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Measurements of longitudinal flow decorrelations in pp and Xe+Xe collisions with the ATLAS detector

The ATLAS Collaboration

Measurements of longitudinal flow decorrelations in 13 TeV pp and 5.44 TeV Xe+Xe collisions with the ATLAS detector are presented. The measurements are performed using the two-particle correlation method, combining charged-particle tracks within $|\eta| < 2.5$ with either calorimeter energy clusters or towers within $4.0 < |\eta| < 4.9$. A template-based subtraction procedure is used to remove non-flow effects in both the pp and the Xe+Xe analyses. The dependence of the longitudinal flow decorrelations on the pseudorapidity separation between the particles is characterized via the slope parameter F_n for the elliptic ($n = 2$) and triangular ($n = 3$) harmonic moments. The results are reported as a function of charged-particle multiplicity for the pp and Xe+Xe collision systems. Comparing the data to a color string-based model of the initial geometry indicates that in pp and peripheral Xe+Xe collisions, sub-nucleonic structure and fluctuations in longitudinal energy deposition are needed to describe the data.

Relativistic heavy-ion collisions are understood to create nucleus-sized droplets of quark-gluon plasma (QGP), where the time evolution is well described by nearly inviscid hydrodynamics [1]. This hydrodynamic modeling of collisions of large nuclei has been successfully extended to collisions of smaller nuclei and even proton-proton (pp) collisions [2]. An accurate description requires a quantitative description of the energy deposited at the earliest time of the collision. Conversely, observables sensitive to hydrodynamic behavior also allow one to learn about the nuclear geometry, nucleon fluctuations, and even sub-nucleonic structure.

In the plane transverse to the beams, an anisotropic initial state (resulting from the intrinsic nuclear geometry and fluctuations at the nucleon, sub-nucleon or even gluon field level [3–5]) evolves hydrodynamically to produce an azimuthally anisotropic final state with particle yields characterized by $dN/d\phi \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_n)]$, where the v_n are Fourier moments referred to as flow coefficients, ϕ is the azimuthal angle in the transverse plane [6], and Ψ_n is the n^{th} order event plane. If the deposited energy is boost invariant [7], the Ψ_n and v_n are rapidity independent. However, if the deposited energy is not boost invariant, i.e., not uniform along the beam direction, there may be a rapidity dependence of Ψ_n and v_n, which is referred to as longitudinal flow decorrelation. Numerous works have modeled longitudinal decorrelations and made specific predictions for experimental observables [8–13]. Other calculations, suggesting strong initial-state momentum anisotropies that may carry through to the final state, have a larger longitudinal decorrelation than ones based on longitudinally fluctuating energy deposition [14, 15].

Experiments have measured longitudinal decorrelations in Pb+Pb [16, 17] and Xe+Xe [18] collisions. Calculations based on initial-state color strings, longitudinally extended objects modeling long-range gluon fields [19], such as AMPT [20], yield a longitudinally dependent geometry from the finite length of the strings and qualitatively describe these data [11]. It is crucial to extend these measurements to pp collisions and lower-multiplicity nucleus-nucleus collisions for understanding the role of sub-nucleonic degrees of freedom where their role is expected to dominate.

In this Letter, longitudinal decorrelations are measured in 13 TeV pp and 5.44 TeV Xe+Xe collisions via the comparison of large-rapidity-gap ($\Delta\eta \approx 7$) to small-rapidity-gap ($\Delta\eta \approx 2$) correlations, similar to the previous measurements, which construct correlations between charged-particle tracks around mid rapidity and a reconstructed event-plane angle Ψ_n at very forward rapidity [16–18]. In the case of pp or low-multiplicity heavy-ion collisions, significant *non-flow* correlations, which are not arising from many-body collective motion, such as from jets and particle decays, can mimic a longitudinal decorrelation signal, and must therefore be corrected for [21]. It is also important to explore these effects in previously measured large systems [18]. Here, the two-particle correlation (2PC) method is employed using charged-particle tracks and energy deposits in the forward calorimeter, which then allows the application of non-flow subtraction (NFS) procedures [22–25]. Because the 2PC method is ubiquitous, a detailed understanding of the longitudinal dependence has great practical importance, for example, when comparing results between experiments with different η acceptances [26, 27].

The ATLAS detector [28] is a general-purpose particle detector with a nearly full solid-angle acceptance and many detector subsystems, which makes it well suited for understanding the underlying correlations between particles across a large range in pseudorapidity. The main subsystems used in this measurement are the tracking detectors, a subset of the calorimeter system, and the trigger system.

