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Disentangling Sources of Momentum Fluctuations in Xe + Xe and Pb + Pb Collisions with the ATLAS Detector

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High-energy nuclear collisions create a quark-gluon plasma, whose initial condition and subsequent expansion vary from event to event, impacting the distribution of the eventwise average transverse momentum $[P([p_{\mathrm{T}}])]$. Disentangling the contributions from fluctuations in the nuclear overlap size (geometrical component) and other sources at a fixed size (intrinsic component) remains a challenge. This problem is addressed by measuring the mean, variance, and skewness of $P([p_{\mathrm{T}}])$ in ^{208}Pb + ^{208}Pb and ^{129}Xe + ^{129}Xe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 5.44 TeV, respectively, using the ATLAS detector at the LHC. All observables show distinct features in ultracentral collisions, which are explained by a suppression of the geometrical component as the overlap area reaches its maximum. These results demonstrate a new technique to separate geometrical and intrinsic fluctuations, providing constraints on initial conditions and properties of the quark-gluon plasma, such as the speed of sound.

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High energy nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) create a strongly interacting state of matter known as quark-gluon plasma (QGP) [1]. The hydrodynamic expansion of the QGP induces a significant boost to the transverse momentum (p_{T}) of the final-state particles. This boost transforms the initial shape anisotropies and size variations of the QGP into final-state anisotropic flow [2–4] and variations in the eventwise average transverse momentum, $[p_{\mathrm{T}}]$ [5]. Comparisons of anisotropic flow with model calculations have provided crucial insights into the initial conditions, such as the overlap area and nucleonic or subnucleonic fluctuations, as well as transport properties of the QGP, such as shear and bulk viscosities [1,6]. However, quantitative extraction of these properties has significant uncertainties due to limited knowledge about the initial conditions [7,8].

Naturally, progress can be achieved by studying the distribution $P([p_{\mathrm{T}}])$ for events with similar impact parameters. Since the $[p_{\mathrm{T}}]$ is sensitive to the radial expansion or radial flow in each event, $P([p_{\mathrm{T}}])$ provides insights into the initial state, the equation of state, and the associated speed-of-sound squared (c_s^2) in the QGP [9–15]. The distribution $P([p_{\mathrm{T}}])$ can be characterized through its moments: the mean $\langle[p_{\mathrm{T}}]\rangle$, variance $\langle(\delta p_{\mathrm{T}})^2\rangle$, and skewness $\langle(\delta p_{\mathrm{T}})^3\rangle$, where $\delta p_{\mathrm{T}} = [p_{\mathrm{T}}] - \langle[p_{\mathrm{T}}]\rangle$, and "$\langle\,\rangle$" denotes an ensemble average.

Most sources contributing to $P([p_{\mathrm{T}}])$ appear stochastic, including fluctuations in the transverse size R of the overlap region, the positions of nucleons and partons in the initial state, energy deposition, and the temperature of the QGP fluid. These sources can be categorized into "geometrical fluctuations" that reflect the hydrodynamic response to event-by-event variations in R with $\delta p_{\mathrm{T}}/\langle[p_{\mathrm{T}}]\rangle \approx -\delta R/\langle R\rangle$ [5] and "intrinsic fluctuations" that include other sources of δp_{T} at a fixed R [11]. If nuclear collisions are considered as a superposition of independent particle production from participating nucleons, followed by final-state interactions, both geometrical and intrinsic fluctuations are expected to approximately scale with the charged-particle multiplicity (N_{ch}): $\langle(\delta p_{\mathrm{T}})^2\rangle \propto 1/N_{\mathrm{ch}}$ and $\langle(\delta p_{\mathrm{T}})^3\rangle \propto 1/N_{\mathrm{ch}}^2$. This is known as the independent superposition scenario [16,17].

These two components of fluctuations can be investigated using moments of $P([p_{\mathrm{T}}])$ in ultracentral collisions (UCC) [11,12,18]. As the impact parameter approaches zero in UCC, R reaches its maximum value, suppressing geometrical fluctuations and leading to a deviation from the anticipated $1/N_{\mathrm{ch}}$ scaling. In contrast, intrinsic fluctuations continue to follow the expected scaling behavior. This interplay between the geometrical and intrinsic fluctuations gives rise to complex behaviors in the moments of $P([p_{\mathrm{T}}])$. Measurements in UCC can constrain the properties of the intrinsic fluctuations, which are sensitive to c_s^2 [9].

