



System size and energy dependence of the mean transverse momentum fluctuations at the LHC

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Abstract Event-by-event fluctuations of the event-wise mean transverse momentum, $\langle p_T \rangle$, of charged particles produced in proton–proton (pp) collisions at $\sqrt{s} = 5.02$ TeV, Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV, and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are studied using the ALICE detector based on the integral correlator $\langle \Delta p_T \Delta p_T \rangle$. The correlator strength is found to decrease monotonically with increasing produced charged-particle multiplicity measured at midrapidity in all three systems. In Xe–Xe and Pb–Pb collisions, the multiplicity dependence of the correlator deviates significantly from a simple power-law scaling as well as from the predictions of the HIJING and AMPT models. The observed deviation from power-law scaling is expected from transverse radial flow in semicentral to central Xe–Xe and Pb–Pb collisions. In pp collisions, the correlation strength is also studied by classifying the events based on the transverse sphericity, S_0 , of the particle production at midrapidity, used as a proxy for the presence of a pronounced back-to-back jet topology. Low-sphericity (jetty) events feature a larger correlation strength than those with high sphericity (isotropic). The strength and multiplicity dependence of jetty and isotropic events are well reproduced by calculations with the PYTHIA 8 and EPOS LHC models.

1 Introduction

Studies of event-by-event fluctuations of event-wise observables measured in heavy-ion collisions are of great interest given that they probe the phase transition from quark–gluon plasma (QGP) to hadron gas (HG) [1–8]. Of particular interest are fluctuations of the average transverse momentum (p_T) of particles measured event-by-event in a specific kinematic range. These fluctuations are expected to be sensitive to energy fluctuations and, arguably, temperature variations of the matter produced in these collisions. In turn, the magnitude of these fluctuations is nominally proportional to

the heat capacity of the hot medium, which is governed by the strong force as described by quantum chromodynamics (QCD) [9, 10]. As such, the temperature fluctuations are predicted to sharply increase in the vicinity of the critical point and near a cross-over phase transition boundary, as a result of a rapid change in the heat capacity of the medium near this boundary [9]. Fluctuations of the mean p_T , $\langle p_T \rangle$, are also highly sensitive to the presence of collective effects and the onset of thermalization in small systems. Measurements of $\langle p_T \rangle$ fluctuations are thus of great interest in the study of the hot and dense matter produced in heavy-ion collisions [3–5].

A significant number of measurements of $\langle p_T \rangle$ fluctuations have already been carried out at SPS [11–14] as well as at RHIC energies [15–22] based on a variety of observables. Traditionally, the measurement of $\langle p_T \rangle$ fluctuations is carried out in terms of the two-particle correlator, $\langle \Delta p_T \Delta p_T \rangle$, which measures the particle momentum correlations based on deviates of p_T relative to $\langle p_T \rangle$ (discussed in Sect. 2). The ALICE Collaboration reported a measurement in Pb–Pb collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 2.76$ TeV [23] using the $\langle \Delta p_T \Delta p_T \rangle$ correlator. These prior measurements identified the presence of finite dynamical fluctuations corresponding to non-vanishing $\langle \Delta p_T \Delta p_T \rangle$ correlations and additionally studied the evolution of the strength of the correlator with collision centrality. The interpretation of the observed fluctuations in terms of temperature fluctuations is, however, challenged by various considerations which are discussed below.

In small collision systems, one expects that the magnitude of the correlator $\langle \Delta p_T \Delta p_T \rangle$ should be primarily determined by elementary particle production processes such as string fragmentation, hadronic resonance decays, and jets. The overall correlation strength measured in small collision systems should thus depend on the relative abundance of these processes and the relative strengths of the correlator for each of these processes. Correlations in large collision systems, on the other hand, should additionally depend on the number of individual nucleon–nucleon (or parton–parton) collisions and whether these produce collective phenomena

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or feature rescatterings of the particles they produce. For collisions involving independent nucleon–nucleon collisions, one expects that the strength of the correlator should evolve in inverse proportion to the number of sources of correlated particles, which is generally expected in a dilution scenario. The dilution results from the superposition of approximately independent particle-emitting sources, i.e., independent nucleon–nucleon collisions with no rescatterings of secondaries [24,25]. This translates into an inverse dependence of the magnitude of the correlator on the average density of charged particles, $\langle dN_{\text{ch}}/d\eta \rangle$, produced in a given interval of collision centrality and pseudorapidity (η). Although prior observations of $\langle\langle\Delta p_T \Delta p_T\rangle\rangle$ at RHIC and LHC have shown that the magnitude of this correlator decreases monotonically from peripheral to central collisions, a sizable deviation from the $\langle dN_{\text{ch}}/d\eta \rangle$ scaling behavior was observed in semicentral to central collisions of large systems [17,23,26]. Fluctuations of the system energy (temperature) can evidently contribute to additional transverse momentum fluctuations and to a relative increase of $\langle\langle\Delta p_T \Delta p_T\rangle\rangle$, but a number of other mechanisms could potentially also explain the observed behavior. These include the onset of collectivity and thermalization [27,28], string percolation [29], as well as initial-state energy density fluctuations [30–32]. Among these, the role of radial flow, well established from measurements of single-particle p_T distributions, may explain much of the deviation from inverse density scaling [27]. However, whether this deviation can be understood quantitatively on the basis of the aforementioned scenarios remains an open question. It is thus of interest to compare the collision centrality dependence of $\langle\langle\Delta p_T \Delta p_T\rangle\rangle$ observed in large collision systems with that found in elementary proton–proton (pp) collisions. As stated above, in nucleus–nucleus (A–A) collisions, one expects that the scaling is primarily driven by the number of (binary) nucleon–nucleon (or possibly parton–parton) interactions resulting in an approximate linear scaling with the total produced multiplicity density. Such scaling is seemingly not expected in pp collisions, but one can nonetheless expect that the magnitude of $\langle\langle\Delta p_T \Delta p_T\rangle\rangle$ should evolve with the number of underlying correlated sources, whether these arise from string fragmentation, jet production, or multipartonic interactions. One must then examine in detail how the strength of $\langle\langle\Delta p_T \Delta p_T\rangle\rangle$ evolves with the particle density in both heavy-ion and pp collisions. Additionally, since stronger correlations are expected from the collimated particle production arising from the hadronization of jets, it is also of interest to compare the strength of the correlator in pp collisions by separating events with a pronounced back-to-back jet topology from events featuring approximately transversely isotropic particle distributions. This particular study is performed based on the transverse sphericity variable known to be sensitive to the transverse

event shape [33–35], which gives information on how the particles are distributed perpendicularly to the collision axis.

This paper presents measurements of event-by-event fluctuations of the event-wise mean transverse momentum, $\langle p_T \rangle$, of charged particles produced in pp collisions at $\sqrt{s} = 5.02$ TeV, Xe–Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV, and Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV as a function of charged-particle multiplicity recorded using the ALICE detector at the LHC. The primary goal of the measurements is to examine how the strength of the $\langle\langle\Delta p_T \Delta p_T\rangle\rangle$ correlator evolves with the collision energy by comparing to previous results from Pb–Pb collisions at $\sqrt{s} = 2.76$ TeV and the collision system size, and determine whether this evolution can be understood quantitatively based on existing models. Additionally, since the presence of jet constituents is likely to influence the magnitude of the measured correlations, particularly in small collision systems, this work also includes an analysis of the strength of the $\langle\langle\Delta p_T \Delta p_T\rangle\rangle$ correlator in pp collisions based on the transverse shape of events (discussed in Sect. 2.3).

The paper is organized as follows: Sect. 2 presents a summary of the techniques used to evaluate the transverse momentum correlator $\langle\langle\Delta p_T \Delta p_T\rangle\rangle$ and derived quantities used in this work. It also includes a short discussion of the definition and techniques used towards measurements of the evolution of the $\langle\langle\Delta p_T \Delta p_T\rangle\rangle$ correlation strength with the transverse event shape in pp collisions. Details of the experimental methods and techniques used to determine systematic uncertainties are discussed in Sect. 3. The main results are presented in Sect. 4 and compared with those of previous measurements and model predictions. The paper is concluded with a summary in Sect. 5.

2 Observable definitions

The formal definition of the $\langle\langle\Delta p_T \Delta p_T\rangle\rangle$ correlator in terms of two-particle density is introduced in Sect. 2.1. In this work, $\langle\langle\Delta p_T \Delta p_T\rangle\rangle$ is measured based on an event-wise estimator and the method of moments presented in Sect. 2.2. The transverse sphericity estimator is defined in Sect. 2.3.