The inner detector (ID) provides charged-particle tracking within $|\eta| < 2.5$ via a combination of subsystems: a silicon-pixel detector (including the insertable B-layer [29, 30]), a silicon microstrip detector, and a straw-tube transition-radiation tracker.

The calorimeter provides full ϕ coverage within $|\eta| < 4.9$ acceptance. The forward regions, $3.2 < |\eta| < 4.9$, are instrumented with liquid-argon calorimeters (FCals) that include both electromagnetic (EM) and hadronic layers. Sets of FCal cells at similar η-ϕ positions, over its multiple layers, are combined into *towers*. Separately, FCal cells can be clustered in three dimensions into topologically connected clusters [31], referred to as topoclusters, which are more closely associated with single-particle energy depositions than the set of towers. Topoclusters cannot be reconstructed in Xe+Xe collisions due to the high occupancy in the FCal, and hence topoclusters are only reconstructed in pp data. The energy in both the towers and clusters is evaluated at the electromagnetic scale [32].

A two-level trigger system [33] is used to select events. The first trigger level is hardware-based and uses a subset of the detector information to restrict the accepted rate to be below 100 kHz. This is followed by a software-based high-level trigger (HLT) stage, which reduces the accepted event rate to a few kHz, depending on the data-taking conditions. An extensive software suite [34] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

The 13 TeV pp analysis uses 1.7 pb^{-1} of collision data recorded throughout 2015–2018 in which the average number of interactions per a crossing was less than 1.25. The collision data was recorded utilizing a variety of triggers, including minimum bias triggers and triggers enhancing the sample of high-multiplicity events [35]. The $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV Xe+Xe analysis uses 3 μb^{-1} of collision data collected in 2017, with the triggers and offline criteria initially selecting minimum-bias events as described in Ref. [18]. Xe+Xe events were further required to satisfy a reconstructed pseudo-rapidity gap requirement similar to that in Ref. [36] to reject the possible contribution of photo-nuclear processes to low-multiplicity events.

For both the pp and Xe+Xe data, the reconstructed primary vertex [37] is required to be within 100 mm of the center of the detector along the z-axis. In the pp data, events with multiple collisions are suppressed by requiring only one reconstructed vertex. Charged-particle tracks are reconstructed in the ID and must satisfy quality criteria related to the number of hits in different ID layers and their projected distance of closest approach to the primary vertex [38]. Tracks used in the correlation analysis are required to have $|\eta| < 2.5$ and $0.3 < p_{\mathrm{T}} < 5.0$ GeV. However, the reconstructed charged-particle multiplicity, $N_{\mathrm{ch}}^{\mathrm{rec}}$, is defined as the number of tracks with $|\eta| < 2.5$ and $p_{\mathrm{T}} > 0.4$ GeV in the event, to match the definition in previous measurements [18, 39].

The 2PC function measures the relative azimuthal angle between particles of type a and so-called reference particles. The a particles are charged-particle tracks with $0.3 < p_{\mathrm{T}} < 5.0$ GeV, and the correlation function is evaluated as a function of their pseudorapidity, η^a. For pp collisions, the reference particles are topoclusters with $0.5 < E_{\mathrm{T}} < 5.0$ GeV and $4.0 < \eta < 4.9$, as measured in the FCal. For Xe+Xe collisions, FCal towers with $E_{\mathrm{T}} < 5$ GeV and $4.0 < \eta < 4.9$ are utilized. As a component of the NFS in Xe+Xe data, detailed below, 5.02 TeV pp collision data, recorded in 2017, is used which utilizes FCal towers as well. Due to the symmetric nature of the collisions and ATLAS acceptance, each event was also analyzed by swapping the pseudorapidity sign and using the other FCal. The two results are compatible within uncertainties.

The track-topocluster or track-tower pair correlation functions of relative azimuthal angle, $\Delta\phi = \phi^a - \phi^{\mathrm{ref}}$, were constructed for all possible pairs as a function of charged-particle track η^a. Each entry in the distributions was weighted by $1/\varepsilon_{\mathrm{trk}}$, where $\varepsilon_{\mathrm{trk}}$ is the p_{T}- and η-dependent tracking efficiency. The efficiency applied to the pp (Xe+Xe) data was obtained using events generated with Pythia8 [19] (Hijing [40]) and passed through a Geant4 simulation [34, 41] of the ATLAS detector. For the track-tower pairs, there is an additional weighting by the calorimeter tower transverse energy to account for the energy