The dependence of the mean and variance of $P([p_{\mathrm{T}}])$ on multiplicity has been measured across various system sizes and collision energies [19–29]. These studies show an increase in $\langle[p_{\mathrm{T}}]\rangle$ toward more central collisions, with the

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variance following the expected power-law scaling. Recently, ALICE reported measurements of skewness and kurtosis in Xe + Xe and Pb + Pb collisions [30], though only within broad multiplicity ranges. CMS performed a detailed study of the behavior of $\langle [p_T] \rangle$ in Pb + Pb UCC, claiming to extract the c_s^2 [31] but with caveats [13–15]. These measurements could not disentangle the geometrical and intrinsic components of $P([p_T])$. To achieve this goal, a precise measurement of higher-order moments in UCC is necessary.

This Letter reports the measurement of the mean, variance, and skewness of $P([p_T])$ as a function of N_{ch} in ^{208}Pb + ^{208}Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and ^{129}Xe + ^{129}Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. A smaller transverse size and multiplicity range in Xe + Xe than Pb + Pb provide a unique opportunity to study the role of system size in the scaling behavior of these moments.

The measurements are performed using the ATLAS inner detector (ID), forward calorimeter (FCal), and zero-degree calorimeters (ZDCs) along with the trigger and data acquisition systems [32–34]. The ID detects charged particles within $|\eta| < 2.5$ [53] using a combination of silicon pixel and microstrip detectors, along with a straw-tube transition-radiation tracker, all immersed in a 2 T axial magnetic field [33]. The FCal consists of three sampling layers, covering $3.2 < |\eta| < 4.9$. The ZDCs are positioned at ±140 m from the interaction point (IP) and detect neutrons with $|\eta| > 8.3$. The ATLAS trigger system [34] consists of a hardware-based level-one (L1) trigger and a software-based high-level trigger. A software suite [35] is used in data simulation, in the reconstruction and analysis of real and simulated data, in the detector operations, and in the trigger and data acquisition systems.

This analysis uses 470 μb^{-1} of Pb + Pb data collected in 2015 and 3 μb^{-1} of Xe + Xe data collected in 2017. Pb + Pb events are selected by requiring the total transverse energy deposited in calorimeters over $|\eta| < 4.9$ at L1 (E_T^{L1}) to exceed 50 GeV. Additionally, dedicated central collision triggers are used to enhance the number of events with large FCal transverse energy [36]. Xe + Xe events are selected by requiring $E_T^{L1} > 4$ GeV.

Charged-particle tracks are reconstructed from hits in the ID using a reconstruction and selection procedure optimized for heavy-ion collisions [37]. Tracks used in this analysis must have $p_T > 0.5$ GeV and $|\eta| < 2.5$, with the total number of such tracks in each event denoted by N_{ch}^{rec}. Events containing multiple inelastic collisions (pileup) are suppressed by exploiting the correlation between N_{ch}^{rec} and the transverse energy measured in the FCal, ΣE_T. The pileup probability is 0.17% in Pb + Pb collisions and a factor of 10 smaller in Xe + Xe collisions. In the Pb + Pb dataset, additional pileup suppression is achieved by exploiting the correlation between the energy deposited in the ZDCs and ΣE_T [38]. The residual pileup fraction is less than 0.01% in central collisions (see Appendix).

Events are categorized into centrality intervals using a Glauber model [39] parametrization of the ΣE_T distribution [36]. Each interval represents a range in ΣE_T, starting at 0% for the most central collisions with the highest ΣE_T value and ending at 80%. In this analysis, events within the top 5% centrality, where observables deviate strongly from power-law scaling, are denoted as UCC. These events correspond to $\Sigma E_T > 3.62$ TeV for Pb + Pb and 2.27 TeV for Xe + Xe collisions, respectively.

The track reconstruction efficiency, $\epsilon(p_T, \eta, N_{ch}^{rec})$, is evaluated using Monte Carlo (MC) simulated events for Pb + Pb and Xe + Xe collisions generated with HIJING [40]. For this evaluation, charged particles are defined according to Ref. [37]. The detector response is simulated using GEANT4 [41,42], and events are reconstructed with the same algorithms used for the data. For charged particles with $p_T > 0.8$ GeV, where the efficiency varies slowly, the efficiency in UCC Pb + Pb collisions ranges from 71% at $\eta \approx 0$ to about 40% for $|\eta| > 2$. The efficiency decreases by 12% from 0.8 to 0.5 GeV, averaged over the full η range. In peripheral collisions, the efficiency is up to 4% higher. The rate of falsely reconstructed ("fake") tracks, $f(p_T, \eta, N_{ch}^{rec})$, is significant for $p_T < 1$ GeV in UCC, ranging from 2% for $|\eta| < 1$ to 8% at larger $|\eta|$. The fake-track rate drops rapidly for higher p_T and more peripheral collisions. Within the N_{ch}^{rec} range covered by UCC events, efficiency drops by 1% with increasing N_{ch}^{rec}, while the fake rate increases by 4%. At the same N_{ch}^{rec}, the efficiency in Xe + Xe is about 2% lower than in Pb + Pb, while fake rates agree within 1%.

