ATLAS measurement of mean momentum fluctuations and correlations with the flow in Xe+Xe and Pb+Pb collisions

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Abstract. The thermal fluctuations in the QGP medium formed in heavy ion collisions present themselves as event-wise mean transverse momentum ($[p_{\mathrm{T}}]$) fluctuations in the final state. Recent studies have shown that the fluctuations are sensitive to radial flow, random thermal motion, and nuclear deformation. They can provide constraints on the extent of thermalization of the QGP droplet. Recently, correlations of $[p_{\mathrm{T}}]$ with flow harmonic coefficients (v_n) also gained interest, as they were found to be sensitive primarily to the initial state fluctuations. This talk presents precise measurements of up to 3rd order $[p_{\mathrm{T}}]$ cumulants as a function of multiplicity and centrality with an emphasis on ultra-central collisions. These results have strong implications for understanding the impacts of the initial condition, medium thermalization, and medium properties on final state $[p_{\mathrm{T}}]$ fluctuations.

1 Introduction

The correlation between flow harmonics v_n and mean transverse momentum $[p_{\mathrm{T}}]$ proved to be an useful tool to study the initial geometry of the nuclei [1]. The first measurement carried by ATLAS [2] set the example of how, with the support of precise modeling in simulation, the initial shapes of the collided objects can be extracted. Difference between the value of the Pearson correlation coefficient ρ for ^{129}Xe and ^{208}Pb collisions was found to be a strong indicator of ^{129}Xe nuclei triaxial shape [2].

Normalizing constituents of the ρ, that are variances of v_n and $[p_{\mathrm{T}}]$ denoted c_k shown in Figure 1, exhibit a nontrivial variation with the centrality. The v_n variance gradually decreases with centrality estimator and in ultra central collisions (UCC) a constant value is assumed. That is attributed to the fact that in the most central collisions the initial geometry is a result of collisions between fully overlapping nuclei. The trends for Pb+Pb and Xe+Xe collision are similar in nature. The evolution of c_k with centrality estimator exhibits a fall and in the most central collision the values fall even faster. The effect in UCC can be seen thanks to a very high statistics of UCC events collected by ATLAS. An in-depth study of $[p_{\mathrm{T}}]$ moments is carried out in order to elucidate this behavior. In addition, the system size impact on observables can be studied by comparing to measurement for Xe+Xe collisions.

2 Mean transverse momentum fluctuations

Until recently, less attention has been paid to a simpler quantity such as the $[p_{\mathrm{T}}]$ and its moments. Inspired by aforementioned features observed in data several predictions appeared concerning the origin of the moments of the $[p_{\mathrm{T}}]$ fluctuations [4], the evolution of the $[p_{\mathrm{T}}]$ in most central collisions, and significance of it in extraction of QGP EOS parameters [6].

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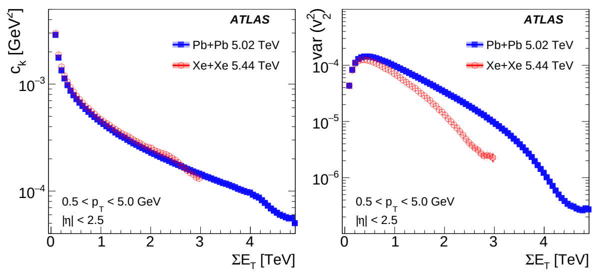

Figure 1. (left) The $[p_{\mathrm{T}}]$ variance estimator c_k and (right) the variance of the second harmonic flow coefficient $var(v_2^2)$ as function of collision centrality estimated using energy deposited in ATLAS Forward Calorimeter, ΣE_{T} [2].

The ATLAS Collaboration [7] has measured first three central moments of $[p_{\mathrm{T}}]$ distribution in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. In the analysis, the cumulants c_n are obtained using the formula:

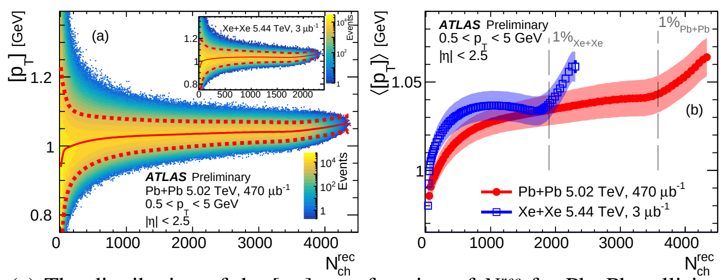

Figure 2. (a) The distribution of the $[p_{\mathrm{T}}]$ as a function of N_{ch}^{rec} for Pb+Pb collisions (and Xe+Xe in the inset). An average over events is shown with continuous red line and the dashed lines denote one standard deviation width of it. (b) The first moment of $[p_{\mathrm{T}}]$ distribution as function of N_{ch}^{rec} for Pb+Pb and Xe+Xe. Vertical lines denote the values of N_{ch}^{rec} for 1% of most central collisions [3].