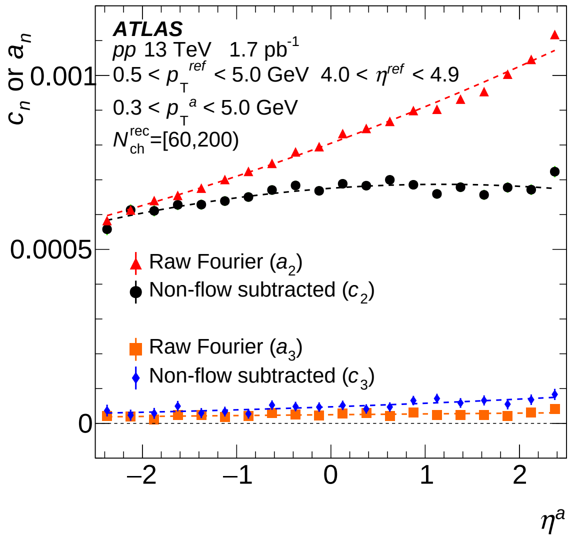

Figure 1: Coefficients a_n and c_n in high-multiplicity 13 TeV pp events for $n = 2, 3$ as a function of track pseudorapidity η^a. The c_n values are obtained from the template fitting method. The dashed lines represent a fit to a quadratic function in η^a for each set of coefficients. The pseudorapidity gap between the cluster and track pair is largest for negative η^a and decreases moving to positive η^a. Only statistical uncertainties are shown.

deposition of particles. As is standard in 2PC analyses [22, 35, 36], the correlation functions were then corrected for the impact of detector non-uniformity through a mixed-event procedure and normalized to a total integral of 2π. The resulting correlation functions, $Y(\Delta\phi, \eta^a)$, were expressed as a Fourier series, $Y = G\left\{1 + 2\sum_{n=1}^{4} a_n(\eta^a)\cos(n\Delta\phi)\right\}$, where the η^a-dependent coefficients a_n are the "raw" Fourier coefficients of order n and G is the normalization factor. An example of the $a_n(\eta^a)$ values in pp collisions is shown in Figure 1.

The contribution of non-flow to the correlation functions was removed using a template-based NFS method [22, 36, 42]. In this method, a low-multiplicity (LM) correlation function is used as a "template" that has a larger non-flow contribution, which then allows the non-flow contribution to be statistically removed from a high-multiplicity (HM) correlation function. To extract the flow coefficients, the template method relies on some assumptions, such as the Fourier a_1 term being completely due to non-flow and the shape of the non-flow correlation not changing with multiplicity. The template method and associated assumptions are standard in flow measurement, and many have been validated in data [22, 23, 26].

In the 13 TeV pp data and the 5.02 TeV pp data (used only as the Xe+Xe LM reference), the LM correlation function is constructed using events with multiplicity $10 \le N_{\mathrm{ch}}^{\mathrm{rec}} < 30$. Each HM correlation function $Y^{\mathrm{HM}}(\Delta\phi)$ was fit with a weighted sum of the analogous LM correlation function, $Y^{\mathrm{LM}}(\Delta\phi)$, and an azimuthally modulated pedestal characterized by a set of flow coefficients c_n, i.e., $Y^{\mathrm{HM}}(\Delta\phi) = w_1 Y^{\mathrm{LM}}(\Delta\phi) + w_2\left(1 + 2\sum_{n=2}^{4} c_n\cos(n\Delta\phi)\right)$, where $w_{1,2}$ are the weight factors. This fitting was performed separately for each η^a selection, resulting in η^a-dependent NFS coefficients $c_n(\eta^a)$, examples of which can also be seen in Figure 1. Example 2PCs for individual η^a bins and their associated template fits can be viewed in the Appendix.

The longitudinal decorrelation effect was measured by fitting the coefficients $c_n(\eta^a)$ and $a_n(\eta^a)$ to the quadratic functional form $A_n\left(1 + F_n \cdot \eta^a + S_n \cdot (\eta^a)^2\right)$, with the following three free parameters: A_n, which accounts for the overall magnitude of the coefficients; F_n, which describes the relative decrease of c_n or a_n with η^a and thus characterizes the linear decorrelation strength; and S_n, which models any higher-order dependence on η^a. Higher order terms $(\eta^a)^n$, i.e., $n > 2$, provide negligible contributions. In previous measurements [16, 18], the decorrelation parameter F_n was defined differently. These definitions are all nearly identical in the limit of small F_n, but the definition used in this Letter is more well-suited for large raw F_n values before NFS, see the Appendix for details.

