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RECENT RESULTS ON FLOW AND CORRELATIONS FROM THE ATLAS EXPERIMENT*

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The azimuthal anisotropy in Xe+Xe collisions at the energy of $\sqrt{s_{NN}} = 5.44$ TeV was recently investigated in the ATLAS experiment at the LHC. Preliminary results on the p_{T} and centrality dependence of v_2 and v_3 harmonics obtained with multi-particle cumulants are presented. The measurements indicate a presence of nearly Gaussian v_n harmonic fluctuations in the Xe+Xe system. For Pb+Pb collisions at the energy of $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, the longitudinal flow harmonic correlations are presented, providing evidence that the correlations between v_n ($n = 2$–4) separated in pseudorapidity do not factorise into the product of single-particle v_n. Additionally, for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, a preliminary determination of the modified Pearson's correlation coefficient for the event-wise mean transverse momentum and v_n^2 ($n = 2$–4) is shown. Significant, non-zero correlation coefficients are measured for all v_n harmonics.

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1. Introduction

In ultra-relativistic heavy-ion collisions at the Large Hadron Collider (LHC), the azimuthal anisotropy is one of the main tools to study quark–gluon plasma (QGP) properties, which resemble those of a nearly perfect fluid [1]. The azimuthal angle distributions of particles produced in heavy-ion collisions are characterised by a Fourier series [2]

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = \frac{N_0}{2\pi}\left(1 + \sum_{n=1} 2v_n \cos\left[n\left(\phi - \Phi_n\right)\right]\right) , \tag{1}$$

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where ϕ is the azimuthal angle of the particle, and v_n and Φ_n are flow harmonics and the reaction plane angles of the n^{th}-order anisotropy, respectively. The second harmonic, called elliptic flow (v_2), and higher-order flow harmonics (v_3, v_4, ...) characterise correspondingly the "elliptical" shape of the initial interaction region and its higher modes.

Recently, the ATLAS experiment [3] measured v_n harmonics in Xe+Xe collisions at the energy of $\sqrt{s_{NN}} = 5.44$ TeV [4]. The results on the flow harmonics in Xe+Xe interactions fill the gap between the measurements obtained in small (pp and p+Pb) and large (Pb+Pb) collision systems at the LHC energies. New measurements of azimuthal anisotropy using multi-particle correlations in Xe+Xe collisions are presented in Section 2.

Particularly challenging for models describing properties of QGP are the results on the longitudinal correlations between flow harmonics [5]. ATLAS measured the longitudinal decorrelation coeffcient in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, as presented in Section 3. Another useful observable for the QGP modelling is the modified Pearson's coefficient characterising the strength of the correlations between v_n and the average p_{T}, thus, providing insight into the interplay between the azimuthal and radial flows in heavy-ion collisions [6, 7]. The results on the Pearson's correlation coefficient in Pb+Pb collisions at the energy $\sqrt{s_{NN}} = 5.02$ TeV [8] are shown in Section 4.

2. Azimuthal anisotropy in Xe+Xe interactions

The measurement of charged particle azimuthal anisotropy in Xe+Xe interactions at $\sqrt{s_{NN}} = 5.44$ TeV is based on the data sample of integrated luminosity of 3 μb^{-1} collected by the ATLAS experiment in October 2017 [4]. The analysis uses charged particles with transverse momentum $p_{\mathrm{T}} > 0.5$ GeV within the pseudorapidity range of $|\eta| < 2.5$, detected in the ATLAS inner detector. To quantify the type and strength of flow fluctuations, $v_n\{2k\}$, $k = 1, 2, 3$ were obtained using $2k$-particle cumulants [9]. Figure 1 shows the $v_2\{4\}$ and $v_3\{4\}$ harmonics as a function of p_{T} measured with the four-particle cumulant method in 5–10% and 40–60% centrality intervals. A typical p_{T}-dependence is observed: first, a rise up to $p_{\mathrm{T}} \approx 3$ GeV and then, for v_2, a decrease at higher p_{T}. The $v_2\{4\}$ dominates and remains significant even at the highest p_{T}.

