FLOW AND TRANSVERSE MOMENTUM CORRELATION IN Pb+Pb AND Xe+Xe COLLISIONS WITH ATLAS: ASSESSING THE INITIAL CONDITION OF THE QGP* **

Somadutta Bhatta

on behalf of the ATLAS Collaboration

Stony Brook University, Stony Brook, New York 11790, USA

Received 27 July 2022, accepted 2 September 2022, published online 14 December 2022

One important challenge in our field is to understand the initial condition of the QGP and constrain it using sensitive experimental observables. Recent studies show that the Pearson Correlation Coefficient between $\boldsymbol{V}_n$ and event-wise mean transverse momentum $[p_{\mathrm{T}}]$, $\rho_n(\boldsymbol{V}_n, [p_{\mathrm{T}}])$ can probe number and size of sources, nuclear deformation, volume fluctuation, and initial-momentum anisotropy in the initial state of heavy-ion collisions. These proceedings present new, precision measurements of $\boldsymbol{V}_n$–$[p_{\mathrm{T}}]$ correlation in $^{129}\mathrm{Xe}+^{129}\mathrm{Xe}$ and $^{208}\mathrm{Pb}+^{208}\mathrm{Pb}$ collisions for harmonics $n = 2$, 3, and 4 using the ATLAS detector at the LHC. The values of ρ_n show rich and non-monotonic dependence on centrality, p_{T} and η, reflecting that different ingredients of the initial state impact different regions of the phase space. The ratio of ρ_2 between the two systems in the ultra-central region suggests that ^{129}Xe has large quadrupole deformation and with a significant triaxiality. All current models fail to describe many of the observed trends in the data.

DOI:10.5506/APhysPolBSupp.16.1-A90

1. Introduction and measurements

Heavy-ion collisions at the LHC and RHIC produce Quark–Gluon Plasma (QGP) whose space-time evolution is well described by relativistic viscous hydrodynamics. Driven by the large pressure gradients, the QGP expands rapidly in the transverse plane, and converts the spatial anisotropy in the initial state into the momentum anisotropy in the final state. The collective

* Presented at the 29th International Conference on Ultrarelativistic Nucleus–Nucleus Collisions: Quark Matter 2022, Kraków, Poland, 4–10 April, 2022.

expansion in each event is quantified by a Fourier expansion of particle distribution in azimuth given by $\frac{\mathrm{d}N}{\mathrm{d}\phi} = \frac{N}{2\pi}(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n))$, where $\boldsymbol{V}_n$ and Φ_n represent the amplitude and phase of the n^{th}-order azimuthal flow vector $\boldsymbol{V}_n = v_n \mathrm{e}^{in\Phi_n}$. Model calculations show that the $\boldsymbol{V}_n$ is approximately proportional to the initial-state eccentricity $\mathcal{E}_n$ for $n = 2$ and 3, as well as for $n = 4$ in central collisions [1]. In addition, the fluctuations in the size of overlap area in the initial state give rise to fluctuations in radial flow which, in turn, lead to event-by-event fluctuation of the average transverse momentum ($[p_{\mathrm{T}}]$). The correlated fluctuations between $\mathcal{E}_n$ and R in the initial state are transferred to the final-state $\boldsymbol{V}_n$–$[p_{\mathrm{T}}]$ correlations via hydrodynamic expansion. A three-particle correlator has been proposed to quantify this correlation [2]:

$$\rho_n = \frac{\mathrm{cov}_n}{\sqrt{\mathrm{var}\left(v_n^2\right)}\sqrt{c_k}}, \qquad \mathrm{cov}_n = \left\langle\left\langle v_n^2 \delta p_{\mathrm{T}} \right\rangle\right\rangle ,$$
$$\mathrm{var}\left(v_n^2\right) = \left\langle v_n^4 \right\rangle - \left\langle v_n^2 \right\rangle^2 , \qquad c_k = \left\langle\left\langle \delta p_{\mathrm{T}} \delta p_{\mathrm{T}} \right\rangle\right\rangle , \tag{1}$$