Figure 1 shows an example of the η^a-dependent correlation coefficients, measured in high-multiplicity ($60 \leq N_{\text{ch}}^{\text{rec}} < 200$) 13 TeV pp collisions. The raw Fourier coefficients a_2 and a_3, which are sensitive to contributions from non-flow effects, decrease in magnitude as the gap between the a particles (tracks) and reference particles (clusters) increases. The correlation coefficient c_2, which has had the NFS procedure applied, shows a weaker variation with track-cluster pseudorapidity separation. The opposite is true for coefficient c_3, which has a stronger variation with separation after NFS. This is a result of contributions from non-flow to a_n, which are of opposite sign for a_2 and a_3. The η^a-dependent differences between the c_n and a_n values highlight the need to account for non-flow effects in the measurement. The results of applying the η^a-dependent fits, used to extract the values of F_n, are also shown and provide a good characterization of the data. Similar examples of correlation coefficients as a function of η^a in Xe+Xe collisions can be viewed in the Appendix.

In the track-tower measurement, since the energy in nearby towers is correlated, a bootstrapping method using pseudo-experiment sampling [43] was used to determine the statistical uncertainties. For both the track-tower and track-topocluster measurements, multiple potential sources of systematic uncertainty were evaluated, with those having a significant impact on the measurement summarized here. The uncertainty associated with the choice of low-multiplicity reference in the template method (nominally $10 \leq N_{\text{ch}}^{\text{rec}} < 30$) was evaluated by using alternative, but partially overlapping, ranges in $N_{\text{ch}}^{\text{rec}}$. The uncertainty in the mixed-event correction procedure was evaluated by changing the required similarity of the mixed events in $N_{\text{ch}}^{\text{rec}}$ and the z-coordinate of the vertex. The sensitivity to the track selection was evaluated by varying the track quality criteria and the reconstruction efficiency ϵ^{trk} by its uncertainty [38]. The sensitivity to the trigger composition in pp data was evaluated by raising the trigger efficiency requirement of 70% to 80%. Different uncertainty sources were dominant in different $N_{\text{ch}}^{\text{rec}}$ ranges, collision systems, and observables, with no single one dominant. For the pp results, the statistical uncertainties are larger than systematic uncertainties in all cases.

Figure 2 presents the longitudinal decorrelation parameters F_n in pp collisions at 13 TeV and Xe+Xe collisions at 5.44 TeV as a function of $N_{\text{ch}}^{\text{rec}}$. The measured F_n values extracted from fits to the correlation coefficients $c_n(\eta^a)$ are shown for $n = 2, 3$, as well as raw values for $n = 1, 2, 3$ obtained from quadratic fits to the Fourier coefficients $a_n(\eta^a)$ before the application of the NFS.

In pp collisions, the raw F_2 values decrease strongly with increasing $N_{\text{ch}}^{\text{rec}}$, reflecting the changing relative contribution from flow and non-flow. With NFS, an $N_{\text{ch}}^{\text{rec}}$-independent $F_2 \approx 0.02$–0.03 is observed. The data also yields a measurement of NFS F_3, which is large and positive at ≈ 0.2. Notably, the effect of NFS is to decrease the F_2 values while increasing those of F_3.

As in pp, the raw F_2 in Xe+Xe decreases strongly with $N_{\text{ch}}^{\text{rec}}$, but with a small increase in the highest $N_{\text{ch}}^{\text{rec}}$ events. These results are similar to the previous measurement performed without NFS [18]. The NFS F_2 values are smaller than the raw ones by more than a factor of three (two) at low $N_{\text{ch}}^{\text{rec}}$ (large $N_{\text{ch}}^{\text{rec}}$), and range from ≈ 0.03 to ≈ 0.005 (note the $\times 2$ applied to the raw Fourier in the left panel of Fig. 2). The measurement of F_3 is less sensitive to the application of NFS, and the resulting values are larger than those for F_2 over most of the multiplicity range.