2.1 Definition of $\langle\langle\Delta p_T \Delta p_T\rangle\rangle$

Nominally, studies of average p_T fluctuations are carried out based on the integral correlator $\langle\langle\Delta p_{T1} \Delta p_{T2}\rangle\rangle$ (see Refs. [27, 36, 37]) defined according to the following formula

$$\langle\langle\Delta p_{T1} \Delta p_{T2}\rangle\rangle \equiv \frac{\int \rho_2(p_{T1}, p_{T2}) \Delta p_{T1} \Delta p_{T2} dp_{T1} dp_{T2}}{\int \rho_2(p_{T1}, p_{T2}) dp_{T1} dp_{T2}}, \quad (1)$$

where $\rho_2(p_{T1}, p_{T2})$ represents a two-particle density. This function is expressed in terms of the transverse momenta p_{T1} and p_{T2} of two particles.

The term $\Delta p_{Ti} = p_{Ti} - \langle p_T \rangle$, where $i = 1, 2$, represents the transverse momentum deviates of particles 1 and 2, of a given pair, relative to the inclusive average $\langle p_T \rangle$. The inclusive average $\langle p_T \rangle$ is defined according to

$$\langle p_T \rangle \equiv \frac{\int \rho_1(p_T) p_T dp_T}{\int \rho_1(p_T) dp_T}, \quad (2)$$

in which $\rho_1(p_T)$ is the inclusive single-particle density.

2.2 Measurement method

The measurements of $\langle \Delta p_{T1} \Delta p_{T2} \rangle$ are obtained based on an event-wise statistical estimator [23, 37, 38] defined according to

$$\langle \Delta p_{T1} \Delta p_{T2} \rangle = \left\langle \frac{\sum_{i,j=1; i \neq j}^{N_{ch}} (p_{Ti} - \langle p_T \rangle)(p_{Tj} - \langle p_T \rangle)}{N_{ch}(N_{ch} - 1)} \right\rangle, \quad (3)$$

with the event-wise average transverse momentum

$$\langle p_T \rangle = \frac{1}{N_{ch}} \sum_{i=1}^{N_{ch}} p_{Ti}. \quad (4)$$

In these equations, N_{ch} represents the total number of charged particles measured within a single event, and $p_{T,i}$ and $p_{T,j}$ denote the transverse momenta of the i th and j th particles, respectively, with $i, j = 1, \dots, N_{ch}$, and $i \neq j$ to avoid self-correlations. The average is said to be an event-wise average because the sum of the product of deviates is divided by the number of pairs of particles in each event. The angle bracket, $\langle O \rangle$, represents the average of the event-wise observable $\langle O \rangle$ computed over an event ensemble of interest. In this analysis, values of the correlator $\langle \Delta p_{T1} \Delta p_{T2} \rangle$ were determined for minimum bias event samples and for specific classes of the events selected based on their charged-particle multiplicity measured in forward and backward detectors (see Sect. 3). Additionally, the pp collisions were categorized into event subsets based on a measurement of their transverse sphericity defined in Sect. 2.3.

Computationally, it is advantageous to reformulate the analysis of $\langle \Delta p_{T1} \Delta p_{T2} \rangle$ with the introduction of an event-wise variable Q_n defined according to

$$Q_n = \sum_{i=1}^{N_{ch}} (p_{Ti})^n, \quad (5)$$

where p_{Ti} represents the transverse momentum of particles, $i = 1, \dots, N_{ch}$, used in the measurement of $\langle \Delta p_{T1} \Delta p_{T2} \rangle$. One verifies that $\langle \Delta p_{T1} \Delta p_{T2} \rangle$ can be readily computed,

according to [39], as

$$\langle \Delta p_{T1} \Delta p_{T2} \rangle = \left\langle \frac{(Q_1)^2 - Q_2}{N_{ch}(N_{ch} - 1)} \right\rangle - \left\langle \frac{Q_1}{N_{ch}} \right\rangle^2. \quad (6)$$

This analytic approach [39] simplifies the computations, thus significantly reducing the analysis time, especially in high-multiplicity events. In order to study the particle-density dependence of the correlator and minimize smearing effects associated with broad bin widths, the analysis is performed in narrow intervals of the charged-particle multiplicity detected at forward rapidity (i.e., the forward detector acceptance as described in Sect. 3).

In the absence of particle correlations, i.e., for purely Poissonian fluctuations of the event-wise $\langle p_T \rangle$, the correlator $\langle \Delta p_{T1} \Delta p_{T2} \rangle$ vanishes. However, it acquires a finite value, either positive or negative, when the transverse momenta of the produced particles are correlated. Note that both the numerator and the denominator of $\langle \Delta p_{T1} \Delta p_{T2} \rangle$ are proportional to the square of the particle detection efficiency making $\langle \Delta p_{T1} \Delta p_{T2} \rangle$ robust against particle losses [23], i.e., efficiencies approximately cancel out in measurements of $\langle \Delta p_{T1} \Delta p_{T2} \rangle$. However, the cancellation is not perfect, particularly if the detection efficiency depends on the p_T of particles.

The $\langle \Delta p_{T1} \Delta p_{T2} \rangle$ correlator measures particle momentum correlations based on deviates relative to the mean momentum. In heavy-ion collisions, the mean momentum is known to depend in part on collective effects and more particularly, radial flow [40]. One thus expects $\langle \Delta p_{T1} \Delta p_{T2} \rangle$ to depend on the magnitude of radial flow. This dependence can be largely suppressed by formulating the results in terms of the dimensionless quantity $\sqrt{\langle \Delta p_{T1} \Delta p_{T2} \rangle} / \langle p_T \rangle$, indicated as the normalized transverse momentum correlator. The use of a dimensionless observable features a number of additional advantages: independence from uncertainties on the momentum scale, partial independence from the magnitude of $\langle p_T \rangle$, and further reduction of sensitivity to the dependence of the particle detection and reconstruction efficiency on the transverse momentum [23]. The results reported here are thus presented in terms of $\sqrt{\langle \Delta p_{T1} \Delta p_{T2} \rangle} / \langle p_T \rangle$, in lieu of $\langle \Delta p_{T1} \Delta p_{T2} \rangle$. Note that at variance with prior notations [17], the double bracket notation is used to clearly denote that the correlator is measured as an event ensemble average of the average pair-wise $\Delta p_T \Delta p_T$ measured event-by-event. The measurement carried out in this work is otherwise equivalent to those reported earlier in Ref. [23].

2.3 Definition of the transverse sphericity

In small collision systems, particularly in pp collisions, the many specific processes contributing to particle production have varying (fluctuating) contributions from one collision to another. Some collisions may thus feature sizable con-

tributions from minijets (created by hard QCD scatterings at intermediate p_T) or jets, while other may be dominated by “soft” multipartonic interactions. Given that, on average, these processes feature different momentum scales and produced multiplicities, it is of interest to examine the relative role they play in influencing the strength of the $\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle$ correlator. This is accomplished by further classifying pp collisions based on their transverse shape estimated with the transverse sphericity observable, S_0 [41].

The observable, S_0 , is defined according to

$$S_0 = \frac{\pi^2}{4} \min_{\hat{n}=(n_x, n_y, 0)} \left(\frac{\sum_{i=1}^{N_{\text{ch}}} \hat{p}_{T_i} \times \hat{n}}{\sum_{i=1}^{N_{\text{ch}}} \hat{p}_{T_i}} \right)^2, \quad (7)$$

where $\hat{p}_{T_i}$ represents transverse momentum unit vectors. The orientation of $\hat{n}$, a two-dimensional unit vector of momentum in the transverse (xy) plane, perpendicular to the beam axis, is chosen such that S_0 is minimized on an event-by-event basis. By construction, S_0 ranges from 0 for pencil-like (jetty) events to a maximum of 1 for circularly symmetric events in the transverse plane, i.e., transversely isotropic events. In this analysis, the p_T -unweighted definition of transverse sphericity ($p_T = 1$), already employed in prior ALICE works [41], is used to quantify the event topology in the transverse plane because it reduces biases otherwise introduced with the original sphericity definition [34].

3 Data analysis

The data samples used in this analysis were collected by the ALICE experiment during the data-taking periods with pp collisions at $\sqrt{s} = 5.02$ and 13 TeV in 2015, Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV in 2015, and Xe–Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV in 2017. The data were acquired with a minimum bias trigger requiring coincident signals in the two scintillator arrays of the V0 detector covering forward ($V0A$, $2.8 < \eta < 5.1$) and backward ($V0C$, $-3.7 < \eta < -1.7$) pseudorapidity intervals. The V0 detector helps to reject the beam-induced background via V0 timing cuts. Detailed descriptions of the ALICE detectors, its components, and their performance, have been reported in Refs. [42, 43].

Charged-particle multiplicities measured with the V0 detectors were additionally used to divide the measured datasets into several multiplicity classes expressed as percentiles of the total hadronic cross section: eleven in Pb–Pb [44] and Xe–Xe [45] collisions, and nine in pp collisions. These classes were used to characterize the $\langle p_T \rangle$ fluctuations with respect to the produced charged-particle multiplicity in pp collisions. In heavy-ion collisions, the charged-particle multiplicity is related to the impact parameter, which is the

distance in the transverse plane between the centers of the colliding nuclei, of Xe–Xe and Pb–Pb collisions.

