Investigating initial state of heavy-ion collisions using $[p_{\mathrm{T}}]$ fluctuations and $v_n - [p_{\mathrm{T}}]$ correlations in ATLAS

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Abstract. This proceeding presents recent studies of event-wise mean transverse momentum, $[p_{\mathrm{T}}]$ that can help differentiate the interplay between the effect of radial collectivity, random thermal motion and deformation in nuclear geometry. In addition, the Pearson Correlation Coefficient (PCC) between flow, v_n and $[p_{\mathrm{T}}]$, $\rho(v_n, [p_{\mathrm{T}}])$, will be shown. The results bear on aspects of the initial state, such as nuclear deformation and initial momentum anisotropy. New precise ATLAS measurements of $[p_{\mathrm{T}}]$ cumulants up to 3rd order and $v_n - [p_{\mathrm{T}}]$ correlations in Xe+Xe, Pb+Pb collisions are presented. These measurements provide the first experimental handle to isolate initial state and medium evolution contributing to final state momentum fluctuations. The PCC coefficients show a non-monotonic dependence on centrality, $[p_{\mathrm{T}}]$ and η, reflecting the fact that different aspects of the initial conditions affect different regions of the phase space. The ratio of $\rho(v_2, [p_{\mathrm{T}}])$ between the two systems in the ultra-central region suggests that ^{129}Xe has large quadrupole deformation with a significant triaxiality. The measurement of $v_n - [p_{\mathrm{T}}]$ correlation provides the first measurement of triaxiality in ^{129}Xe using heavy ion collisions and provides new constraints to current models which fail to describe many of the observed trends in data.

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1 Introduction

High-energy nuclear collisions at RHIC and LHC create quark-gluon plasma (QGP), a strongly interacting state of matter. Hydrodynamic expansion of QGP boosts the transverse momentum (p_{T}) of final-state particles, converting initial-state anisotropies into anisotropic flow and fluctuation of the initial-state energy density into event-by-event average particles momenta $[p_{\mathrm{T}}]$ fluctuations. Measurements of correlation of $[p_{\mathrm{T}}]$ with second flow harmonic and moments of $[p_{\mathrm{T}}]$ distributions using ATLAS [1] are reported in these proceeding.

2 Measurement of $v_2 - [p_{\mathrm{T}}]$ correlation coefficient in Xe+Xe and Pb+Pb.

The modified Pearson correlation coefficient ρ_n proposed first in Ref. [2] was found later in Ref. [3] to offer an insight into initial conditions of ultrarealtivistic ion collisions. This coefficient was measured by ATLAS [4] in Pb+Pb abd Xe+Xe collisions in a wide range of collision centralities for harmonics v_2, v_3, and v_4. The coefficient was found to vary significantly between peripheral collisions, where it approaches to zero or becomes negative, and

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more central collisions where it has higher value. This indicates a strong correlation between the two quantities. Behaviors for Pb+Pb and Xe+Xe collisions were found qualitatively similar even if the correlation is weaker in case of Xe+Xe collisions. The ratio of the two as a function of centrality was found to be amenable to comparison with models that involve hydrodynamic QGP evolution starting from multiple initial conditions for both Pb and Xe nuclei [5]. These conditions concern the initial shape of the nuclei. The radius is parametrized customarily in spherical coordinates with $R(\theta, \phi) = R_0 (1 + \beta [\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}])$ where R_0 is the average nuclear radius, $Y_{l,m}$ are spherical harmonics, β and γ are quadrupole deformation parameters. Figure 1 shows such a comparison. Provided a very good resolution of the data points a specific model with nearly spherical Pb nuclei and tri-axially deformed Xe nuclei ($\beta = 0.2, \gamma = 30^\circ$) is favoured by the data. This result is the first confirmation of the triaxiality in of ^{129}Xe and proves usefulness of the method for this class of measurements [6].