The moments of $P([p_T])$ are calculated using computational methods similar to those developed for the anisotropic flow [43,44]. The $[p_T]$ and n-particle correlators in a single event are computed as $[p_T] = \sum_i w_i p_i / \sum_i w_i$, $c_2 = \sum_{i\neq j} w_i w_j \delta p_i \delta p_j / \sum_{i\neq j} w_i w_j$, and $c_3 = \sum_{i\neq j\neq k} w_i w_j w_k \delta p_i \delta p_j \delta p_k / \sum_{i\neq j\neq k} w_i w_j w_k$. Here, $\delta p_i \equiv p_{T,i} - \langle [p_T] \rangle$, and w_i are weights applied to track i to correct for reconstruction efficiency ϵ_i and fake rate f_i: $w_i \equiv (1 - f_i)/\epsilon_i$ [45]. This track-by-track weighting procedure is sufficient since the migrations in η, ϕ, and p_T between the truth and reconstructed tracks are minimal [38]. The nth central moment of the corresponding $P([p_T])$ is obtained by averaging c_n over a given event ensemble in unit N_{ch}^{rec} intervals, denoted as $\langle c_n \rangle = \langle (\delta p_T)^n \rangle$. The N_{ch} is calculated as $N_{ch} = \sum_i w_i$, using tracks in $0.5 < p_T < 5$ GeV and $|\eta| < 2.5$.

The variance and skewness are normalized into dimensionless quantities,

$$k_2 = \frac{\langle c_2 \rangle}{\langle [p_T] \rangle^2}, \qquad k_3 = \frac{\langle c_3 \rangle}{\langle [p_T] \rangle^3},$$
$$\gamma = \frac{\langle c_3 \rangle}{\langle c_2 \rangle^{3/2}}, \qquad \Gamma = \frac{\langle c_3 \rangle \langle [p_T] \rangle}{\langle c_2 \rangle^2}. \tag{1}$$

The "standard skewness" γ corresponds to the skewness for a distribution with unit variance, while Γ is referred to as the "intensive skewness" [46]. Statistical uncertainties for these observables are computed using a Poisson bootstrap method [47]. In the independent superposition scenario, $k_2 \propto 1/N_{\mathrm{ch}}$, $k_3 \propto 1/(N_{\mathrm{ch}})^2$, $\gamma \propto 1/\sqrt{N_{\mathrm{ch}}}$, while Γ should be roughly independent of N_{ch}.

Systematic uncertainties stem from track selection, reconstruction efficiency, residual pileup, centrality definition, and MC consistency check. Their values in the 0%–60% centrality range are summarized as follows. Track selection uncertainties are assessed by comparing nominal results against those obtained under stricter criteria, resulting in deviations of $< 0.5\%$ for $\langle [p_{\mathrm{T}}] \rangle$, 0.5%–3% for k_2, 0%–1.5% for k_3, 0.5%–4% for γ, and 0.5%–1.5% for Γ. Uncertainties in the efficiency, partially due to modeling of the detector material in GEANT4, can be as large as 4% [45]. The impact of the efficiency uncertainties on the measured moments are around 1% for $\langle [p_{\mathrm{T}}] \rangle$, 0.5% for k_2, 2%–2.5% for k_3, 1%–1.5% for γ, and 1.5%–2.5% for Γ. The impact of the azimuthal efficiency variation is assessed by including it in the track weight; no observable changes are found in the results. Residual pileup effects are estimated by adjusting the pileup rejection criteria, leading to uncertainties less than 0.5% for all observables. Centrality definition uncertainties, accessed by varying the Glauber model parameters, are relevant only when results are presented in centrality intervals and are below 0.5% in UCC for all observables.

The HIJING MC samples are used to evaluate the consistency of the $[p_{\mathrm{T}}]$ moments, obtained using truth particles or the reconstructed tracks with the same correction procedures for the real data applied [36,48,54]. This check also accounts for the smearing of measured $[p_{\mathrm{T}}]$ and N_{ch} from the true values. The differences are less than 0.25% for $\langle [p_{\mathrm{T}}] \rangle$ and k_2 and are about 1.2% for k_3, γ, and Γ.

Total systematic uncertainties for each observable are obtained by adding the individual sources in quadrature. Track selection is the dominant source of systematic uncertainty, particularly in midcentral and central collisions. The total uncertainties are less than 1% for $\langle [p_{\mathrm{T}}] \rangle$, 2%–4% for k_2, 2%–5% for k_3, and 2%–4% for γ and Γ in both systems; they are smaller than the statistical uncertainties except for $\langle [p_{\mathrm{T}}] \rangle$. The uncertainty for N_{ch} is dominated by the correction on tracking efficiency and fake tracks and reaches up to 3% in Pb + Pb UCC.