Measurements of $\langle p_T \rangle$ fluctuations were based on charged-particle tracks reconstructed with the ITS and the Time Projection Chamber (TPC). The analysis was further restricted to particles emitted within the pseudorapidity range $|\eta| < 0.8$ and the transverse momentum range $0.15 < p_T < 2$ GeV/ c . The selection on p_T is designed to focus the analysis of soft particle production in the “bulk” while minimizing contributions from the fragmentation of jets. The pseudorapidity range is selected to ensure uniform particle detection efficiency.

The events with a reconstructed primary vertex within 10 cm of the nominal interaction point along the beam direction ($|V_z| < 10$ cm) are chosen to ensure uniform acceptance in pseudorapidity in $|\eta| < 0.8$ for the ITS. Additionally, events were considered in the analysis if at least one accepted charged particle contributed to the reconstruction of the primary vertex. Furthermore, events featuring more than one reconstructed primary interaction vertex were rejected to suppress the possibility of event pile-up. In all, 13 million, 1.4 million, and 104 million events passed the above criteria and were retained towards the analysis of $\langle p_T \rangle$ fluctuations from Pb–Pb, Xe–Xe, and pp ($\sqrt{s} = 5.02$ TeV) collisions, respectively.

Individual charged-particle tracks were also subjected to track-quality selection criteria and to specific selections to limit the analysis to primary particles, i.e., particles with a mean proper lifetime τ larger than 1 cm/ c , which are either produced directly in the interaction, or from decays of particles with τ smaller than 1 cm/ c , restricted to decay chains leading to the interaction [46]. In pp collisions, the analysis was limited to charged tracks with a minimum of $N_{\text{TPC}} = 70$ reconstructed space points in the TPC, out of a maximum of 159, whereas in Pb–Pb and Xe–Xe collisions, a p_T -dependent cut, $N_{\text{TPC}} = 70 + 1.5 \times \frac{p_T}{\text{GeV}/c}$, was applied to further limit the probability of split tracks which is more relevant for events with high hit occupancy in the TPC. This occurs when a single particle is reconstructed as multiple separate tracks. Additionally, in order to suppress secondary charged particles, the track distance-of-closest-approach (DCA) to the reconstructed primary interaction vertex was limited to $|d_z| < 1$ cm in the longitudinal direction and $|d_{xy}| < 1$ cm in the transverse direction in Pb–Pb and Xe–Xe collisions. Finally, the DCA selection criteria, $|d_z| < 2$ cm and $|d_{xy}| < 0.0182 + 0.0350/p_T^{1.01}$ cm, with p_T expressed in units of GeV/ c were used to minimize contamination from secondary particles in pp collisions [47].

Charged particles selected for the determination of S_0 were measured within the TPC and the ITS and required to have transverse momentum $p_T > 0.15$ GeV/ c and lie within the pseudorapidity interval $|\eta| < 0.8$. The event shape-dependent analysis was further restricted to events featur-

ing a minimum of five charged particles, $N_{\text{ch}} \geq 5$, to ensure that the notion of transverse topology (a.k.a. transverse event shape) is meaningful. The analysis of $\langle\langle\Delta p_{T1} \Delta p_{T2}\rangle\rangle$ was carried out as a function of the strength of S_0 and is reported for jetty events and isotropic events, based on two sphericity event classes corresponding to the lowest and top 20 percentile of all accepted events, respectively.

A comprehensive analysis was conducted to understand the impact of the detector response and analysis procedure on the measured observables, utilizing simulations based on different Monte Carlo event generators and on the GEANT3 [48] transport code, including a detailed description of the ALICE detector components and their performance. Observables of interest were computed at the generator level, i.e., directly based on the output of event generators, and at the detector level, i.e., based on the output of the reconstruction of simulated events. Ratios of the detector-level and generator-level results were considered in what is known as a closure test. The generator level computation involves no particle losses and no resolution smearing, whereas the reconstructed level includes both losses and smearing effects, as well as potential sources of contamination of the signal (poorly reconstructed tracks, tracks resulting from secondary particles, etc.). The event generators used for the MC closure tests were HIJING [49] for Pb–Pb and Xe–Xe collisions, and PYTHIA8 [50] for pp collisions. From the analysis of the closure test, it was found that the detector-level results matched those obtained at the generator level within 2%. This difference was assigned as a systematic uncertainty, as discussed in Sect. 3.1.

The overall good closure obtained from the simulated data indicates, in particular, that the observable $\sqrt{\langle\langle\Delta p_{T1} \Delta p_{T2}\rangle\rangle} / \langle\langle p_T \rangle\rangle$ is robust against particle losses and the analysis reported thus does not include corrections for such losses.

In addition to HIJING and PYTHIA 8, the AMPT [51] and EPOS LHC [52] models were used to compute the magnitude of the $\sqrt{\langle\langle\Delta p_{T1} \Delta p_{T2}\rangle\rangle} / \langle\langle p_T \rangle\rangle$ correlator and its evolution with collision centrality in Xe–Xe and Pb–Pb collisions to provide insight into the interpretation of the data. The subsequent paragraphs provide a succinct overview of the models utilized for the different collision systems.

AMPT is a heavy-ion collision model that features partonic scattering and string fragmentation components in addition to a transport model. It has had considerable successes in reproducing observables measured in heavy-ion collisions at both RHIC and LHC energies, such as the strength of anisotropic flow harmonics [51, 53]. However, it has encountered mitigated success in the prediction of correlation and fluctuation observables [54]. The data presented in this paper will enable further testing of the underlying physics hypotheses of the model. AMPT simulations were performed with default and string melting settings. In the default mode, the model assumes that hadrons are produced directly from

strings via Lund string fragmentation whereas in the string melting mode, the model melts these strings into their constituent partons. Thus, all produced hadrons are decomposed into partons immediately after their formation. After the partonic phase, partons recombine to form hadrons through quark coalescence.

HIJING is a perturbative QCD inspired MC event generator for the study of jet and multiparticle production in high-energy pp and heavy-ion collisions. The model includes multi-minijet production, nuclear shadowing of parton distribution functions, and mechanisms of jet interactions in a dense medium. In this analysis, HIJING simulations are used for comparisons with results from heavy-ion collisions.

PYTHIA is a MC event generator designed to simulate high-energy collisions between electrons, protons, photons, and heavy-nuclei. It features hard and soft interactions, sampling of parton distributions, initial- and final-state parton showers, multiparton interactions, as well as fragmentation and decays. Two tunes of PYTHIA are used in this analysis. PYTHIA 6 Perugia 2011 includes the revised set of parameters of flavor and fragmentation, which improves the overall description of Tevatron data and the reliability of their extrapolations to LHC energies [55]. The minimum bias and underlying event data from the LHC are taken into account in Perugia 2011 tune. PYTHIA 8 Monash tune includes a default parameterization of the model based on multiparton interactions and color reconnection mechanism. Following the hard scattering and parton showers, colored strings are formed with the final-state partons. PYTHIA 8 has a hadronization mechanism based on the fragmentation model which is followed by particle decays, which leads to the production of jets and the underlying event [50].

The EPOS LHC model features particle production from core and corona components. Particle production in the corona is described in the context of the parton-based Gribov–Regge theory, whereas the core, expected to feature high parton densities, is described with ideal hydrodynamics. EPOS LHC is tuned to the LHC data via the color exchange mechanism of string excitation [56].

3.1 Systematic uncertainties

Several potential sources of systematic uncertainties were considered including effects due to collision pile-up, contributions from tracks reconstructed with limited precision, secondary tracks, non-uniformity of the acceptance, and possible dependencies of the track reconstruction efficiency on the position of the primary vertex. Testing for these contributions was accomplished by studying the magnitude of the $\sqrt{\langle\langle\Delta p_{T1} \Delta p_{T2}\rangle\rangle} / \langle\langle p_T \rangle\rangle$ correlator in response to variations of event and track quality selection criteria used in the analysis and also by comparing different data subsets. The systematic uncertainty for each source was determined based on the

Table 1 Contributions to the relative (%) systematic uncertainty on $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}/\langle p_T\rangle$ of primary charged particles in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV

Source of uncertainty	pp, 5.02 TeV	Xe–Xe, 5.44 TeV	Pb–Pb, 5.02 TeV
Vertex selection	< 2.1%	< 3.7%	< 2.2%
Pile-up	< 2.0%	< 3.3%	0.1–3.5%
No. of TPC clusters	0.1–2.0%	< 2.2%	< 0.5%
d_{xy}	0.2–4.0%	< 1.5%	< 0.3%
d_z	3.1–5.5%	< 3.1%	< 0.8%
MC closure	1.3%	1.8%	1.5%
Total	4.0–7.1%	1.8–6.7%	2.2–3.8%

maximum difference between the results obtained with the default analysis configuration and with the different variations of the selection criteria.