where $\delta p_{\mathrm{T}} = p_{\mathrm{T}} - [p_{\mathrm{T}}]$ and the "$\langle\langle\rangle\rangle$" denotes averaging over all pairs or triplets for events with similar particle multiplicity, while the "$\langle\rangle$" denotes averaging over events. ρ_n describes the initial-state correlation between size and eccentricity. Another factor determining the shape and size of overlap area in the initial state is the "nuclear shape" described by the following function [3]:

$$R(\theta, \phi) = R_0 \left(1 + \beta[\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}]\right) , \tag{2}$$

where R_0 is the nuclear radius, $Y_{l,m}$ are spherical harmonics, β and γ are quadrupole deformation parameters. The parameter β is the magnitude of the deformation, while the angle γ, in the range of $0 \le \gamma \le 60^\circ$, describes the length imbalance of the three semi-axes of the ellipsoid, also known as triaxiality. The nuclear deformation parameters β and γ are generally determined by low-energy spectroscopic measurements. However, the approximations used in such an estimate works well only for even mass nuclei. Recent studies have shown that the final-state observables in heavy-ion collisions are sensitive to nuclear deformation parameters [4, 5]. In this work, we show the strength of heavy-ion collisions in providing additional handle to constrain the deformation parameters for ^{129}Xe.

The measurement of the cov_n, $\mathrm{var}\left(v_n^2\right)$, and c_k follows a similar procedure as detailed in Ref. [6] and uses data from the ATLAS detector [7]. The observables in each event are averaged over events with similar multiplicity and are then combined in broader multiplicity ranges of the event ensemble to obtain statistically more precise results. The Pearson coefficient ρ_n is then obtained via Eq. (1). The event averaging procedure is necessary to reduce the effects of centrality fluctuation within each event class definition.

Figure 1 provides a direct comparison of the Pb+Pb and Xe+Xe ρ_n values as a function of centrality (top) and ΣE_{T} (bottom). The ρ_2 values reach a minimum in the peripheral collisions, increase to a positive maximum value, and then decrease in the most central collisions; the ρ_3 values show a mild increase towards central collisions; the ρ_4 values show an increase then a gradual decrease towards central collisions. In the ultracentral collision region, all the ρ_n show a sharp decrease towards the most central collisions starting at around the location of the knee. For events having ΣE_{T} values beyond the knee, all nucleons participate in the collision leading to suppression of geometrical correlations. At the same centralities, the Xe+Xe ρ_2 values are everywhere smaller than the Pb+Pb values. When compared using ΣE_{T}, the Pb+Pb and Xe+Xe ρ_2 values agree for small ΣE_{T} values ($\Sigma E_{\mathrm{T}} < 0.5$ TeV) but differ for larger ΣE_{T}. Recently, it was argued that ρ_2 is a sensitive probe of the nature of collectivity in small collision systems in particular for isolating the contribution from and peripheral heavy-ion collisions, initial-momentum anisotropy (ϵ_p) in a gluon saturation picture [9]. The centrality dependence of ρ_2, after considering both the initial-state and final-state effects, is predicted to exhibit an increasing trend toward the most peripheral centrality. Figure 2 compares the centrality dependence of ρ_2 in $|\eta| < 2.5$ and $|\eta| < 1$ based on ΣE_{T} and $N_{\mathrm{ch}}^{\mathrm{rec}}$ in more detail over the 60–84% centrality range. The successive reduction of the ρ_2 from the standard