The p_{T}-integrated v_2 and v_3 harmonics for four- and six-particle cumulants are shown in the left panel of Fig. 2 as a function of the collision centrality. The elliptic flow signal is strongly dependent on the collision centrality, while the v_3 shows a weaker dependence, consistent with the expected significant contribution from fluctuations of the initial geometry to the triangular anisotropy. Similar magnitudes of $v_2\{4\}$ and $v_2\{6\}$ harmonics

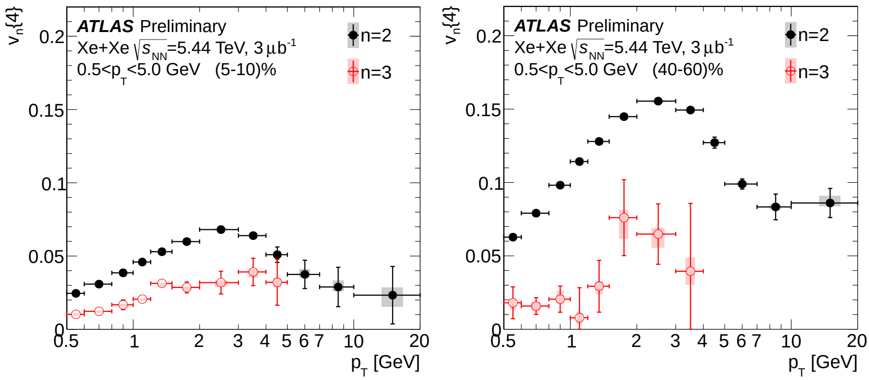

Fig. 1. The v_2 and v_3 as a function of p_T measured with the four-particle cumulants in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV for two centrality intervals: 5–10% (left) and 40–60% (right) [4]. Vertical error bars and shaded boxes show statistical and systematic uncertainties, respectively.

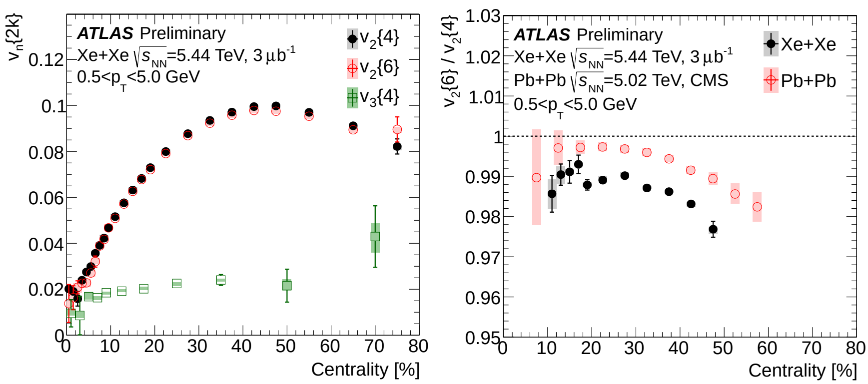

Fig. 2. Centrality dependence of v_2 measured using multi-particle cumulants in Xe+Xe collisions (left) [4]. The ratio $v_2\{6\}/v_2\{4\}$ in Xe+Xe collisions [4] compared to Pb+Pb results from Ref. [10] (right). Vertical error bars and shaded boxes show statistical and systematic uncertainties, respectively.

indicate that the non-flow effects are negligible and v_2 fluctuations are close to Gaussian. Particularly interesting is the ratio $v_2\{6\}/v_2\{4\}$, shown in the right panel of Fig. 2, which for a Gaussian fluctuation model, is expected to be unity. In the Xe+Xe collisions, the ratio amounts to 0.98–0.99. A comparison of this ratio to one measured in 5.02 TeV Pb+Pb collisions, also shown in this panel, suggests that the non-Gaussian component in Xe+Xe may be more significant than in the larger Pb+Pb system.

3. Elliptic flow decorrelations in Pb+Pb collisions

The study of longitudinal flow correlations provides insight into the boost invariance of the initial conditions and space-time evolution of the QGP medium. The correlation is measured between flow vectors [2], q_n [1], separated in pseudorapidity by $\Delta\eta \equiv (\eta - (-\eta)) = 2\eta$, where one flow vector is evaluated at positive η and the other one at negative η. It is quantified by the decorrelation coefficient of the k^{th} moment defined as [5]

$$r_{n|n;k}(\eta) = \frac{\langle q_n^k(-\eta) q_n^{\star k}(\eta_{\mathrm{ref}})\rangle}{\langle q_n^k(\eta) q_n^{\star k}(\eta_{\mathrm{ref}})\rangle}\,, \tag{2}$$