At the event level, the selections on the reconstructed position of the primary vertex along the beam axis (V_z), and on the presence of multiple reconstructed primary vertices to suppress events with collision pile-up were varied. Events with out-of-bunch pile-ups are identified and rejected exploiting the fact that the event multiplicity estimated from the signals measured with detectors with different readout times are affected differently by out-of-bunch pileup. Variables sensitive to multiplicity, extracted from detectors with different readout times, are used as tools to tag and remove events with out-of-bunch pile-ups. This effectively removes most of the event pileup accumulated during the TPC drift and readout time. For the default configuration, a pile-up selection based on ITS and TPC clusters are applied. For systematic uncertainty, the selection is removed and the difference is conservatively quoted as systematic uncertainty due to pile-up. The V_z selection is varied to $|V_z| < 8$ cm and contributes to relative uncertainties smaller than 2.1% for pp collisions, 3.7% for Xe–Xe collisions, and 2.2% in Pb–Pb collisions. The relative uncertainties due to remaining pile-up contamination are less than 2% and 3.3% for pp and Xe–Xe collisions, respectively, and vary from a minimum of 0.1% to a maximum of 3.5% for Pb–Pb collisions. At the track level, the track-quality and primary-particle selection criteria were varied including the longitudinal and transverse DCA of each track and the minimum number of TPC clusters required on a track. The maximum contribution to the systematic uncertainty due to the track selection criteria arises from the d_z selection, and it is less than 5.5%, 3.1%, and 0.8% in pp, Xe–Xe, and Pb–Pb collisions, respectively. Other relevant contributions to the systematic uncertainty on the track selection are due to the d_{xy} cut (up to 4% in pp collisions), the d_z cut (up to 5.5% in pp collisions), and the request of a minimum number of TPC clusters (up to 2.2% in Xe–Xe collisions). The analysis of the closure test results showed that deviations between detector and generator levels do not

exceed 2% in all studied collision systems. The minor deviations from perfect closure are conservatively added to the systematic uncertainties. The estimated values of the relative systematic uncertainties for the three collision systems are summarized in Table 1. For the sources of uncertainty that depend on multiplicity a range of values is reported. Individual contributions are summed in quadrature to obtain the total systematic uncertainties. We report the minimum and maximum values of systematic uncertainty due to different sources across all $\langle dN_{ch}/d\eta \rangle$ values. The total systematic uncertainty gives a lower and upper limit across bins of $\langle dN_{ch}/d\eta \rangle$. The total systematic uncertainties are smaller than 7.1%, 6.7%, and 3.8% for pp, Xe–Xe and Pb–Pb collisions, respectively.

4 Results

Results of the study of the dependence of the magnitude of the $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}/\langle p_T\rangle$ correlator on the produced particle density measured in pp, Xe–Xe, and Pb–Pb collision systems are presented in Sect. 4.1. The comparison of the measurements to theoretical predictions, and the energy dependence of the correlator are discussed in Sects. 4.2 and 4.3, respectively. The dependence of the $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}/\langle p_T\rangle$ on the event sphericity S_0 measured in pp collisions is discussed in Sect. 4.4

4.1 System size dependence of event-by-event $\langle p_T \rangle$ fluctuations

The event-by-event $\langle p_T \rangle$ fluctuations are reported based on the two-particle correlator $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}/\langle p_T\rangle$ defined in Eq. (1) and computed according to Eq. (3). The top panel of Fig. 1 presents the magnitude of $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}/\langle p_T\rangle$ measured as a function of the pseudorapidity density of charged particles produced in the collision, $\langle dN_{ch}/d\eta \rangle$, determined in the kinematic range $0.15 < p_T < 2$ GeV/c and $|\eta| < 0.8$, in pp collisions at $\sqrt{s} = 5.02$ TeV, Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV, and Pb–Pb collisions at $\sqrt{s_{NN}}$

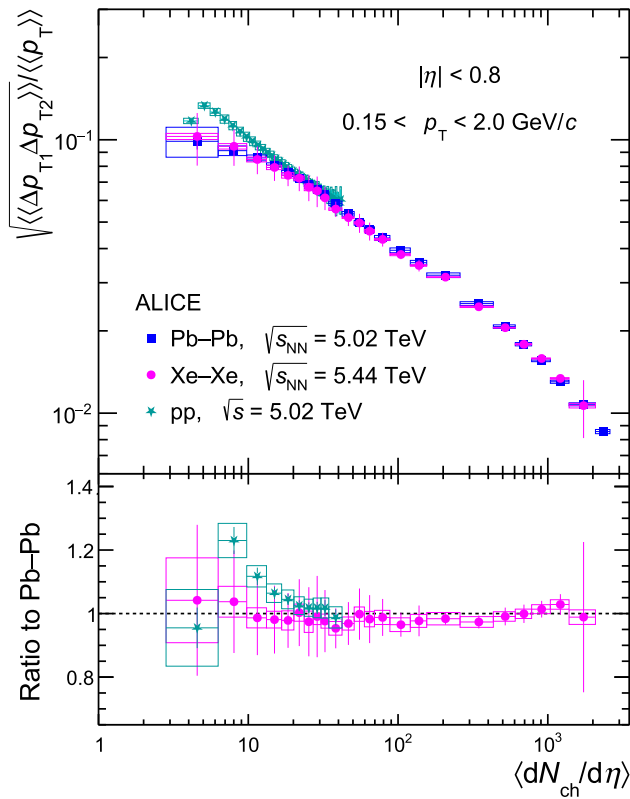


Fig. 1 (top) Normalized transverse momentum correlator, $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}/\langle p_T\rangle$, shown as a function of the charged-particle multiplicity density, $\langle dN_{ch}/d\eta\rangle$, measured in the pseudorapidity range $|\eta| < 0.8$ in pp collisions at $\sqrt{s} = 5.02$ TeV, Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV, and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV; (bottom) Ratio of values of $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}/\langle p_T\rangle$ measured in pp and Xe–Xe collisions to those observed in Pb–Pb collisions. Statistical and systematic uncertainties are represented by vertical bars and boxes, respectively

= 5.02 TeV. The strength of $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}/\langle p_T\rangle$ is evidently non-vanishing and exhibits an approximate power-law dependence on the produced charged-particle density. Fluctuations of the event-wise average momentum $\langle p_T\rangle$ are accordingly non-Poissonian and exhibit a strong dependence on the particle density in all three collision systems studied. These new results confirm and corroborate prior observations of non-Poissonian fluctuations in heavy-ion collisions and make it possible to carry out a detailed study of the system size and energy dependence of the fluctuations [11–13, 17, 18, 23, 57–59].

The correlator strength is observed to decrease by more than one order of magnitude with increasing multiplicity for Xe–Xe and Pb–Pb collisions. One notes, however, that this multiplicity dependence cannot be described by a single power-law across the whole range of $\langle dN_{ch}/d\eta\rangle$. One finds, indeed, that in both Pb–Pb (blue square) and Xe–Xe (magenta circle) collisions, the dependence can be characterized by three power-law regimes with distinct slopes in the ranges $3 < \langle dN_{ch}/d\eta\rangle < 20$, $20 < \langle dN_{ch}/d\eta\rangle < 300$,

and $\langle dN_{ch}/d\eta\rangle > 300$, respectively. This suggests that the strength of the correlation is influenced by several distinct mechanisms (or system properties) from the most peripheral to the most central collisions considered in this study, as discussed in more detail in the following.

The lower panel of Fig. 1 displays the evolution of the ratio of the correlation strength measured in pp and Xe–Xe collisions relative to that observed in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. To compute the ratio, the pp and Xe–Xe results were rebinned to the $\langle dN_{ch}/d\eta\rangle$ intervals used for Pb–Pb results, using a fit function. It is apparent that the magnitude of the correlators measured in Pb–Pb and Xe–Xe are consistent between each other and feature essentially the same dependence on $\langle dN_{ch}/d\eta\rangle$. By contrast, however, the evolution of the correlator strength measured in pp collisions differs from that observed in the larger systems. Nevertheless, in pp collisions at the higher values (>20) of particle multiplicities, $\langle dN_{ch}/d\eta\rangle$, the correlator strength is in very good agreement, within statistical uncertainties, to that reported in Pb–Pb and Xe–Xe at the same particle density. For decreasing $\langle dN_{ch}/d\eta\rangle$ the correlation strength measured in pp progressively deviates from the values observed for the larger systems. The scaling seen for Pb–Pb and Xe–Xe at low multiplicity, seems to be caused by the dilution of the correlator with increasing number of correlator sources which grow with participant number [60]. At low multiplicities, large non-Gaussian fluctuations deviate from the expected linear scaling, unlike in pp collisions where the number of sources fluctuates less. In pp collisions, the scaling would be similar but in terms of the number of partonic collisions resulting in variations in MPI, mini jets, or jets that may lead to a smoothly varying number of correlated sources. One consequently observes an approximately $A^{-0.5}$ scaling. The nuclear structures of Xe and Pb are distinct due to their different sizes, neutron-to-proton ratios, and shell structure. The Pb nucleus is notably heavier, and features a larger neutron skin, but is otherwise more spherical. Correlations between deformation, anisotropic flow, and transverse momentum have been reported by ATLAS [61]. However, the current measurement does not enable us to readily discern effects associated with deviations from a spherical structure. Overall, one finds that the evolution of $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}/\langle p_T\rangle$ with $\langle dN_{ch}/d\eta\rangle$ follows similar trends in Pb–Pb and Xe–Xe whereas pp interactions reveals discrepancies at low multiplicities.