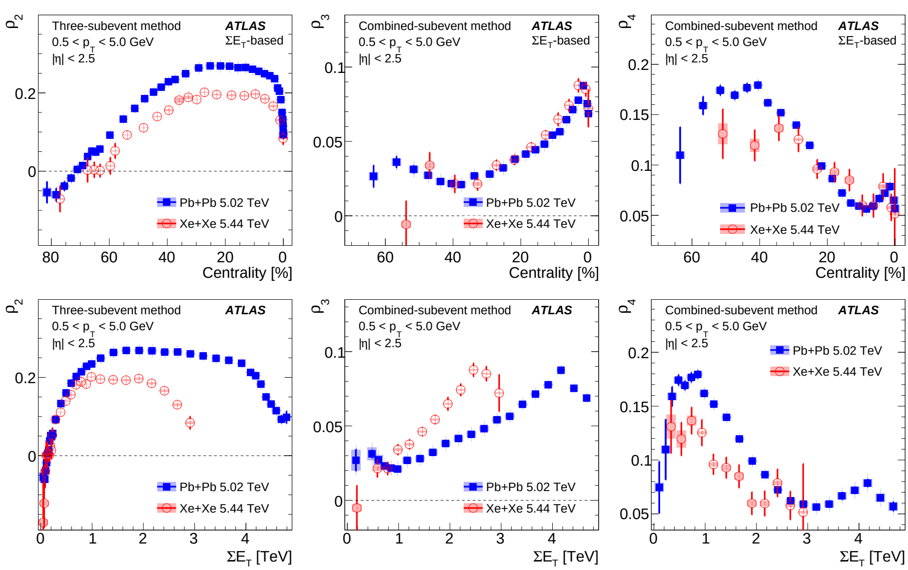

Fig. 1. The centrality (top) and ΣE_{T} (bottom) dependencies of ρ_n for $n = 2$ (left), 3 (middle), and 4 (right) in Pb+Pb and Xe+Xe collisions calculated using the event-averaging procedure based on ΣE_{T} [8].

method in the left panel, to the two-subevent method in the middle panel, and to the three-subevent method in the right panel is a robust feature of suppression of the non-flow correlations. The results from this measurement

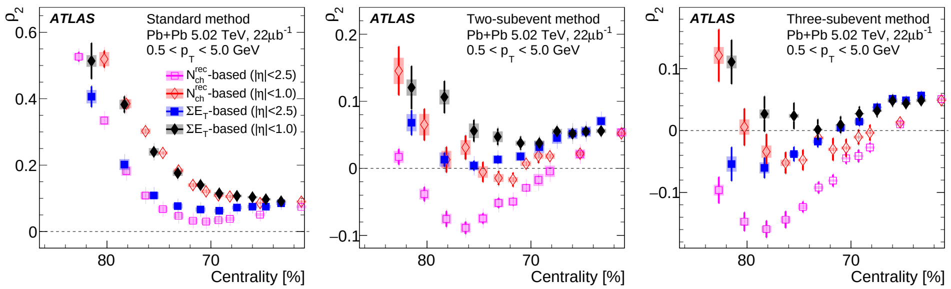

Fig. 2. The centrality dependence of ρ_2 in Pb+Pb collisions in the peripheral region of 60–84% for the standard method (left), two-subevent method (middle), and three-subevent method (right), compared between the $N_{\mathrm{ch}}^{\mathrm{rec}}$-based and ΣE_{T}-based event-averaging procedures and two η ranges [8].

do not show clear evidence for initial-state momentum anisotropy. Figure 3 shows the ρ_2 and ρ_3 values for two p_{T} ranges in Pb+Pb (top) and Xe+Xe (bottom) collisions. They are compared with the initial-state Trento model, 2D boost-invariant v-USPhydro model, and the Trajectum model as well as

