RECENT RESULTS ON FLOW AND CORRELATIONS FROM THE ATLAS EXPERIMENT

ADAM TRZUPEK

on behalf of the ATLAS Collaboration

Institute of Nuclear Physics Polish Academy of Sciences
Radzikowskiego 152, 31-342 Kraków, Poland

(Received December 20, 2018)

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.

DOI:10.5506/APhysPolBSupp.12.411

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]

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

* Presented at the XIII Workshop on Particle Correlations and Femtoscopy, Kraków, Poland, May 22–26, 2018.
where $\phi$ is the azimuthal angle of the particle, and $v_n$ and $\Phi_n$ 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 ($v_3, v_4, \ldots$) 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 coefficient 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 $3 \mu$b$^{-1}$ collected by the ATLAS experiment in October 2017 [4]. The analysis uses charged particles with transverse momentum $p_T > 0.5$ 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 2$k$-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 $p_T \approx 3$ 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
Recent Results on Flow and Correlations from the ATLAS Experiment

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 \( q_n \), separated in pseudorapidity by \( \Delta \eta \equiv (\eta - (-\eta)) = 2\eta \), where one flow vector is evaluated at positive \( \eta \) and the other one at negative \( \eta \). It is quantified by the decorrelation coefficient of the \( k \)th moment defined as [5]

\[
\rho_{n|n;k}(\eta) = \frac{\langle q_n^k(-\eta)q_n^{*k}(\eta_{\text{ref}}) \rangle}{\langle q_n^k(\eta)q_n^{*k}(\eta_{\text{ref}}) \rangle},
\]

(2)

where \( q_n(\eta) \) is the flow vector of particles in narrow pseudorapidity intervals covering \( |\eta| < 2.4 \) and \( q_n(\eta_{\text{ref}}) \) is the reference flow vector obtained from the energy deposits in the ATLAS forward calorimeter towers at \( |\eta_{\text{ref}}| > 4 \). The \( \rho_{n|n;k}(\eta) \neq 1 \) 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 pseudorapidity separation \( \Delta \eta/2 = \eta \) [5].](image)

\(^1\) A complex number is used to represent the real two-dimensional flow vector [5]. The \( q_n^* \) stands for conjugate flow vector.
4. The $v_n$-mean $p_T$ correlations in Pb+Pb collisions

The modified Pearson’s coefficient, $\rho$, can be used to measure the strength of the $v_n-[p_T]$ correlation, where $[p_T]$ denotes the mean transverse momentum of charged particles in an event [7]. It is defined as

$$\rho(v_n^2, [p_T]) = \frac{\text{cov}(v_n^2 \{2\}, [p_T])}{\sqrt{\text{Var}(v_n^2 \{2\})_{\text{dyn}}} \sqrt{c_k}},$$

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

The measurement of the $\rho$ 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 $\rho(v_2^2, [p_T])$ and $\rho(v_3^2, [p_T])$ as a function of centrality expressed by the average number of nucleons participating in Pb+Pb collisions, $N_{\text{part}}$. For all $p_T$ intervals, $\rho(v_2^2, [p_T])$ increases with collision centrality starting from negative values at $N_{\text{part}} < 40$. The strongest correlations, $\rho(v_2^2, [p_T]) = 0.24–0.30$, are observed at $N_{\text{part}} \sim 320$. For higher $N_{\text{part}}$, thus for the most central collisions, $\rho(v_2^2, [p_T])$ starts to decrease. The significant

![Fig. 4](image-url)
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 \( \rho(v_2^2, [p_T]) \) is also measured. The results, displayed in Fig. 4, show that \( \rho(v_2^2, [p_T]) \) is smaller and has a weaker centrality dependence as compared to \( \rho(v_2^3, [p_T]) \). It is positive for a broad range of centralities, except for \( N_{\text{part}} < 100 \), 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 \( N_{\text{part}} > 100 \) and those obtained with the higher maximum \( p_T \) threshold are larger.

The values of \( \rho(v_3^3, [p_T]) \), 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 < \( p_T \) < 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 \( \eta \) separation between the two particles.

The measurement of the modified Pearson’s correlation coefficient \( \rho \) 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 \( \rho(v_2^2, [p_T]) \) is observed in mid-central and central collisions, while negative values are measured for peripheral events. The correlation \( \rho(v_2^3, [p_T]) \) 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.
This work was supported in part by the National Science Centre, Poland (NCN) grant 2016/23/B/ST2/00702 and by PL-Grid Infrastructure.

REFERENCES