4.2 Comparison to theoretical predictions

Figure 2 shows the comparison of the evolution of the measured $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}/\langle p_T\rangle$ as a function of $\langle dN_{ch}/d\eta\rangle$ in Pb–Pb (left) and Xe–Xe (right) collisions with the results obtained using HIJING and AMPT models. The presented AMPT calculations were obtained for two scenarios: AMPT default and AMPT string melting.

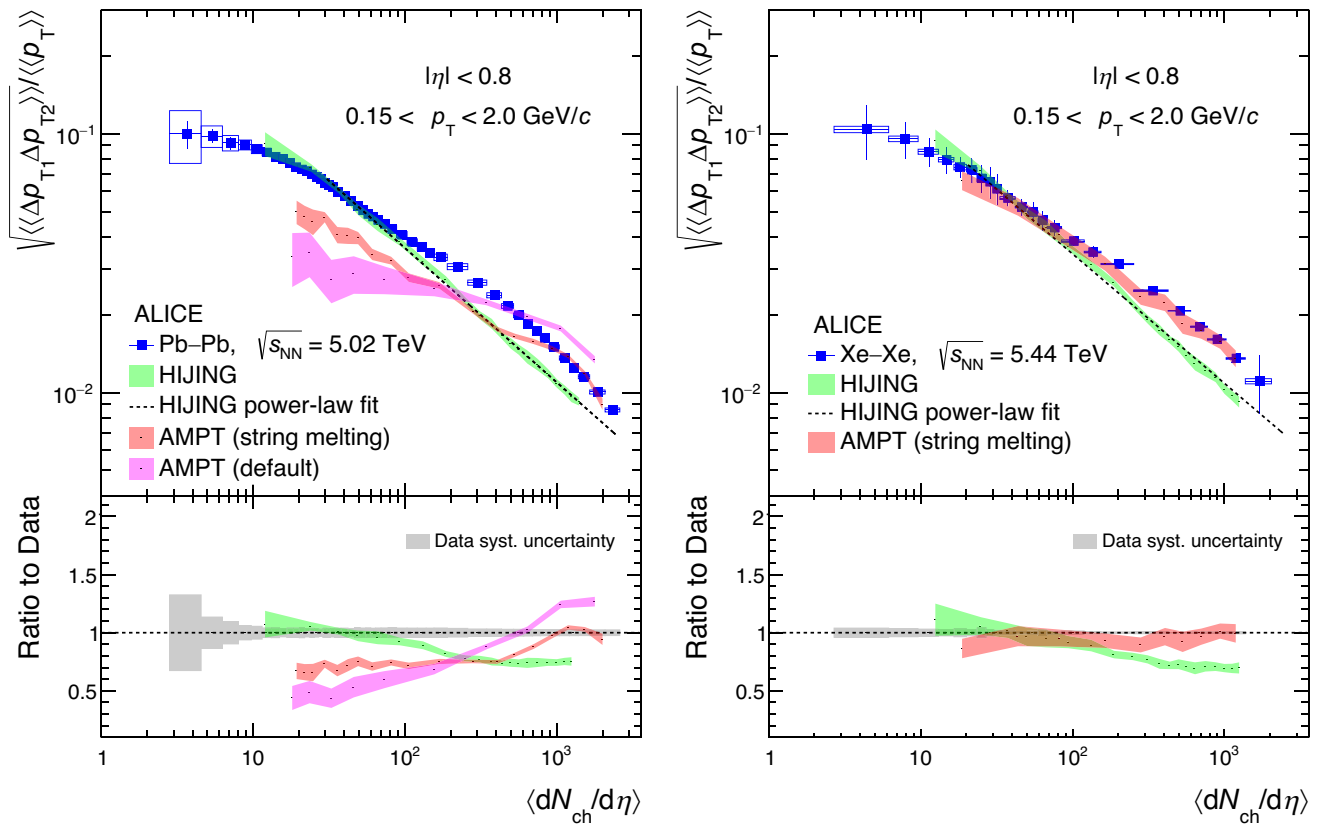


Fig. 2 Upper panels: comparisons of the evolution of the strength of $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle/\langle p_T\rangle}$ with produced charged-particle multiplicity densities, $\langle dN_{ch}/d\eta\rangle$, in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (left) and Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV (right) with calculations using the HIJING and AMPT models. Lower panels: ratios of the model cal-

culations to measured $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle/\langle p_T\rangle}$. Solid symbols represent the measured data with statistical (vertical bars) and systematic (boxes) uncertainties. Model calculations are shown with shaded bands denoting their statistical uncertainty

The bottom panels of Fig. 2 show ratios of HIJING and AMPT calculations to the measured data. The observed magnitude of the normalized transverse momentum correlator, $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle/\langle p_T\rangle}$, obtained with the HIJING model exhibits a simple power-law dependence. This behavior is accurately depicted by a fit of $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle/\langle p_T\rangle} \propto \langle dN_{ch}/d\eta\rangle^\alpha$ where the exponent α is determined to be -0.504 ± 0.007 within the charged particle multiplicity density interval of $20 < \langle dN_{ch}/d\eta\rangle < 2500$.

This power-law dependence and the exponent value are consistent with the behavior expected for a system consisting of a simple superposition of nucleon–nucleon collisions without rescattering of the secondaries as modeled by HIJING. One finds, however, that while the evolution of the correlator measured in both Pb–Pb and Xe–Xe approximately follows the HIJING power-law fit in the low-multiplicity range $10 < \langle dN_{ch}/d\eta\rangle < 50$, it clearly deviates from this simple trend at $\langle dN_{ch}/d\eta\rangle > 50$. This is also highlighted in Fig. 3 that shows the ratio of the magnitude of the $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle/\langle p_T\rangle}$ correlator in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (left) and in Xe–Xe collisions at $\sqrt{s_{NN}} =$

5.44 TeV (right) to the power-law fit of $\langle p_T\rangle$ fluctuations of HIJING model. This indicates that the final-state particle production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Xe–Xe at $\sqrt{s_{NN}} = 5.44$ TeV cannot be described by a mere superposition of independent particle-emitting sources. It also corroborates the earlier findings by the ALICE Collaboration in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [23] and those of the STAR Collaboration at RHIC energies [17–19].

Deviations from a superposition model of independent particle-emitting sources, in A–A collisions, are known to arise in measurements of nuclear modification factor [47], and anisotropic flow [62], and other measurements of two-particle correlation functions [57,63]. It is thus reasonable to seek theoretical guidance from a model such as AMPT, which has had relative success in the description of data obtained at RHIC and LHC. One finds that the two versions of AMPT considered strongly under-predict the strength of the $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle/\langle p_T\rangle}$ correlator in the most peripheral Pb–Pb collisions. AMPT operated with string melting generates stronger collective flow because it effectively produces a dense partonic medium where interactions among

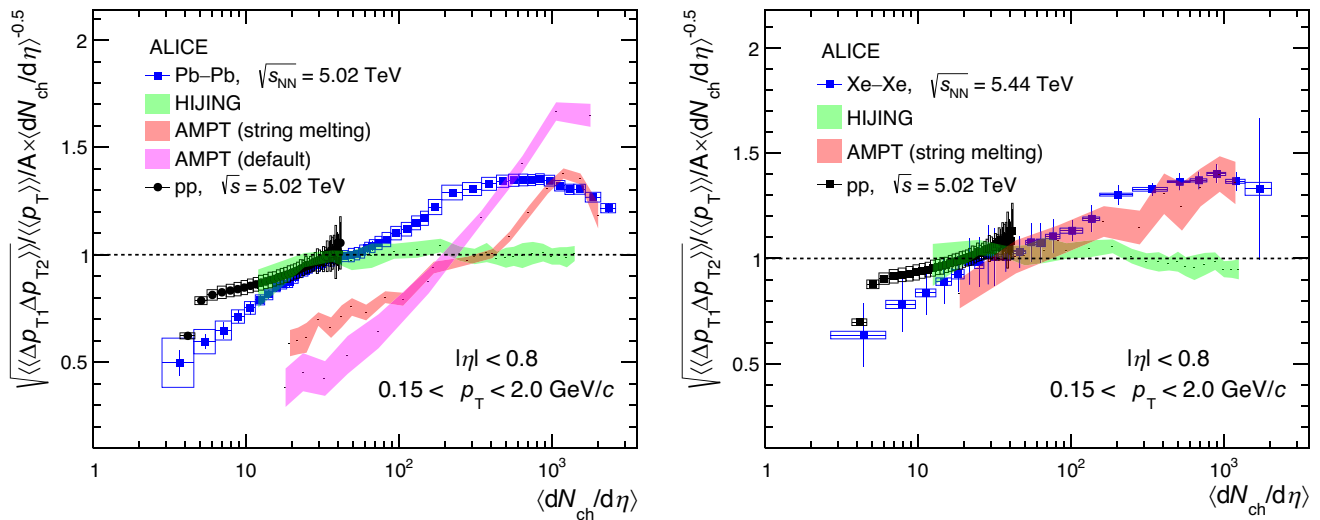


Fig. 3 Evolution of the ratio of $\sqrt{\langle \Delta p_{T1} \Delta p_{T2} \rangle} / \langle p_T \rangle$ to results of a power-law fit to HIJING calculations: (left) pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV; (right) pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. The power-law fit was performed on correlator values obtained with HIJING for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV for left and