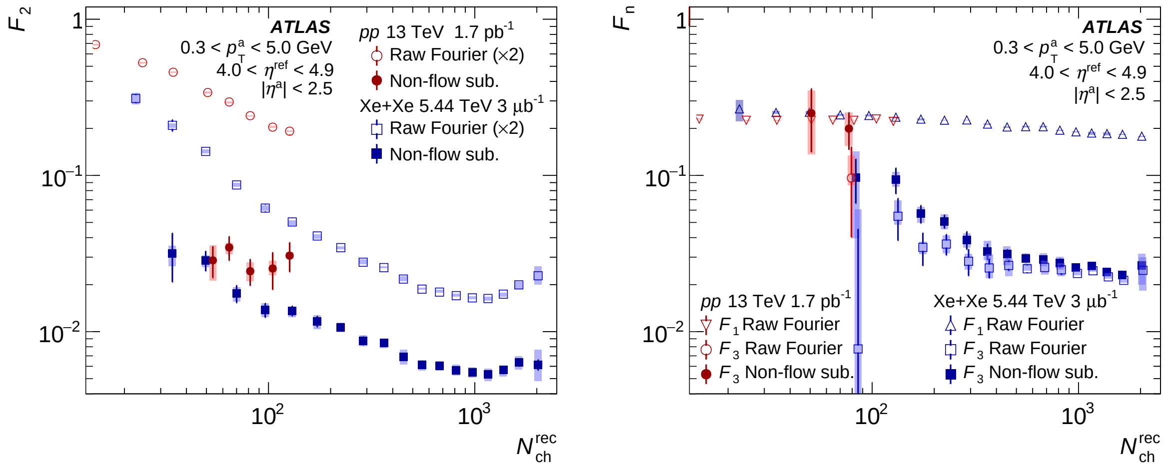

Figure 2: Longitudinal decorrelation parameters F_n for 13 TeV pp (red) and 5.44 TeV Xe+Xe (blue) for $n = 2$ (left) and $n = 1, 3$ (right) as a function of $N_{\mathrm{ch}}^{\mathrm{rec}}$. The parameters are reported after the application of the NFS to the correlation function (solid markers), and those derived from fits to the raw Fourier coefficients (open markers). The statistical (systematic) uncertainties are drawn as vertical lines (shaded boxes). Points with errors exceeding 0.15 are not shown.

Even in the highest $N_{\mathrm{ch}}^{\mathrm{rec}}$ Xe+Xe collisions, there are important non-flow corrections to F_2 and F_3. However, the template fitting method assumes that there is no modification to the non-flow correlation shape as a function of $N_{\mathrm{ch}}^{\mathrm{rec}}$. Jet quenching effects, where partons lose energy in the QGP, are known to suppress the yields of jet-correlated particles and modify their angular distributions [44, 45]. Additionally, the slow change of F_1 with $N_{\mathrm{ch}}^{\mathrm{rec}}$, which reflects only non-flow, may indicate a shape modification or the presence of another source of first harmonic correlations [23, 46]. Further exploration of these possible effects, or other observables less sensitive to non-flow [21], may be required for precision data-model comparisons in this large-$N_{\mathrm{ch}}^{\mathrm{rec}}$ region.

For the template fit to give an unbiased measurement of flow decorrelation, the flow decorrelation in the template and the HM data must be similar, see the Appendix for details. In the case of the pp analysis, the NFS F_2 results are consistent with an $N_{\mathrm{ch}}^{\mathrm{rec}}$-independent flow decorrelation and thus no bias is incurred. However, the Xe+Xe F_2 is not $N_{\mathrm{ch}}^{\mathrm{rec}}$ independent, thus a precise calculation of the possible incurred bias has to be performed. Given a range of possible 5.02 TeV pp F_2 values of 0.00–0.07, this potential bias was determined to be at the 0 to +10% level.

At the lowest multiplicities, $N_{\mathrm{ch}}^{\mathrm{rec}} \approx 30$–$50$, where the Xe+Xe events have a large contribution from single nucleon-nucleon collision configurations, the F_2 values with NFS are similar to those in pp events. At larger multiplicities, the F_2 values remain large in pp collisions but decrease in Xe+Xe collisions, indicating that the mechanism of additional particle production is different in the two systems. These results, along with the lack of $N_{\mathrm{ch}}^{\mathrm{rec}}$ dependence of azimuthal anisotropy in pp collisions [35], suggest that the correlation between the initial-state geometry and overall particle production is different at sub-nucleonic scales than at nucleonic scales. The F_3 results in pp and Xe+Xe collisions are statistically compatible, agreeing with the qualitative picture indicated by the F_2 results.