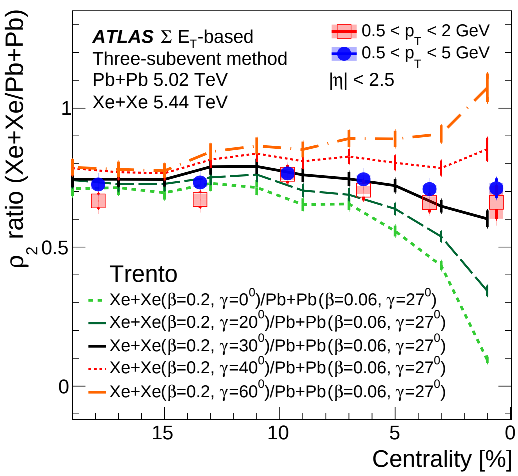

Figure 1. The comparison of the double ratio of correlation coefficients ρ_2 Xe+Xe/Pb+Pb with the Trento model for various quadrupole deformation parameter values [5] in two p_{T} ranges [4].

3 Average particles momenta fluctuations in Pb+Pb and Xe+Xe collisions

An intriguing behavior of aforementioned correlations observed in central collisions was investigated further and attributed to the decrease of magnitude of average momenta fluctuations. It is understood that in 1% of ultra central collisions the geometric contribution to fluctuation is greatly reduced and the intrinsic fluctuations start to be significant.

At the same time a positive correlation between multiplicity of produced particles and average momenta was anticipated. This is because fluctuating down (up) initial-state size would correlate with higher (lower) initial energy density and effective temperature during evolution T_{eff}. When translated to experimental observables the $[p_{\mathrm{T}}] \propto 1/R$ where R would be initial-state radii and $N_{\mathrm{ch}} \propto T_{\mathrm{eff}}$. Therefore a positive correlation between N_{ch} and $[p_{\mathrm{T}}]$ is expected. This is shown in Figure 2 where distribution of $[p_{\mathrm{T}}]$ as function of N_{ch} is shown as well as its dimensionless moments $k_2 = \langle c_2 \rangle / \langle [p_{\mathrm{T}}] \rangle^2$ and $k_3 = \langle c_3 \rangle / \langle [p_{\mathrm{T}}] \rangle^3$ where c_n are n-particle momentum correlations [7]. The $\langle [p_{\mathrm{T}}] \rangle$ grows mildly with multiplicity with an

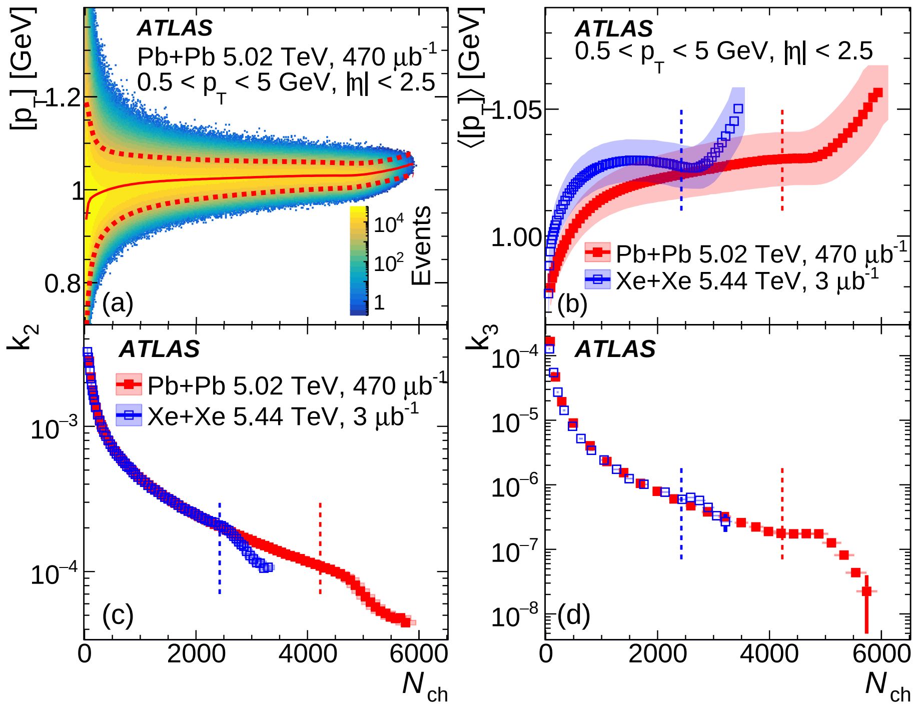

Figure 2. (top left) Distribution of $[p_T]$ of charged particles in an event as a function of number of charged particles N_{ch}. (top right) $[p_T]$ as a function of N_{ch}, (bottom left) variance of $[p_T]$ and (bottom right) skewness of $[p_T]$ [7]. Blue points show data for Xe+Xe and red for Pb+Pb collisions.