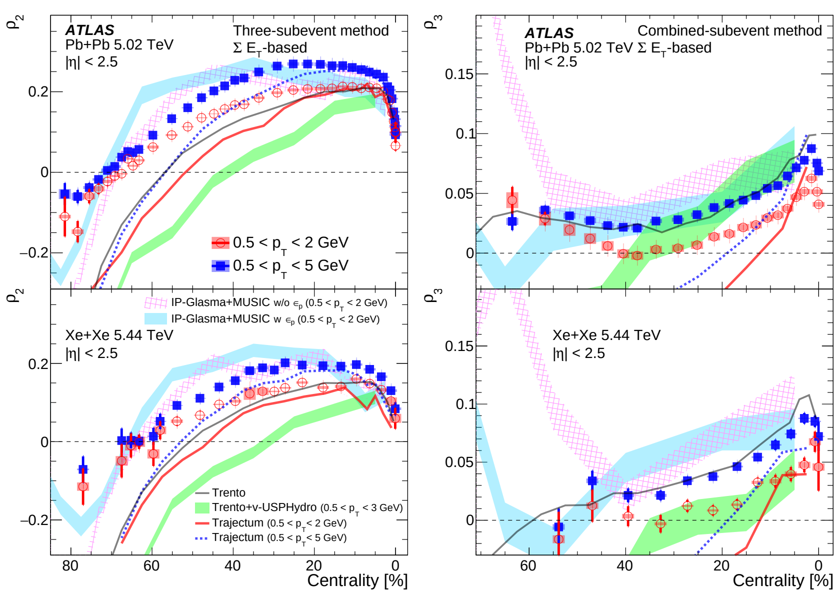

Fig. 3. The ρ_2 (left) and ρ_3 (right) values in Pb+Pb (top) and Xe+Xe (bottom) collisions in two p_{T} ranges and $|\eta| < 2.5$ compared with various models [8].

full three-dimensional (3D) IP-Glasma+MUSIC hydrodynamic model. In the 0–10% centrality interval, where effects of nuclear deformation are important, all models show reasonable agreement with each other and with data. The Trajectum model quantitatively reproduces the ordering between $0.5 < p_{\mathrm{T}} < 2$ GeV and $0.5 < p_{\mathrm{T}} < 5$ GeV. In non-central collisions, these models show significant differences from each other, which were recently shown to mainly reflect the different parameter values for the initial condition such as the nucleon size [10]. In the peripheral collisions, all model predictions for ρ_2 show a sharp decrease and a sign-change, qualitatively consistent with the ATLAS data. The IP-Glasma+MUSIC model with ϵ_p shows differences from the model without ϵ_p in peripheral collisions beyond 70% centrality.

Figure 4 compares ρ_2 data in the 0–20% centrality range with the Trento model calculations to investigate the influence of triaxiality [11]. Due to the large quadrupole deformation of the ^{129}Xe nucleus, $\beta_{\mathrm{Xe}} \sim 0.2$, the ρ_2