$$c_n = \frac{\sum'_{i_1,\ldots,i_n} w_{i_1} p_{\mathrm{T},i_1} - \langle [p_{\mathrm{T}}] \rangle) \cdot \ldots \cdot w_{i_n}(p_{\mathrm{T},i_n} - \langle [p_{\mathrm{T}}] \rangle)}{\sum'_{i_1,\ldots,i_n} w_{i_1} \cdot \ldots \cdot w_{i_n}}$$

where the w_i denote experimental correction weights applied to each charged particle tracks depending on the p_{T}, rapidity and centrality, p_{i_n} is particle momentum, and the indices are not repeated in the sums Σ'. Moments are defined using c_n: the variance $k_2 = \langle c_2 \rangle / \langle [p_{\mathrm{T}}] \rangle^2$, the skewness $k_3 = \langle c_3 \rangle / \langle [p_{\mathrm{T}}] \rangle^3$, and a normalized skewness $\gamma = \langle c_3 \rangle / \langle c_2 \rangle^{3/2}$. Figure 2 presents the measurement of the $[p_{\mathrm{T}}]$ and $\langle [p_{\mathrm{T}}] \rangle$ evolution with the centrality estimator that is the number of reconstructed charged particles $N_{ch}^{rec,scaled}$ within ATLAS tracking detector acceptance and with $0.5 < p_{\mathrm{T}} < 5$ GeV. The $N_{ch}^{rec,scaled}$ is obtained from N_{ch}^{rec} by scaling it by a value $1/N_{ch}^{rec}$ obtained for 1% centrality interval independently for Pb+Pb and Xe+Xe and allows for a better comparison between the two systems. The $\langle [p_{\mathrm{T}}] \rangle$ exhibits rapid rise from peripheral to central collisions and a plateau for broad range of mid-central collisions. An additional rise of about 3% is observed in UCC. The sources of $[p_{\mathrm{T}}]$ fluctuations for a given centrality interval are stochastic in nature and therefore the moments are expected to scale with the number of collision participants N_{part}: $k_2 \propto N_{part}^{-1}$ and $k_3 \propto N_{part}^{-2}$. Experimentally the N_{part} is replaced by the N_{ch}^{rec}. Higher order moments of $[p_{\mathrm{T}}]$ scaled by N_{ch}^{rec} are shown in

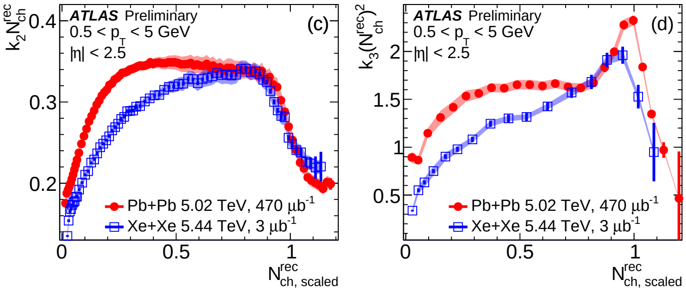

Figure 3. The distribution of the N_{ch}^{rec} scaled moment of $[p_{\mathrm{T}}]$ distribution as a function of $N_{ch}^{rec,scaled}$ in Pb+Pb and Xe+Xe collisions [3].

Figure 3. The $k_2(N_{ch}^{rec})$ evolution with centrality can be divided into three regions, the peripheral collisions where the rapid increase is attributed to an onset of thermalisation, the plateau is where the independent sources picture describes the data well and UCC region where the fluctuations are reduced due to disappearance of impact parameter variation. In this picture the thermalisation in Xe+Xe collisions fully develop only in very central collisions. The $k_3 \cdot (N_{ch}^{rec})^2$ evolution with centrality exhibits similar rise in peripheral collisions but evolution in UCC becomes nonmonotonic. The rapid and distinctive features of the evolution in the UCC region offer an opportunity to shed light on the sources and magnitudes of momentum fluctuations.