The two-dimensional (2D) distribution of $[p_{\mathrm{T}}]$ versus N_{ch} is shown in Fig. 1(a) for Pb + Pb collisions, whose mean and widths at fixed N_{ch} are indicated by the solid and dashed lines, respectively. The data show a mild increase of the means and a narrowing of the widths with increasing N_{ch}.

Figures 1(b)–1(d) present the measured moments in Pb + Pb and Xe + Xe collisions. An increase of $\langle [p_{\mathrm{T}}] \rangle$ with N_{ch} is observed in peripheral collisions, which weakens in midcentral collisions. The values of k_2 and k_3 show a power-law-like decrease with increasing N_{ch}. In UCC, all three observables deviate sharply from their midcentral trends: $\langle [p_{\mathrm{T}}] \rangle$ increases while k_2 and k_3 decrease toward higher N_{ch} values.

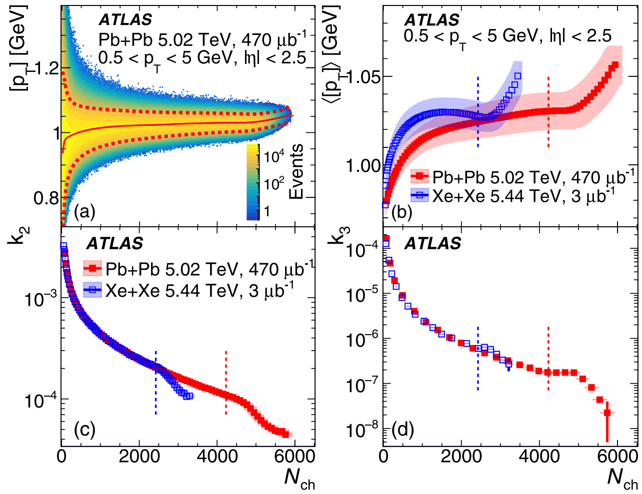

FIG. 1. (a) Depicts the 2D distribution of $[p_{\mathrm{T}}]$ versus N_{ch} in Pb + Pb collisions, where the solid and dashed lines indicate the mean and 2 standard deviations, respectively. (b),(c),(d) The N_{ch} dependence of $\langle [p_{\mathrm{T}}] \rangle$, k_2, and k_3, respectively. The error bars represent statistical uncertainties of the measurement, whereas the shaded boxes represent the systematic uncertainties in both x and y axes. The vertical dashed lines mark the N_{ch} values 4230 and 2425, corresponding to 5% centrality in Pb + Pb and Xe + Xe collisions, respectively.

Figure 2 displays N_{ch} dependence of $(N_{\mathrm{ch}})^{n-1} k_n$ and Γ, which quantify any deviations from the expected power-law scaling behavior. Increases of $N_{\mathrm{ch}} k_2$ and $(N_{\mathrm{ch}})^2 k_3$ with N_{ch}, consistent with the onset of radial flow [49], are observed up to $N_{\mathrm{ch}} \approx 1500$ in Pb + Pb and Xe + Xe collisions. Beyond this range, both observables vary more gradually until the UCC region. Meanwhile, Γ decreases slightly from peripheral to midcentral collisions, remaining flat until the UCC region.

In UCC, $N_{\mathrm{ch}} k_2$ decreases significantly, while $(N_{\mathrm{ch}})^2 k_3$ and Γ show abrupt increases followed by sharp decreases. These nonmonotonic trends are consistent with the expected suppression of the distribution of R, $P(R)$, on the larger R side [11]. This suppression initially leads to a positive skew, which eventually vanishes as the variance of $P(R)$ approaches zero.

To better illustrate these nonmonotonic behaviors in UCC, Fig. 3 presents $\langle [p_{\mathrm{T}}] \rangle$ and the normalized observables from Eq. (1), each scaled by their respective values at 5% centrality. The observables are then plotted as a function of $N_{\mathrm{ch}}/N_{\mathrm{ch}}^{5\%}$, N_{ch} normalized by its value at 5% centrality, allowing for comparing the two systems on a similar scale along the x axis.