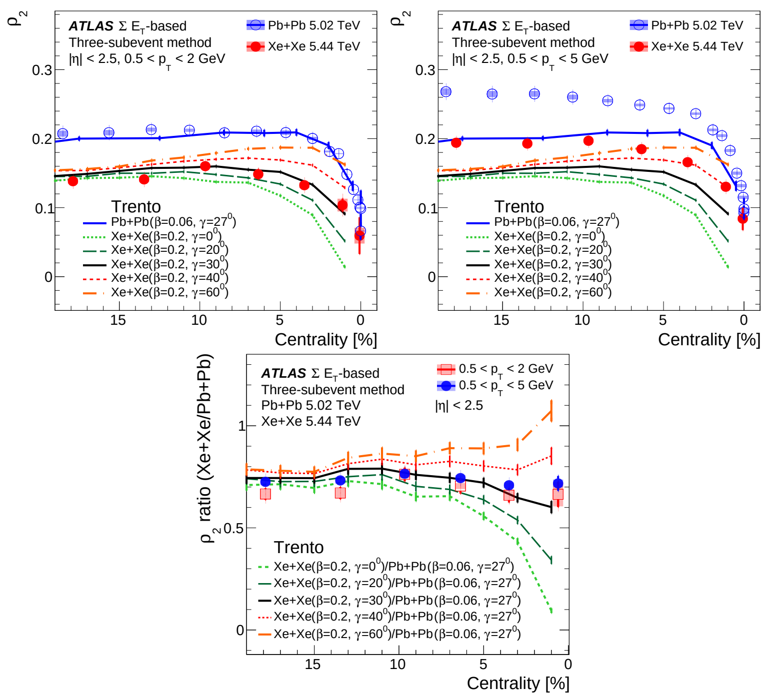

Fig. 4. (Top) Comparison of ρ_2 in Xe+Xe and Pb+Pb collisions with the Trento model for various β and γ values [11] in the range of $0.5 < p_{\mathrm{T}} < 2$ GeV (left) and $0.5 < p_{\mathrm{T}} < 5$ GeV (right) as a function of centrality. (Bottom) Comparison of $\rho_{2,\mathrm{Xe+Xe}}/\rho_{2,\mathrm{Pb+Pb}}$ with the Trento model for various β_{Xe} and γ_{Xe} [11] in two p_{T} ranges [8].

should be sensitive to the triaxiality parameter $\gamma_{\rm Xe}$ [12]. In order to cancel out the $p_{\rm T}$ dependence in the data, ratios of ρ_2 values between Xe+Xe and Pb+Pb are calculated for the two $p_{\rm T}$ ranges and compared with the ratios obtained in the Trento model in figure 4. In the 0–10% centrality range, where the predicted ρ_2 values show a significant dependence on the triaxiality, the comparison between the model and data favors a $\gamma_{\rm Xe} \sim 30^{\circ}$. This comparison provides clear evidence that flow measurements in central heavy-ion collisions can be used to constrain the quadrupole deformation, including the triaxiality, of the colliding nuclei.

2. Summary

These proceedings have presented experimental results on $\boldsymbol{V}_n$–$[p_{\rm T}]$ correlations from ATLAS. We observed that ρ_n depends on centrality fluctuations and final-state $p_{\rm T}$ and η ranges but the dependencies are not very strong, suggesting that they are dominated by the initial state. In peripheral centralities, evidence of initial $p_{\rm T}$ anisotropy (using ρ_2) is complicated by residual non-flow and centrality fluctuation. We have also provided the first experimental constraint on triaxiality of the odd mass nucleus ^{129}Xe ($\beta = 0.2$, $\gamma = 30^0$) from heavy-ion collisions.

REFERENCES

[1] D. Teaney, L. Yan, *Phys. Rev. C* **83**, 064904 (2011).

[2] P. Bożek, *Phys. Rev. C* **93**, 044908 (2016).

[3] A. Bohr, B.R. Mottelson, «Nuclear Structure», *World Scientific*, 1998.

[4] C. Zhang, J. Jia, *Phys. Rev. Lett.* **128**, 022301 (2022), `arXiv:2109.01631 [nucl-th]`.

[5] G. Giacalone, J. Jia, C. Zhang, *Phys. Rev. Lett.* **127**, 242301 (2021), `arXiv:2105.01638 [nucl-th]`.

[6] ATLAS Collaboration (G. Aad *et al.*), *Eur. Phys. J. C* **79**, 985 (2019), `arXiv:1907.05176 [nucl-ex]`.

[7] ATLAS Collaboration (G. Aad *et al.*), *J. Instrum.* **3**, S08003 (2008).

[8] ATLAS Collaboration, `arXiv:2205.00039 [nucl-ex]`.

[9] G. Giacalone, B. Schenke, C. Shen, *Phys. Rev. Lett.* **125**, 192301 (2020), `arXiv:2006.15721 [nucl-th]`.

[10] G. Giacalone, B. Schenke, C. Shen, *Phys. Rev. Lett.* **128**, 042301 (2022).

[11] B. Bally, M. Bender, G. Giacalone, V. Somà, *Phys. Rev. Lett.* **128**, 082301 (2022), `arXiv:2108.09578 [nucl-th]`.

[12] J. Jia, *Phys. Rev. C* **105**, 044905 (2022).