This is mostly because in these collisions the geometric component related to non-zero impact parameter is diminished. An phenomenological model is proposed [4] in which the fluctuations in N_{ch}^{rec} and $[p_{\mathrm{T}}]$ are described by a 2D gaussian distribution with a correlation term. Comparison of the data to the predictions of this model are shown in Figure 4. It is shown for a 5% most central collisions and and each moment is scaled by its value at 5% centrality interval limit. The model, whose parameters are obtained from the fit to N_{ch}^{rec} spectra describe very well the data. Accordingly, the $[p_{\mathrm{T}}]$ fluctuations are a compositions of intrinsic (quantum) fluctuations and a term that is driven by geometry [4]. In UCC collisions only the former plays the role. Higher order moments k_3 and γ exhibit a non-monotonic behavior due to the fact that the underlying N_{ch}^{rec} distribution gets right-truncated in UCC [5]. The trends are comparable between Xe+Xe and Pb+Pb. The rise of the $\langle[p_{\mathrm{T}}]\rangle$ with the value

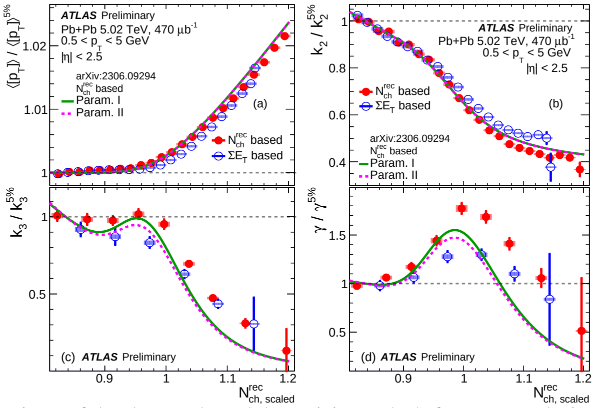

Figure 4. The comparison of the data and model precisions [4, 5] for $[p_{\mathrm{T}}]$ evolution with centrality. The N_{ch}^{rec} is scaled by the mean value for 1% most central collisions independently for Pb+Pb and Xe+Xe. In addition the moments are scaled by their values at 5% centrality interval limit [3].

of centrality estimator was predicted to be linked to the speed of sound in QGP [6] with the relation:

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

where the $\langle N_{ch}^{rec}\rangle$ and $\langle[p_{\mathrm{T}}]\rangle$ are the averages for 1% most central collisions. Then, in slices of ΣE_T the relative variation of N_{ch}^{rec} and $\langle[p_{\mathrm{T}}]\rangle$, denoted respectively Δp_{T} and ΔN_{ch}^{rec} obtained. They are shown in Figure 5 and a clear correlation can be observed for these two quantities. It is found to be nearly identical for Xe+Xe and Pb+Pb but the slope strongly depends on the choice of particles momentum interval. Superimposed lines show results obtained from MC simulations. The predictions by MUSIC [5, 8], boost-invariant hydrodynamic model with parameters, in particular the feeze-out temperature, set according to current state of knowledge, capture the trend observed in the data very well and further studies are needed to disentangle the impact of p_{T} interval accessible experimentally in extraction of c_s^2. At the same time Hijing MC fails to describe the data.

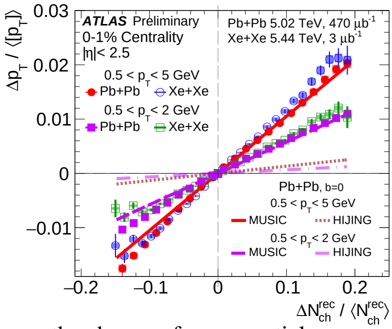

Figure 5. The correlation between the change of mean particles momentum per event Δp_{T} and change of mean multiplicity in an event ΔN_{ch}^{rec} in UCC Pb+Pb and Xe+Xe collisions [3]. The lines show predictions of MUSIC [5, 8] and Hijing [9]. The trends are shown for two charged particles momenta intervals.

3 Summary

Following the successful measurement of $v_n - [p_{\mathrm{T}}]$ correlations the ATLAS experiment has measured fluctuations of the mean particles momentum in the event. The centrality scaling properties following independent source scenario were confirmed in broad range of centralities however an intriguing feature was observed in peripheral and central collisions. Detailed studies of fluctuations in UCC allowed to validate a proposed model of $[p_{\mathrm{T}}]$ fluctuations. Moreover the correlation between the $[p_{\mathrm{T}}]$ and N_{ch}^{rec} allows for extraction of QGP speed of sound directly from data or at least provides a strong constraint on models.

4 Acknowledgements

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