additional increase in the most central collisions. Higher order moments fall monotonically with multiplicity. The rate of decrease is additionally steeper in for 1% most central events. The moments are expected to scale with multiplicity obeying the power law with exponent equal to $n-1$ where n is the rank of the correlator. Such scaling is shown in Figure 3. In addition to aforementioned moments the intensive skewness $\Gamma = \langle c_3\rangle\langle[p_T]\rangle/\langle c_2\rangle^2$ is shown. A rapid increase at low multiplicities is attributed to onset of radial flow and thermalisation. In multiplicity range between 2000 and 4000 for Pb+Pb and in narrower range for Xe+Xe a saturation is observed for various moments corroborating the power-law scaling scenario. Behavior in ultra central collisions is highly nontrivial. In order to better visualize that region Figure 4 shows the moments scaled by the respective values at the 5% centrality percentile. The data points are compared to result of model in which the observed fluctuations are due to two independent effects, each fluctuating in a gaussian manner [8]. One contribution has geometric origin and changes rapidly with multiplicity in most central collisions whereas the intrinsic fluctuations change mildly with N_{ch}. Higher order moments, k_2, k_3, and Γ, indicate that both contributions are necessary to describe the data providing unique tool to disentangle quantitatively the two [9].

The steady rise of $\langle[p_T]\rangle$ was suggested to provide a mean to determine QGP equation of state parameter, the speed of sound c_s^2 [10] [11]. It was predicted that the slope of the $\langle[p_T]\rangle$ as function of N_{ch} could be used to determine this parameter. For a better presentation ATLAS is showing the evolution scaled to an average values in 1% most central collisions as shows in Figure 5. The results for Pb+Pb and Xe+Xe exhibit clear universality. The

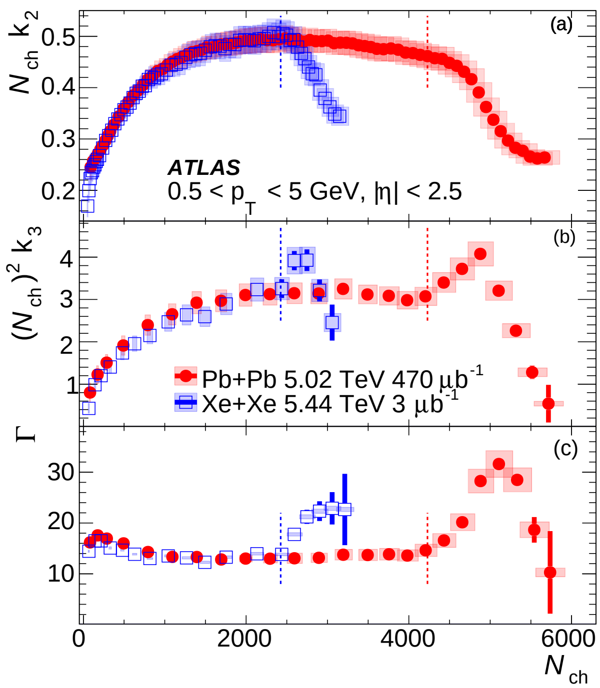

Figure 3. The N_{ch} evolution of various moments of $[p_{\mathrm{T}}]$ scaled by N_{ch} as denoted on axis description [7]. Blue points show data for Xe+Xe and red for Pb+Pb collisions.

slope however depends on the range of the particles momenta used in the measurement and therefore extraction of c_s^2 can be done only with the help of models. For that reason the data trends are compared to them. Hijing fails to describe the data. On the other hand the MUSIC [10] model describes the data very well when the parameter c_s^2 is about 0.23 and effective temperature during QGP evolution is T_{eff} is 222 MeV were assumed in simulation.