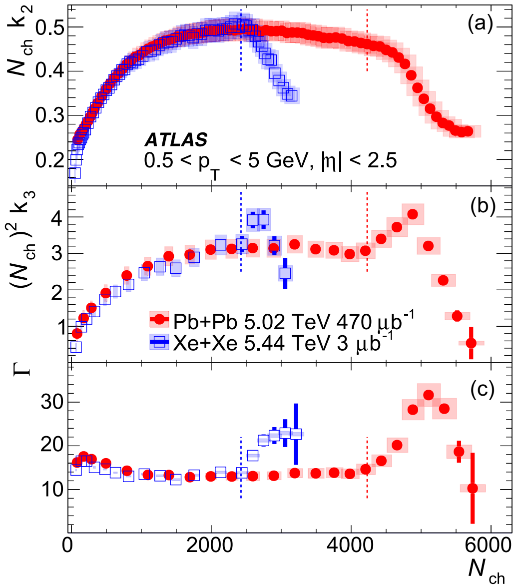

FIG. 2. The values of (a) $N_{\mathrm{ch}}k_2$, (b) $(N_{\mathrm{ch}})^2k_3$, and (c) Γ, as a function of N_{ch} in Pb + Pb and Xe + Xe collisions. The error bars represent the statistical uncertainties of the measurement, whereas the shaded boxes represent the systematic uncertainties of the data along the x and y axes. The vertical dashed lines mark the N_{ch} values corresponding to 5% centrality in Pb + Pb and Xe + Xe collisions, respectively.

Qualitatively similar behaviors are observed across all observables in both systems, though the variations are slightly weaker in Xe + Xe collisions. This outcome is expected: the smaller mass number of Xe compared to Pb

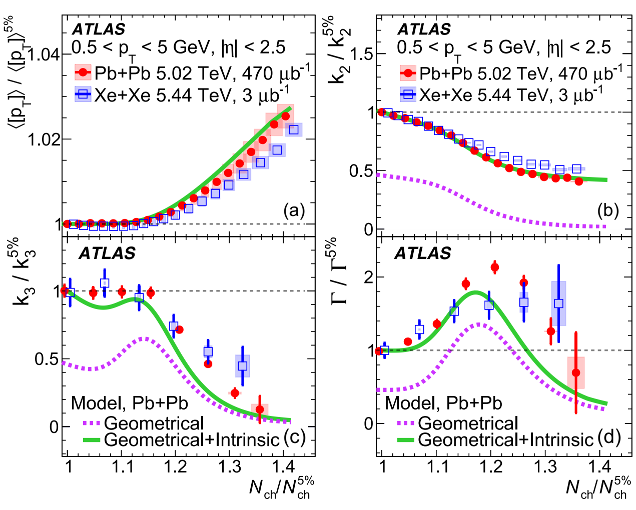

FIG. 3. The (a) $\langle[p_{\mathrm{T}}]\rangle$, (b) k_2, (c) k_3, and (d) Γ, scaled by their values at 5% centrality as a function of $N_{\mathrm{ch}}/N_{\mathrm{ch}}^{5\%}$ in Pb + Pb and Xe + Xe collisions. This scaling partially cancels out systematic uncertainties. The error bars represent statistical uncertainties of the measurement, whereas the shaded boxes represent the systematic uncertainties of the data along the x and y axes. The data are compared to predictions from Ref. [12], where the estimated geometrical component is also shown.

yields a broader distribution of $N_{\mathrm{ch}}/N_{\mathrm{ch}}^{5\%}$ in Xe + Xe collisions. This broader distribution leads to a weaker suppression of the geometrical component, demonstrating the value of comparing data from collisions involving nuclei of different sizes. It is worth noting that the 8% higher $\sqrt{s_{\mathrm{NN}}}$ in Xe + Xe compared to Pb + Pb collisions is estimated to increase N_{ch} only by 2.5% [50], which should have negligible effects on the scaled quantities in Fig. 3.

Recent studies [11,12] have modeled $P([p_{\mathrm{T}}])$ as a 2D Gaussian function of N_{ch} and impact parameter, where the fluctuations of $[p_{\mathrm{T}}]$ at a given N_{ch} are driven solely by the variations in the impact parameter and R. In this model, the increase in $\langle[p_{\mathrm{T}}]\rangle$ arises from enhanced intrinsic fluctuations at fixed R, whereas k_2 arises from both geometrical and intrinsic contributions. The k_3 originates from a geometrical contribution and a cross term between geometrical and intrinsic components, but has no contribution from pure intrinsic component [12]. Figure 3 compares predictions from this model to the Pb + Pb data. The model reasonably captures the increase in $\langle[p_{\mathrm{T}}]\rangle$ and the decrease in k_2. However, the predicted k_3 values decrease more steeply with $N_{\mathrm{ch}}/N_{\mathrm{ch}}^{5\%}$, a trend also observed in Γ. The larger k_3 and Γ values in the data suggest the need for additional sources of skewness in $P([p_{\mathrm{T}}])$ [46]. Most variations in k_2, k_3, and Γ can be largely attributed to the geometrical component, as indicated by the dashed lines. Although the separation into the two components is clearly feasible within a given model framework, a more detailed investigation of the sensitivities to model parameters is still required.

