^{\text{PbPb}}$ from data [22] (solid symbols) and model [51, 52] (solid lines) and $v_n^{\text{XeXe}}/v_n^{\text{PbPb}}$ from data [31] (open symbols) and model [32] (dashed lines) as a function of centrality for $n = 2$ (left), $n = 3$ (middle panel) and $n = 4$ (right), 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.

the hydrodynamic model from Ref. [32] describes quantitatively the trend of the v_n -ratios, the agreement with the F_n -ratios is worse and in particular the model [51, 52] overestimates the F_2 - and F_3 -ratios for centrality percentiles beyond 20–30%. This comparison suggests that the longitudinal structure of the initial geometry may have a different system-size dependence from its transverse structure.

In summary, ATLAS presents the first measurement of longitudinal decorrelations for harmonic flow amplitudes v_n in Xe+Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV, based on $3 \mu\text{b}^{-1}$ of data collected at the LHC. The decorrelation signal increases approximately linearly as a function of the η separation between the two particles. The slope of this dependence is nearly independent of centrality percentile and p_T for $n = 3$ and 4. For $n = 2$, the effect is smallest in mid-central collisions and increases for more-central or more-peripheral collisions, and the slope also depends on p_T . A comparison with Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV shows that the slope in most of the centrality range is larger in Xe+Xe collisions than in Pb+Pb collisions for $n = 2$, while the opposite trend is observed for $n = 3$. This reverse ordering was not observed for the ratios of v_2 and v_3 harmonic flows between the two collision 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 models tuned to describe the transverse dynamics may not necessarily describe the longitudinal structure of the initial-state geometry. System-size dependence of flow decorrelations provides new insights into the dynamics of v_n in the longitudinal direction. This measurement provides important input for the complete modeling of the three-dimensional initial conditions of heavy-ion collisions used in hydrodynamic models.

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