where $q_n(\eta)$ is the flow vector of particles in narrow pseudorapidity intervals covering $|\eta| < 2.4$ and $q_n(\eta_{\mathrm{ref}})$ is the reference flow vector obtained from the energy deposits in the ATLAS forward calorimeter towers at $|\eta_{\mathrm{ref}}| > 4$. The $r_{n|n;k}(\eta) \neq 1$ provides evidence that the correlation between v_n harmonics does not factorise into the product of single-particle v_n coefficients. ATLAS performed extensive measurements of longitudinal flow correlations for charged particles in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV [5]. In particular, Fig. 3 shows that $r_{2|2;1}(\eta) < 1$, indicating a significant decorrelation in Pb+Pb interactions. The flow decorrelation increases approximately linearly with the pseudorapidity separation. Similar trend, shown in Ref. [5], is also observed for third and fourth order harmonics with a stronger decorrelation at $\sqrt{s_{NN}} = 2.76$ TeV than at $\sqrt{s_{NN}} = 5.02$ TeV.

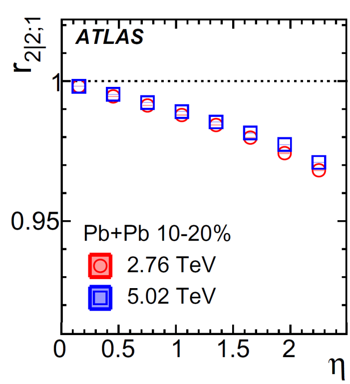

Fig. 3. The $r_{2|2;1}$ in 10–20% central Pb+Pb collisions at two energies as a function of pseudorapidty separation $\Delta\eta/2 = \eta$ [5].

[1] A complex number is used to represent the real two-dimensional flow vector [5]. The $q_n^\star$ stands for conjugate flow vector.

4. The v_n-mean p_{T} correlations in Pb+Pb collisions

The modified Pearson's coefficient, ρ, can be used to measure the strength of the v_n–$[p_{\mathrm{T}}]$ correlation, where $[p_{\mathrm{T}}]$ denotes the mean transverse momentum of charged particles in an event [7]. It is defined as

$$\rho\left(v_n^2,[p_{\mathrm{T}}]\right) = \frac{\mathrm{cov}\left(v_n\{2\}^2,[p_{\mathrm{T}}]\right)}{\sqrt{\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}}\sqrt{c_k}}\,,$$

where in the numerator the covariance between the $v_n\{2\}^2$ and $[p_{\mathrm{T}}]$ is used. To suppress non-flow effects, the $v_n\{2\}^2$ values are obtained using sub-events separated by 1.5 unit in pseudorpidity, $|\eta| > 0.75$, while the event mean transverse momentum, $[p_{\mathrm{T}}]$, is obtained using charged particles with $|\eta| < 0.5$. The variance of $v_n\{2\}^2$ is approximated by using the physical variance of flow harmonics fluctuations: $\mathrm{Var}(v_n^2)_{\mathrm{dyn}} = v_n\{2\}^4 - v_n\{4\}^4$, where $v_n\{2\}$ and $v_n\{4\}$ are the v_n harmonics obtained from two- and four-particle cumulants [9]. The $[p_{\mathrm{T}}]$ variance, denoted by c_k, is calculated by the prescription given in Refs. [8, 11, 12].

The measurement of the ρ coefficient is done for the minimum-bias Pb+Pb collisions at the energy of $\sqrt{s_{NN}} = 5.02$ TeV [8]. It is performed for four different p_{T} intervals probing the soft and hard part of the p_{T}-spectrum. Figure 4 shows $\rho(v_2^2,[p_{\mathrm{T}}])$ and $\rho(v_3^2,[p_{\mathrm{T}}])$ as a function of centrality expressed by the average number of nucleons participating in Pb+Pb collisions, N_{part}. For all p_{T} intervals, $\rho(v_2^2,[p_{\mathrm{T}}])$ increases with collision centrality starting from negative values at $N_{\mathrm{part}} < 40$. The strongest correlations, $\rho(v_2^2,[p_{\mathrm{T}}]) = 0.24$–$0.30$, are observed at $N_{\mathrm{part}} \sim 320$. For higher N_{part}, thus for the most central collisions, $\rho(v_2^2,[p_{\mathrm{T}}])$ starts to decrease. The significant