For a more direct study of the correlation between $[p_{\mathrm{T}}]$ and N_{ch} in UCC, a detailed analysis of the 0%–1% most central events is performed. The average values of $[p_{\mathrm{T}}]$ and N_{ch} for these events are denoted as $\langle[p_{\mathrm{T}}]\rangle_{0\%–1\%}$ and $\langle N_{\mathrm{ch}}\rangle_{0\%–1\%}$, respectively. Next, $\langle[p_{\mathrm{T}}]\rangle$ is calculated by averaging $[p_{\mathrm{T}}]$ over events within narrow N_{ch} slices to obtain $\Delta p_{\mathrm{T}}/\langle[p_{\mathrm{T}}]\rangle_{0\%–1\%}$ as a function of $\Delta N_{\mathrm{ch}}/\langle N_{\mathrm{ch}}\rangle_{0\%–1\%}$. Here, $\Delta p_{\mathrm{T}} = \langle[p_{\mathrm{T}}]\rangle - \langle[p_{\mathrm{T}}]\rangle_{0\%–1\%}$ and $\Delta N_{\mathrm{ch}} = N_{\mathrm{ch}} - \langle N_{\mathrm{ch}}\rangle_{0\%–1\%}$. Figure 4 shows $\Delta p_{\mathrm{T}}/\langle[p_{\mathrm{T}}]\rangle_{0\%–1\%}$ plotted against $\Delta N_{\mathrm{ch}}/\langle N_{\mathrm{ch}}\rangle_{0\%–1\%}$ for two p_{T} ranges. A nearly linear relationship is observed, with similar slopes in both systems. However, the slope varies depending on the selected p_{T} range, indicating a kinematic sensitivity to radial flow effects. Compared to Fig. 3, the better consistency between the two systems can be attributed to the more restrictive centrality range used for normalization in both x and y axes.

The Pb + Pb data are compared to two models: the HIJING model [40], which lacks final-state interactions, and the state-of-the-art MUSIC model [51], which incorporates the full hydrodynamic response of the QGP to its initial-state geometry. The HIJING model grossly underpredicts the slope observed in the data, whereas the MUSIC model reproduces the slopes across both p_{T} ranges. This finding indicates that the slopes reflect the hydrodynamic response

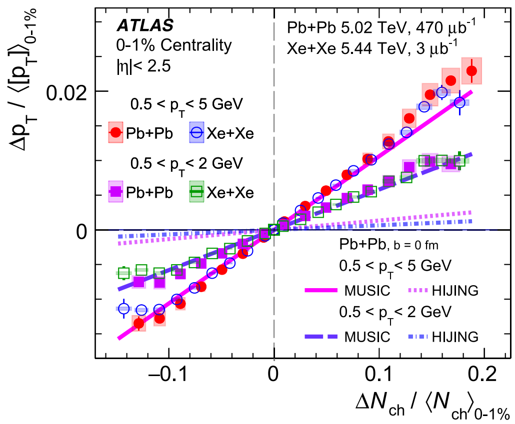

FIG. 4. Correlation between $\Delta p_{\mathrm{T}}/\langle[p_{\mathrm{T}}]\rangle_{0\%-1\%}$ and $\Delta N_{\mathrm{ch}}/\langle N_{\mathrm{ch}}\rangle_{0\%-1\%}$ in the 0%–1% most central Pb + Pb and Xe + Xe collisions for two p_{T} ranges. The error bars represent the statistical uncertainties of the measurement, whereas the shaded boxes represent the systematic uncertainties of the data along the x and y axes. The data are compared to the MUSIC hydrodynamic model with $c_s^2 \approx 0.23$ at $T_{\mathrm{eff}} \approx 222$ MeV and the HIJING model, both at zero impact parameter ($b = 0$ fm) [11].

of the QGP in UCC, where the initial transverse size is fixed, but the energy density varies strongly.

A recent study [10] connected the increase of $[p_{\mathrm{T}}]$ in UCC to the speed of sound of the QGP [9], calculated as $c_s^2(T) = d\ln T/d\ln s$, where T and s are the medium's temperature and entropy density, respectively. Since T evolves throughout the QGP's lifetime, c_s^2 was estimated at an effective temperature T_{eff}, approximately 1/3 of the average p_{T} calculated for all particles [9,10],

$$c_s^2(T_{\mathrm{eff}}) \propto \frac{d\ln(\langle[p_{\mathrm{T}}]\rangle)}{d\ln(N_{\mathrm{ch}})} \approx \frac{\Delta p_{\mathrm{T}}/\langle[p_{\mathrm{T}}]\rangle}{\Delta N_{\mathrm{ch}}/\langle N_{\mathrm{ch}}\rangle}.$$