right panel, respectively, as described in the text. Solid symbols represent the measured data reported in this work with statistical (vertical bars) and systematic (boxes) uncertainties. Calculations of the ratios obtained with HIJING and AMPT calculations are shown with shaded bands denoting their statistical uncertainty

quarks and gluons contribute significantly to the build-up of flow. Simulations with the AMPT model, with string melting, are in reasonable agreement with the data for Xe–Xe, and Pb–Pb collisions in the high-multiplicity regions. However, it is evident that both HIJING and AMPT lack some important features that determine the strength and evolution of $\sqrt{\langle \Delta p_{T1} \Delta p_{T2} \rangle} / \langle p_T \rangle$ with collision centrality for Pb–Pb collisions. For Xe–Xe collisions, AMPT with string melting on, shows a better agreement with data than for Pb–Pb collisions for low multiplicity region.

In order to guide further theoretical inquiries, the strength and evolution of $\sqrt{\langle \Delta p_{T1} \Delta p_{T2} \rangle} / \langle p_T \rangle$ observed in pp, Pb–Pb and Xe–Xe collisions are compared in more detail.

Figure 3 shows the ratio of measured values of $\sqrt{\langle \Delta p_{T1} \Delta p_{T2} \rangle} / \langle p_T \rangle$ to the HIJING results estimated by a power-law fit to the correlator values. Results are drawn as a function of the charged-particle multiplicity, $\langle dN_{ch}/d\eta \rangle$. The fitting procedure was carried over the range $25 < \langle dN_{ch}/d\eta \rangle < 2500$ with a fixed exponent value of $\alpha = -0.5$. The shaded green band is approximately centered at unity and shows that the power-law fit is a good description of the evolution of the strength of $\sqrt{\langle \Delta p_{T1} \Delta p_{T2} \rangle} / \langle p_T \rangle$ with $\langle dN_{ch}/d\eta \rangle$ predicted by HIJING. Indeed, HIJING produces a progressive dilution of the correlator with rising values of $\langle dN_{ch}/d\eta \rangle$ as expected. By contrast, one finds that correlations observed in Pb–Pb and Xe–Xe increasingly undershoot the power-law fit at small densities while they significantly exceed the fit at $\langle dN_{ch}/d\eta \rangle$ above 70–80, thereby signaling a considerable departure from a system consisting of

a superposition of independent nucleon–nucleon collisions. One additionally finds that both AMPT calculations considerably violate the density scaling. However, measurements in pp are well matched by HIJING simulations at multiplicities greater than 10.

4.3 Energy dependence of event-by-event $\langle p_T \rangle$ fluctuations

Figure 4 shows the dependence of the correlator strength $\sqrt{\langle \Delta p_{T1} \Delta p_{T2} \rangle} / \langle p_T \rangle$ as a function of charged-particle multiplicity ($\langle dN_{ch}/d\eta \rangle$) for Pb–Pb collisions at two energies, $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV. The lower panel of the figure shows the ratio of 5.02 TeV correlator to that of 2.76 TeV. The ratio is close to unity at low values of $\langle dN_{ch}/d\eta \rangle$ and increases with increasing multiplicity. For central collisions (large values of $\langle dN_{ch}/d\eta \rangle$), the correlator at 5.02 TeV is up to 20% larger compared to the one at 2.76 TeV.

Figure 5 (left panel) shows the dependence of the correlator as a function of the number of participant nucleons (N_{part}) for Pb–Pb collisions at two LHC energies and Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC [17]. As shown in the ratio plot, the collision energy dependence in Pb–Pb collisions disappears when the correlator is shown as a function ($\langle N_{part} \rangle$). This suggests that for a given initial-state overlap geometry, the correlator strength is independent of the collision energy. However, an energy dependence is observed when comparing RHIC and LHC energies. The behavior in Fig. 4 could be due to the dependence of the $\langle p_T \rangle$ fluctuations on the collision energy or could be due

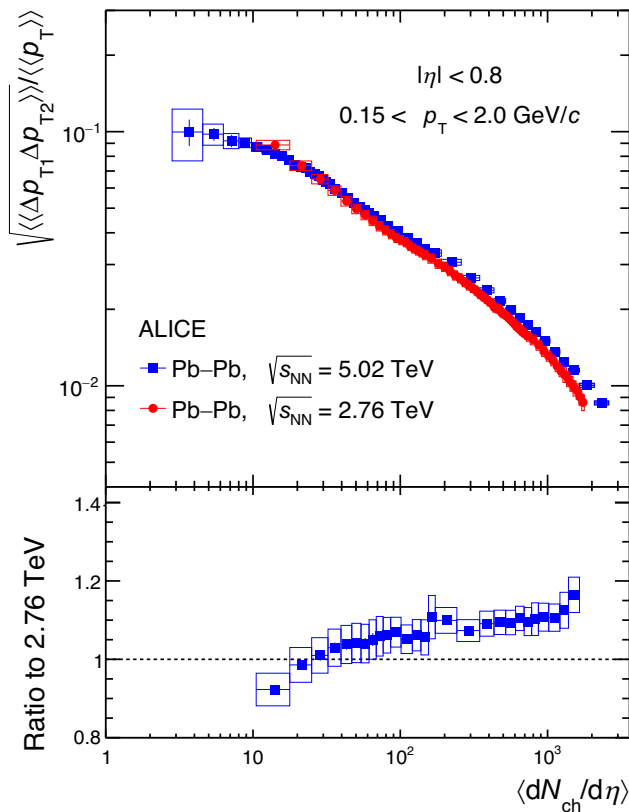


Fig. 4 (top) Normalized transverse momentum correlator, $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$, shown as a function of the charged-particle multiplicity density, $\langle dN_{ch}/d\eta\rangle$, in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ [23] and 5.02 TeV; (bottom) Ratio of values of $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$ measured at $\sqrt{s_{NN}} = 5.02$ TeV to the corresponding results at $\sqrt{s_{NN}} = 2.76$ TeV. The statistical and systematic uncertainties for both energies are represented by vertical bars and boxes, respectively

to the larger number of particles produced at $\sqrt{s_{NN}} = 5.02$ TeV that shifts $\langle dN_{ch}/d\eta\rangle$ to a higher value as compared to $\sqrt{s_{NN}} = 2.76$ TeV. The energy dependence as a function of $\langle N_{part}\rangle$ in Fig. 5 corroborates with the above statement. The right panel of Fig. 5 shows that similar values of $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$ are observed in Pb–Pb and Xe–Xe collisions for $\langle N_{part}\rangle > 25$ but differ by as much as 15% at smaller $\langle N_{part}\rangle$ (i.e. very peripheral collisions). One can infer that the observed difference is caused by the intrinsic deformation of the Xe nucleus. Indeed, evidence for the role of nuclear deformation on correlation observables has been reported in recent studies [61]. However, reaching a definitive conclusion on the role of geometry fluctuations associated with the deformed Xe nucleus likely requires detailed simulations of the strength of $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$ with and without the inclusion of deformation. Such simulations were deemed beyond the scope of this work but will be considered in the future.