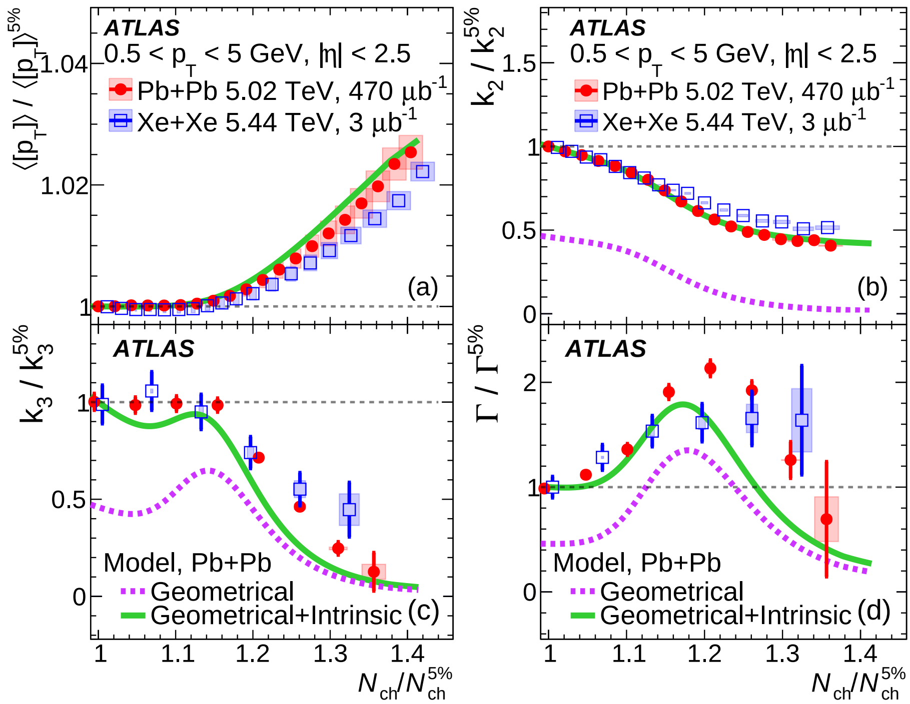

Figure 4. The N_{ch} evolution of various moments of $[p_{\mathrm{T}}]$ from most central collisions. The variables on the axes are scaled by respective value at 5% centrality [7]. Blue points show data for Xe+Xe and red for Pb+Pb collisions and lines are predictions of fluctuations model [9].

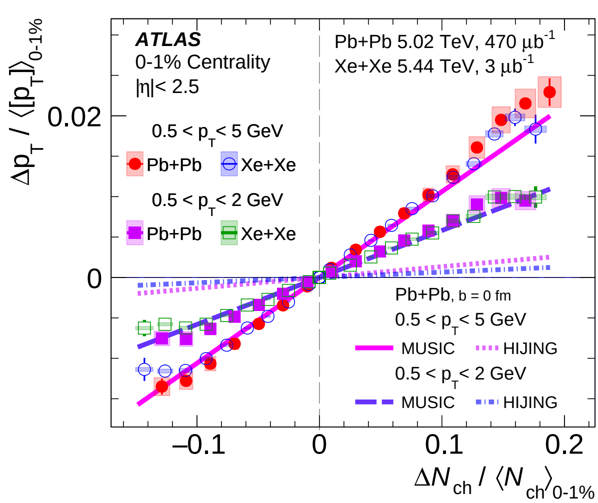

Figure 5. The N_{ch} evolution of $[p_{\mathrm{T}}]$ scaled by average values in 1% most central collisions [7] compared to Hijing and MUSIC simulation predictions [8]. Blue points show data for Xe+Xe and red for Pb+Pb collisions.

4 Summary and Acknowledgements

The results on correlations between flow harmonics and mean particles momenta as well as fluctuations of the momenta itself in the event were presented. They offer an insight into the initial-state conditions of ultrarealtivistic nuclear collisions that is highly demanded information at the era of precision studies of quark gluon plasma. Author is grateful for invitation to speak at the Hard Probes 2024 conference.

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