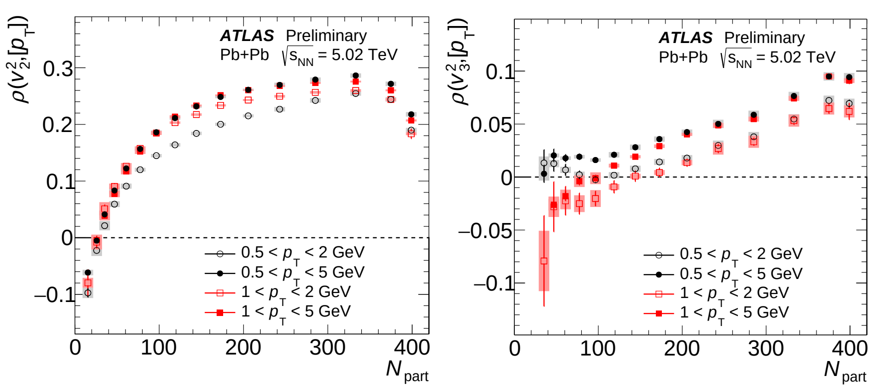

Fig. 4. The modified Pearson's coefficient $\rho(v_2^2,[p_{\mathrm{T}}])$ (left) and $\rho(v_3^2,[p_{\mathrm{T}}])$ (right) as a function of N_{part} in 5.02 TeV Pb+Pb collisions [8]. Vertical error bars and shaded boxes show statistical and systematic uncertainties, respectively.

correlation observed for mid-central events is attributed to a stronger hydrodynamic response to the initial state eccentricities [8]. The correlation coefficient values calculated with the upper p_{T} limit of 2 GeV are 10–20% smaller than the values obtained with p_{T} limit of 5 GeV.

The correlation coefficient $\rho(v_3^2, [p_{\mathrm{T}}])$ is also measured. The results, displayed in Fig. 4, show that $\rho(v_3^2, [p_{\mathrm{T}}])$ is smaller and has a weaker centrality dependence as compared to $\rho(v_2^2, [p_{\mathrm{T}}])$. It is positive for a broad range of centralities, except for $N_{\mathrm{part}} < 100$, where it is negative or consistent with 0. The correlation for the p_{T} ranges with the same maximum p_{T} are consistent with each other for $N_{\mathrm{part}} > 100$ and those obtained with the higher maximum p_{T} threshold are larger.

The values of $\rho(v_4^2, [p_{\mathrm{T}}])$, shown in Ref. [8], are found to be positive over the entire centrality range studied.

5. Summary

This report presents measurements of azimuthal anisotropy of charged particles in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV in the ATLAS experiment at the LHC. The v_2 and v_3 harmonics are measured using the multi-particle cumulant method over a wide transverse momentum ($0.5 < p_{\mathrm{T}} < 20$ GeV) and centrality (0–80%) ranges. A typical p_{T} dependence for the harmonics is observed: first, an increase with p_{T} up to a maximum around 3–4 GeV and then, for v_2, a decrease for higher p_{T}. As a function of centrality, the v_2 harmonic varies significantly, while the v_3 shows a much weaker trend. The multi-particle cumulant results suggest that the v_n fluctuations are nearly Gaussian. The ratio $v_2\{6\}/v_2\{4\} < 1$ indicates a small residual non-Gaussian component, which is larger in the Xe+Xe than in Pb+Pb system.

Measurements of longitudinal flow correlations for charged particles are presented for Pb+Pb data at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. The factorisation of two-particle azimuthal correlations into single-particle flow harmonics v_n is found to be broken, and the amount of the factorisation breakdown, measured by the decorrelation coefficient $r_{2|2;1}$, increases approximately linearly as a function of the η separation between the two particles.

The measurement of the modified Pearson's correlation coefficient ρ between the flow harmonics and the per-event mean transverse momentum is performed using minimum-bias 5.02 TeV Pb+Pb data. A strong positive correlation $\rho(v_2^2, [p_{\mathrm{T}}])$ is observed in mid-central and central collisions, while negative values are measured for peripheral events. The correlation $\rho(v_3^2, [p_{\mathrm{T}}])$ is found to be weaker.

These new measurements can be used to improve our understanding of the underlying mechanism of QGP dynamics and to help constraining theoretical models.

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