The data are further compared with calculations from the AMPT model [20] as shown in Fig. 3. AMPT is a kinetic transport model that starts from a full three-dimensional initial state of color strings, evolves partons from those strings, the partons scatter, and finally hadronize via a coalescence prescription. AMPT

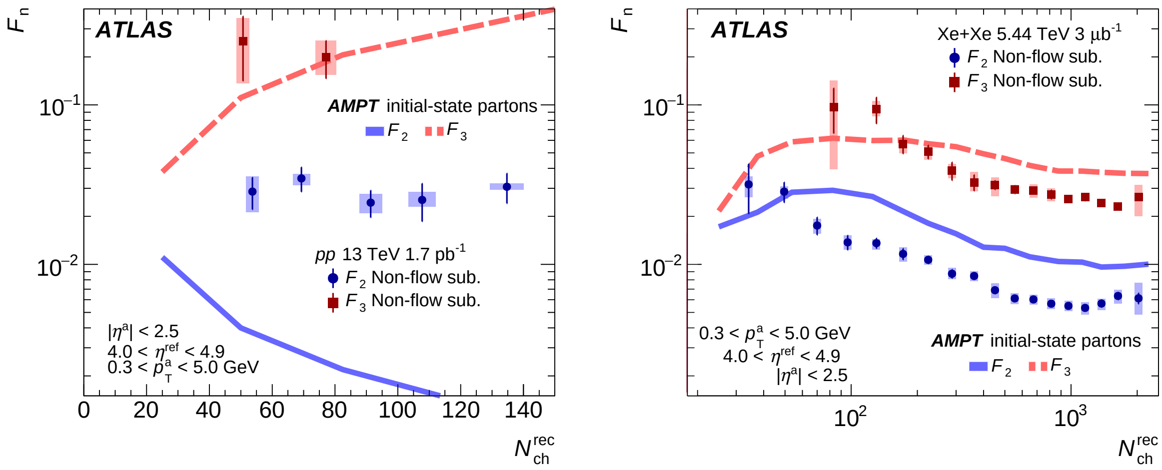

Figure 3: Comparison of AMPT theory calculations to the 13 TeV pp (left) and 5.44 TeV Xe+Xe (right) results. In data, the non-flow subtracted F_n values are shown as a function of N_{ch}^{rec}. The statistical (systematic) uncertainties are drawn as vertical lines (shaded bands).

has been shown to reproduce a broad range of observables related to bulk collectivity in nucleus-nucleus collisions [47]. Since the initial-state geometry in AMPT is known, the F_n parameters can be calculated directly via the decorrelation of the spatial eccentricity vectors [11] as a function of pseudorapidity separation, thus avoiding the non-flow effects introduced by 2PC methods. The spatial eccentricity vectors are calculated from the positions of the partons when they form via the color strings. The AMPT Xe+Xe charged particle multiplicity was scaled by a factor of 0.5, to reproduce the distribution of N_{ch}^{rec} in data. No rescaling was applied to the AMPT pp predictions.

For pp collisions, the simple geometric description in AMPT in terms of two color strings spanning a large longitudinal extent (thus resulting in small F_2) is highly disfavored by the data. In contrast the F_3 is well described and should arise primarily via geometry fluctuations. In the case of Xe+Xe, AMPT shows a qualitative agreement for the multiplicity dependence of $F_{2,3}$, though a factor of two higher than the data for $N_{ch}^{rec} > 250$. Moving to lower N_{ch}^{rec} Xe+Xe collisions, the AMPT $F_{2,3}$ values turn over and begin to decrease, which is not present in the data. This decreasing behavior is likely due to the prevalence of geometries with very few strings, including the single nucleon-nucleon (i.e., pp-like) case.

In conclusion, this paper presents the measurements of longitudinal flow decorrelation parameters F_n in 13 TeV pp and 5.44 TeV Xe+Xe collisions. These results are derived from pseudorapidity-separated two-particle correlations, after the application of a template-based non-flow subtraction. Both the systems feature large decorrelation signals in low-multiplicity events that are N_{ch}^{rec}-independent in pp and decrease with increasing N_{ch}^{rec} in Xe+Xe. The data were compared with the AMPT color-string geometry calculations, which have a good qualitative modeling for the large N_{ch}^{rec} Xe+Xe data but significantly under-predict the decorrelation effects in single nucleon-nucleon collisions, both in the pp collisions and potentially the Xe+Xe collisions. The results when compared with a color string-based model of the initial geometry indicate that in pp and low-multiplicity Xe+Xe collisions, sub-nucleonic structure and fluctuations in longitudinal energy deposition are needed to describe the data. In contrast, high-multiplicity Xe+Xe and Pb+Pb collisions have longitudinal decorrelations reasonably understood in terms of intrinsic nuclear geometry and fluctuating longitudinal energy deposition at the nucleon scale.