4.4 Transverse sphericity dependence of $\langle p_T\rangle$ fluctuations in pp collisions

The results presented in Fig. 3 indicate that the strength of the correlator in central Pb–Pb and Xe–Xe collisions deviates by as much as 30% from the trivial scaling expected in the dilution scenario of independent particle-emitting sources. Although this deviation might stem largely from the kinematic focusing of correlated pairs associated with radial flow, it is of interest to examine whether the enhanced correlation values might arise from fluctuations associated with jet production and, more particularly, event-by-event variations in the number of jets and their composition. One might naively expect that fluctuations in the number or constituents of jets relative to “baseline” collisions (with no jet) could increase fluctuations and thus change the magnitude of the correlator. It is thus interesting to investigate, based on pp collisions alone, how the magnitude of the correlator changes from collisions where effects of jets are less pronounced to those featuring prominent jets. This investigation is conducted by studying the magnitude of the $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$ correlator relative to the shape of particle emission in the transverse plane. The sphericity observable, described in Sect. 2, is used to select collisions based on their transverse shape. Collisions with $S_0 = 1$ are expected to feature few or no jets, as by construction these are isotropic events without any preferred direction. This can be also possible for events with multijets. Whereas, events with $S_0 \sim 0$ are expected to feature back-to-back jets. It is then nominally possible to get insight into the impact of jets on the magnitude of $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$.

Figure 6 presents measurements of the evolution of the strength of the correlator $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$ as a function of $\langle dN_{ch}/d\eta\rangle$ in pp collisions at $\sqrt{s} = 5.02$ TeV for selected sphericity classes. Black squares display inclusive events, i.e., events with no sphericity selection; red circles present events characterized by a back-to-back jet topology denoted as “jetty” in the following, with $S_0 < 0.425$ corresponding to the 20% of events with lower sphericity; and blue stars are for the 20% most isotropic events, with $S_0 > 0.745$. Low-sphericity events feature $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$ values larger than those observed for isotropic events. The presence of a pronounced back-to-back jet topology is found to enhance the magnitude of the correlator by about 20% in high-multiplicity collisions. This enhancement likely results from jet particles being emitted in a narrow cone and thus being more correlated on average than other particles.

It is interesting to consider whether the observed 20% correlation strength difference between collisions dominated by a back-to-back jet topology and isotropic events may entail for correlation in larger systems. Since high- p_T particles and jets are suppressed in mid to central heavy-ion collisions, one expects that contributions to the $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$

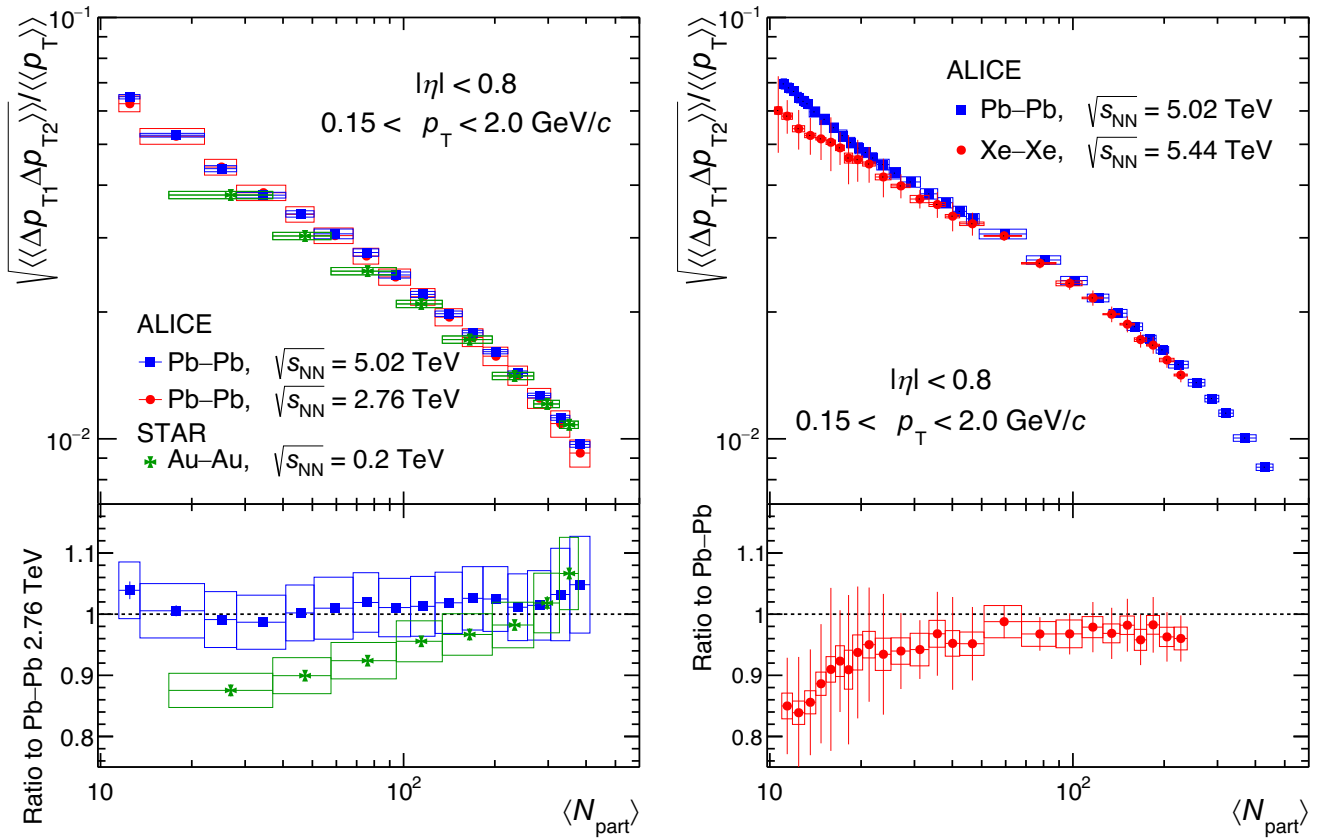


Fig. 5 Left: normalized transverse momentum correlator, $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$, shown as a function of the average number of participant nucleons, $\langle N_{part}\rangle$, in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV and Au–Au collisions at 0.2 TeV. Right: normalized

transverse momentum correlator, $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$, plotted as a function $\langle N_{part}\rangle$ in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The statistical and systematic uncertainties are represented by vertical bars and boxes respectively

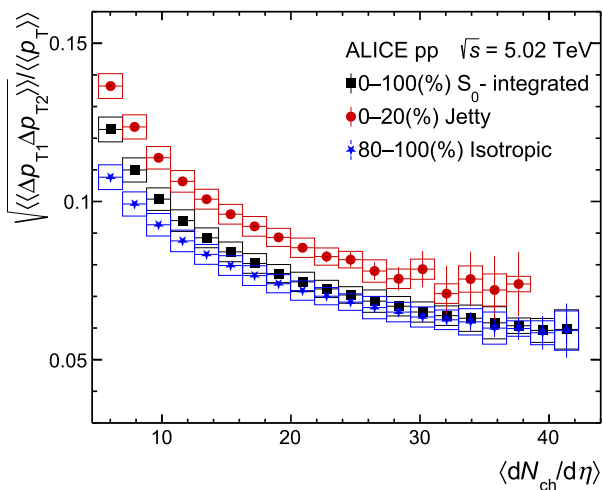


Fig. 6 Comparison of the normalized transverse momentum correlator, $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$ as a function of the charged-particle multiplicity density for sphericity-integrated (black), jetty (red), and isotropic (blue) events in pp collisions at $\sqrt{s} = 5.02$ TeV. The statistical and systematic uncertainties of the measured data for all sphericity classes are represented by vertical bars and boxes respectively

correlator, from jet particles, might also be suppressed. This should then reduce the correlation strength relative to the scaled dependence resulting from the dilution of the correlator in mid to central heavy-ion collisions. However, note that an excess is observed relative to the scaled dependence in both Xe–Xe and Pb–Pb collisions. One can then infer that the excess of correlation strength observed in these systems is not likely linked to jets but rather arises from other causes. A possible cause of the increased strength may be the strong transverse radial flow arising from the rapid expansion of the matter formed in heavy-ion collisions [64–66]. Indeed, one expects that the transverse radial expansion should accelerate correlated particles resulting from resonance (high mass hadrons) decays, string fragmentation, or QGP hadronization, giving thus rise to larger $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$ correlator values.

It is also interesting to consider how the magnitude of $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$ evolves with $\sqrt{s}$ in pp collisions. Figure 7 compares the dependence of $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$ on $\langle dN_{ch}/d\eta\rangle$ for inclusive, low- and high-sphericity events measured in pp collisions at $\sqrt{s} = 5.02$ TeV and 13 TeV.