According to this model, the measured slope in Fig. 4 can be used to estimate $c_s^2(T_{\mathrm{eff}})$. The MUSIC model achieves reasonable agreement with the Pb + Pb data, including its p_{T} dependence, by using $c_s^2 \approx 0.23$ with $T_{\mathrm{eff}} \approx 222$ MeV [9], values consistent with those reported by the CMS Collaboration [31]. However, the extraction of the c_s^2 was shown to be sensitive to several factors, including the kinematic selection of the particles used to define the centrality and $\langle[p_{\mathrm{T}}]\rangle$ [13,15]. Additionally, because the slopes in Fig. 4 are driven by the intrinsic component of $P([p_{\mathrm{T}}])$, which can be independently constrained using the higher-order moments in Fig. 3, it is crucial that any model aiming to extract c_s^2 can describe these observables simultaneously.

Understanding the initial-state geometry of the QGP and how it drives the hydrodynamic response is a key objective in high-energy nuclear physics. This can be pursued by analyzing the moments of event-by-event transverse momentum distribution $P([p_{\mathrm{T}}])$. This Letter presents the first attempt to disentangle geometrical and intrinsic fluctuations by examining the mean, variance, and skewness of $P([p_{\mathrm{T}}])$ in ^{208}Pb + ^{208}Pb and ^{129}Xe + ^{129}Xe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and 5.44 TeV, respectively. Across a wide N_{ch} range, the variance and skewness exhibit an approximate power-law scaling consistent with expectations from an independent superposition scenario. However, in ultracentral collisions, all observables deviate from this scaling: the mean shows a distinctive rise, the variance sharply decreases, and the skewness exhibits an increase followed by a sharp decrease. Moreover, the linear rise in $\langle[p_{\mathrm{T}}]\rangle$ with increasing N_{ch} is reproduced by a hydrodynamic model using $c_s^2 \approx 0.23$ at an effective temperature $T_{\mathrm{eff}} \approx 222$ MeV. The centrality dependence of these observables in ultracentral collisions is slightly weaker in the smaller Xe + Xe collisions, and studies involving even smaller nuclei could probe the system size dependence further. Investigating $[p_{\mathrm{T}}]$ fluctuations offers a valuable tool for constraining the initial-state fluctuations and the hydrodynamic response in heavy-ion collisions.

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[53] ATLAS uses a right-handed coordinate system with its origin at the nominal 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 $\eta = -\ln\tan(\theta/2)$.
[54] Although the $[p_{\rm T}]$ moments in HIJING differ from those in data, this study primarily checks if the analysis procedure applied to real data can reproduce $[p_{\rm T}]$ moments at the truth level.

End Matter

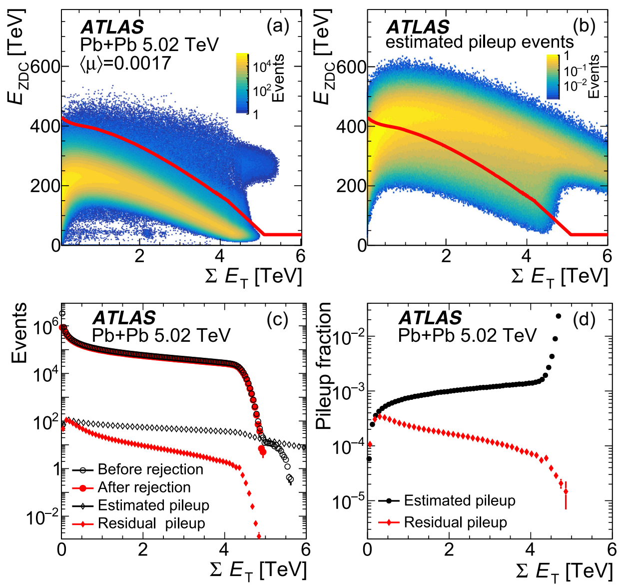

FIG. 5. (a),(c) The distributions of energy deposited in the ZDCs versus FCal for (a) all events and (b) estimated pileup events; the red line represents the line used for selection of good events. (c),(d) As a function $\Sigma E_{\rm T}$, (c) the distributions of all events, pileup events, good events, and residual pileup events and (d) the fraction of pileup events before and after pileup rejection. The results are obtained for 5.02 TeV Pb + Pb collisions.