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Appendix

Correlation functions and coefficients

Examples of the 2PC functions are shown in Fig. 4 for pp in the left two panels and Xe+Xe in the right two panels for different $N_{\mathrm{ch}}^{\mathrm{rec}}$ selections. In all cases, the ID charged-particle tracks are used as a-type particles and FCal topoclusters (towers) are used as reference particles for pp collisions (Xe+Xe collisions). In all cases, there is peak-like feature centered at $\Delta\Phi = \pi$, which is dominated by contributions from non-flow correlations, specifically dijets, and is well described by the low multiplicity template $Y^{\mathrm{LM}}(\Delta\Phi)$. The residual flow-like correlation after NFS is shown in the lower panels.

The resulting correlation coefficients from the raw Fourier fit and NFS for Xe+Xe collisions in two $N_{\mathrm{ch}}^{\mathrm{rec}}$ ranges are shown in Fig. 5.

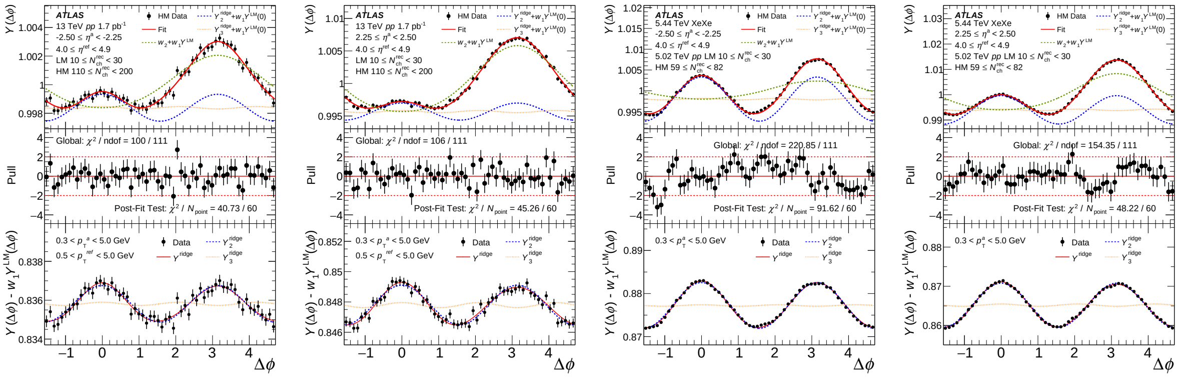

Figure 4: Selected example 2PC template fit results for two η^a intervals in 13 TeV pp collisions (left) and 5.44 TeV Xe+Xe collisions (right). In the top panels, the solid red line shows the total fit to the HM data, shown in black markers. The dashed green line shows the scaled LM reference correlation plus pedestal, while the dashed blue and dotted yellow lines indicate the two flow contributions to the fit, $Y_2^{\text{ridge}} = w_2[1 + 2c_2 \cos(2\Delta\phi)]$ and $Y_3^{\text{ridge}} = w_2[1 + 2c_3 \cos(3\Delta\phi)]$, shifted upwards by $w_1 Y^{\text{LM}}(0)$ for visibility. The middle panels show the pull distribution for the template fits. The global χ^2/ndf is calculated from the simultaneous fit to the HM and LM correlations. The post-fit χ^2/N_{point} is calculated from the pull distribution in the panel. The bottom panels show the same set of data and fit components, where the scaled LM distribution was subtracted from each to better isolate the modulation.