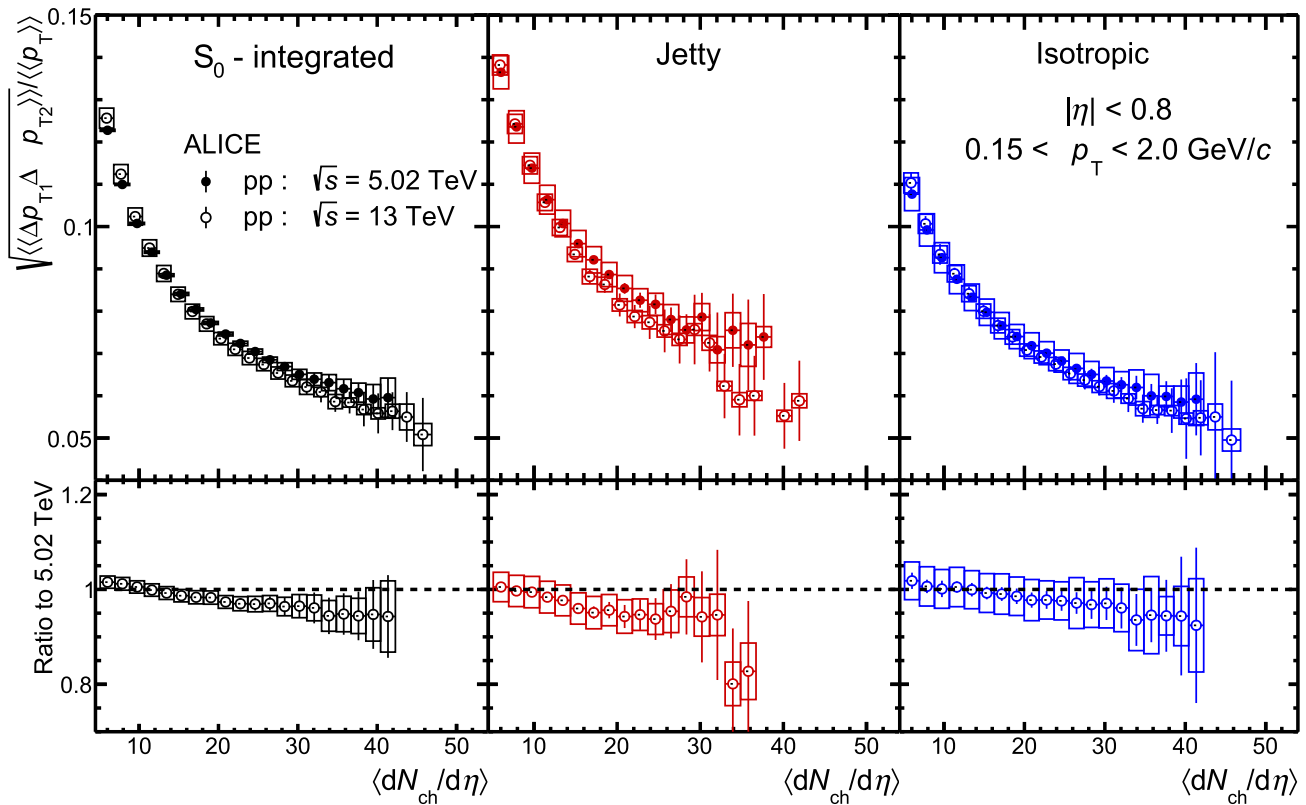


Fig. 7 Upper panels: comparison of the normalized transverse momentum correlator, $\sqrt{\langle\langle\Delta p_{T1} \Delta p_{T2}\rangle\rangle} / \langle\langle p_T \rangle\rangle$ as a function of charged-particle density in pp collisions at $\sqrt{s} = 5.02$ and $\sqrt{s} = 13$ TeV for sphericity-integrated (left), jetty (middle) and isotropic (right) events; Lower pan-

els: ratio of the $\sqrt{\langle\langle\Delta p_{T1} \Delta p_{T2}\rangle\rangle} / \langle\langle p_T \rangle\rangle$ in pp collisions at $\sqrt{s} = 13$ TeV to $\sqrt{s} = 5.02$ TeV. The statistical and systematic uncertainties of the measured data for all sphericity classes are represented by vertical bars and boxes, respectively

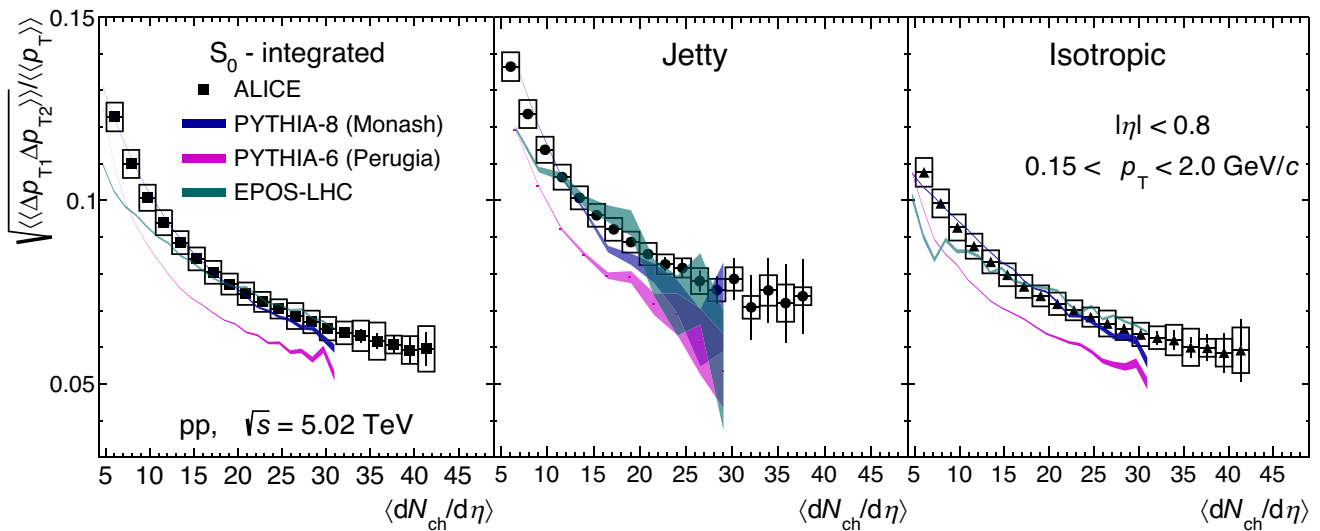


Fig. 8 Comparison of normalized transverse momentum correlator, $\sqrt{\langle\langle\Delta p_{T1} \Delta p_{T2}\rangle\rangle} / \langle\langle p_T \rangle\rangle$ as a function of the produced particle multiplicity for integrated (left), jetty (middle), and isotropic (right) pp collisions at $\sqrt{s} = 5.02$ TeV with calculations from the PYTHIA and EPOS mod-

els. See text for details. The statistical and systematic uncertainties of the measured data for all sphericity classes are represented by vertical bars and boxes, respectively

One observes the correlation strength exhibits only a small dependence, if any, on the energy of the pp collisions in both jetty and isotropic events. This indicates that changes in the strength of $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}$ are essentially compensated by the rise in $\langle p_T \rangle$ associated with the increase in the collision energy.

The measured $\langle p_T \rangle$ fluctuations for different sphericity classes are compared in Fig. 8 with calculations performed with the MC generators PYTHIA 6 [67], PYTHIA 8 [50], and EPOS LHC [56]. PYTHIA 6 significantly underestimates the magnitude of $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}/\langle p_T \rangle$, while PYTHIA 8 reproduces the data rather well. This indicates that the MPI mechanism is crucial for the description of particle production in PYTHIA. In addition, EPOS LHC, a model with core-corona approach, also reproduces the data well in both sphericity classes.

5 Summary and conclusions

Event-by-event $\langle p_T \rangle$ fluctuations of charged particles produced in Pb–Pb and Xe–Xe collisions at $\sqrt{s_{NN}} = 5.02$ and 5.44 TeV, respectively, and in pp collisions at $\sqrt{s} = 5.02$ TeV are studied based on the normalized $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}/\langle p_T \rangle$ integral correlator. The correlation strength is measured as a function of produced charged-particle multiplicity in all three collision systems and as a function of the sphericity of produced particles at midrapidity in pp collisions. The correlator strength is positive, thus indicating that significant dynamical fluctuations are observed in heavy-ion collisions and corroborating prior measurements reported by the STAR and ALICE Collaborations [66,68]. The strength of $\sqrt{\langle\Delta p_{T1}\Delta p_{T2}\rangle}/\langle p_T \rangle$ is also observed to monotonically decrease with increasing multiplicity in all measured systems, likely resulting in part from a dilution of the correlation strength associated with an increase in particle production. The observed decrease with multiplicity, however, significantly deviates from a power scaling of the form $\langle dN_{ch}/d\eta \rangle^{-1/2}$ expected for a source consisting of a superposition of independent nucleon–nucleon (or parton–parton) collisions with no re-scattering of the secondaries. A comparison of the correlation strength measured in low- and high-sphericity pp collisions shows that the selection of events characterized by a back-to-back jet topology yields a 20% increase in the correlator strength relative to isotropic events. Given that the production of high p_T particles and jets is known to be quenched in mid to central A–A collisions, one concludes that the observed deviation from $\langle dN_{ch}/d\eta \rangle^{-1/2}$ is likely not associated with a change in jet production but originates from other sources. A prime candidate for such a source is the large transverse radial flow arising in mid to central A–A collisions [64,65].

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