Appendix—The pileup probability is $\langle\mu\rangle = 0.0017$ in Pb + Pb collisions and 0.00019 in Xe + Xe collisions. Pileup events are not uniformly distributed across $N_{\rm ch}$ and tend to contribute more significantly in UCC. The impact of pileup events can be estimated and rejected using the anticorrelation between ZDC energy ($E_{\rm ZDC}$) and FCal $\Sigma E_{\rm T}$ as shown in Fig. 5(a). A typical pileup event in the UCC region consists of a genuine central event with small $E_{\rm ZDC}$ and large $\Sigma E_{\rm T}$ and a peripheral or midcentral event with large $E_{\rm ZDC}$ and small $\Sigma E_{\rm T}$, contributing to the satellite band. Good events are selected within a 6 standard deviation window from the peak value of $E_{\rm ZDC}$ at a given $\Sigma E_{\rm T}$, as indicated by the red line. Convolving the distribution of good events according to the pileup probability yields an estimate of the pileup event distribution shown in Fig. 5(b).

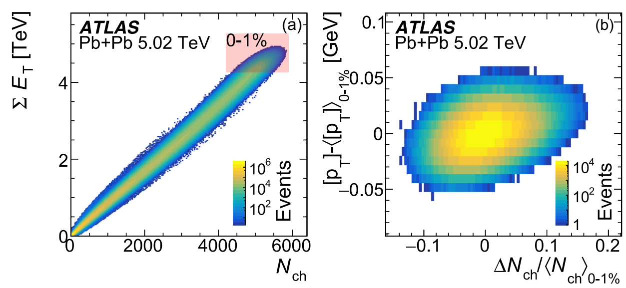

FIG. 6. (a) Correlation between FCal $\Sigma E_{\rm T}$ and $N_{\rm ch}$ in Pb + Pb collisions, where the shaded region covers 0%–1% most central events and (b) correlation between $[p_{\rm T}]$ and $\Delta N_{\rm ch}/\langle N_{\rm ch}\rangle_{0\%-1\%}$.

Figure 5(c) shows the distributions of all events and estimated pileup events as a function of $\Sigma E_{\rm T}$, along with the distributions of good events and residual pileup events after applying the selection criteria. These criteria significantly reduce the pileup contribution, bringing its fraction down to $\lesssim 0.01\%$ in UCC, as shown in Fig. 5(d). The robustness of

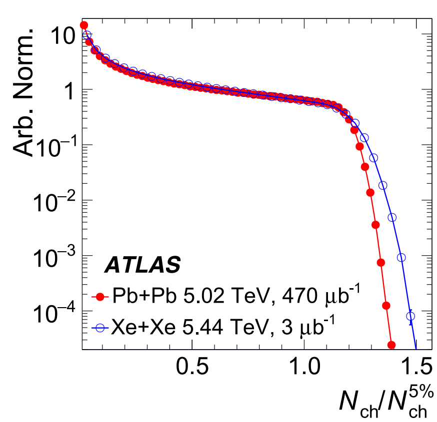

FIG. 7. The distributions of $N_{\rm ch}/N_{\rm ch}^{5\%}$ in Pb + Pb and Xe + Xe collisions.

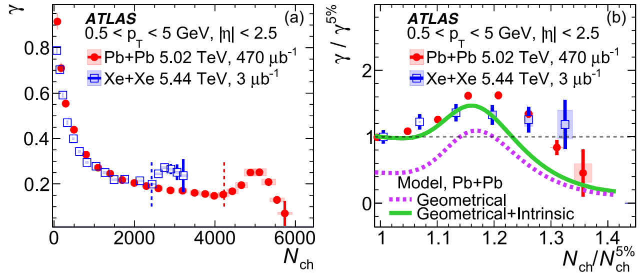

FIG. 8. (a) γ as a function of $N_{\rm ch}$ and (b) scaled γ as a function of $N_{\rm ch}/N_{\rm ch}^{5\%}$ in Pb + Pb and Xe + Xe collisions compared to predictions from Ref. [12]. The error bars and shaded area represent statistical and systematic uncertainties, respectively. The vertical dashed lines in (a) mark the $N_{\rm ch}$ values corresponding to 5% centrality in Pb + Pb and Xe + Xe collisions.

the pileup rejection is tested by relaxing the selection criteria, and the results remain largely insensitive to variations in the residual pileup fraction.

Figure 6(a) shows the correlation between $\Sigma E_{\rm T}$ and $N_{\rm ch}$. The correlation is smeared, implying that the 0%–1% most central events selected based on $\Sigma E_{\rm T}$ span a large range of $N_{\rm ch}$, as indicated by the shaded box. Consequently, the $[p_{\rm T}]$ values for these events also span a large range $\Delta N_{\rm ch}/\langle N_{\rm ch}\rangle_{0\%-1\%}$, as shown by the x axis in Fig. 4.

Figure 7 displays the distribution of $N_{\rm ch}/N_{\rm ch}^{5\%}$ in Pb + Pb and Xe + Xe collisions, showing the distribution is broader in the smaller Xe + Xe system.

Figure 8 displays the multiplicity dependence of γ and scaled γ in the two systems. They can be derived from Figs. 1 and 3, but are shown here for completeness.

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