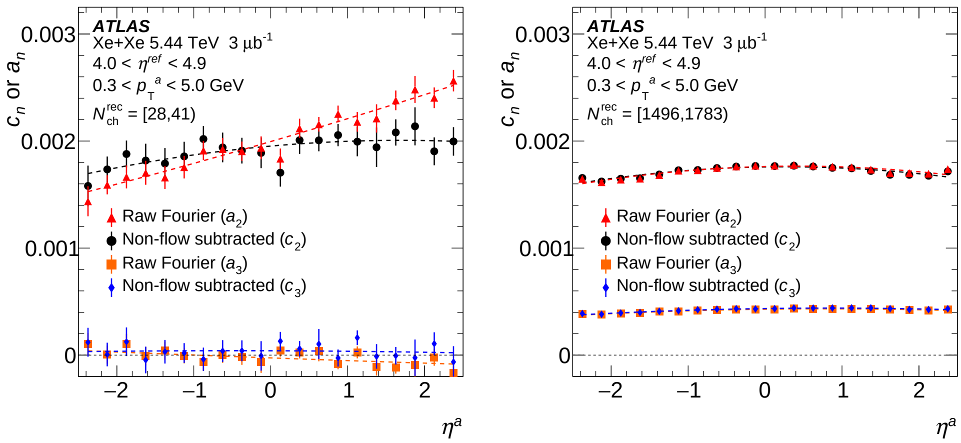

Figure 5: Coefficients a_n and c_n in low-multiplicity (high-multiplicity) 5.44 TeV Xe+Xe events are shown in the left (right) panel, for $n = 2, 3$ as a function of track pseudorapidity η^a. The c_n values are obtained from the template fitting method. The dashed lines represent a fit to a quadratic function in η^a for each set of coefficients. The pseudorapidity gap between the tower and track pair is largest for negative η^a and decreases moving to positive η^a. Only the statistical uncertainties are shown.

Further details on decorrelation extraction

There are two additional details that are important for (i) relating these results to other experimental measurements of longitudinal flow decorrelations and for (ii) understanding potential biases introduced in the template NFS procedure from one of nultiple assumptions.

First, in previous heavy-ion analyses of longitudinal decorrelations [17, 18], a set of specific ratios of correlation coefficients were taken. The r_n ratio as a function of $|\eta^a|$, is defined as

$$r_n(|\eta^a|) = \frac{c_n(-|\eta^a|)}{c_n(|\eta^a|)}, \tag{1}$$

which also applies to coefficient a_n and can be substituted for c_n. If c_n is thought of as $c_n(\eta^a) \propto 1 + F_n\eta^a$, which is the case in this paper, then the above equation yields $r_n(|\eta^a|) \approx 1 - 2F_n|\eta^a| + 2F_n^2|\eta^a|^2$. Thus a fit to $r_n(|\eta^a|)$ with $1 - 2P_0|\eta^a|$ can be used to extract F_n, where $F_n = P_0$. However, if F_n is large, the next higher-order term in $|\eta^a|$ leads to a systematically smaller extracted F_n. The decorrelations measured in large systems in the literature, as well as the coefficients with NFS in this analysis, are sufficiently small that this effect is negligible. In contrast the measured raw Fourier moments in small systems have large non-linear trends with η^a and such a method leads to underestimates of F_n.

Second, the true flow coefficients of the HM correlation, $c_n^{\mathrm{HM}}(\eta^a)$, are not measured directly by the template-based NFS. Rather, the $c_n(\eta^a)$ coefficients are measured and a set of criteria need to be met for these measured coefficients to be exactly equal to $c_n^{\mathrm{HM}}(\eta^a)$. Similarly, when measuring the linear moment of the η^a dependence of $c_n(\eta^a)$ through the methods detailed in this Letter, the resulting, F_n, has a set of criteria that must be fulfilled for this measured flow decorrelation to correspond to the true flow decorrelation in the HM selection F_n^{HM}. These criteria relate to the mid-rapidity flow $c_n^{\mathrm{LM}}|^{\eta^a=0}$ and flow decorrelation F_n^{LM} in the template LM selection. The mathematical representation of the criteria is

$$F_n \approx \frac{c_n^{\mathrm{HM}}|^{\eta^a=0} F_n^{\mathrm{HM}} - w_1 c_n^{\mathrm{LM}}|^{\eta^a=0} F_n^{\mathrm{LM}}}{c_n^{\mathrm{HM}}|^{\eta^a=0} - w_1 c_n^{\mathrm{LM}}|^{\eta^a=0}}. \tag{2}$$

One observes implicitly that if F_n^{LM} and F_n^{HM} are equal, F_n corresponds to the true flow decorrelation in the HM selection. Within uncertainties, this is the case for the F_n results in 13 TeV pp collisions. For the Xe+Xe results, because the extracted F_n values are found to vary with $N_{\mathrm{ch}}^{\mathrm{rec}}$, the above equation can be used to measure the potential bias. Inserting all the parameters and varying F_n^{LM} from 0.0–0.07, the deviation of F_n^{HM} and the reported F_n is found to be 0 to 10% level. Because F_n^{LM} is the true flow decorrelation (after NFS), with the current technique, it is impossible to know what it is because this multiplicity range is used for the NFS itself by definition. Thus the range used to quantify this specific possible bias in the template fitting procedure (0 to 0.07) is arbitrarily chosen to demonstrate that even a large range of possible F_n^{LM} produces systematic effects that are about the size of the uncertainties of the measurement.

Eq. 2 can be derived by starting with Eq. 14 from Ref. [49], introducing a linear dependence of the correlation coefficients on η^a, constructing the r_n ratio from Eq. 2, and setting it equal to $1 - 2F_n$.

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