AZIMUTHAL ANISOTROPY IN HEAVY-ION COLLISIONS WITH THE ATLAS DETECTOR AT THE LHC*

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The high-statistics experimental data collected by the ATLAS experiment during the 2015 Pb+Pb and 2017 Xe+Xe LHC runs are used to measure charged particle azimuthal anisotropy. ATLAS measurements of differential and global Fourier harmonics of charged particles (ν_n) in 5.02 TeV Pb+Pb and 5.44 TeV collisions in a wide range of transverse momenta (up to 60 GeV), pseudorapidity ($|\eta| < 2.5$) and collision centrality (0–80%) are presented. The higher order harmonics, sensitive to fluctuations in the initial state, are measured up to $n = 7$ using the two-particle correlation, cumulant and scalar-product methods. The dynamic properties of the QGP are studied using a modified Pearson's correlation coefficient, $\rho(\nu_n, p_{\mathrm{T}})$, between the eventwise mean transverse momentum and the magnitude of the flow vector in 5.02 TeV Pb+Pb and p+Pb collisions. The flow results allow to improve the understanding of initial conditions of nuclear collisions, hydrodynamical behaviour of Quark–Gluon Plasma and parton energy loss.

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1. Introduction

The ATLAS detector [1] at the Large Hadron Collider (LHC) at CERN in Switzerland is an excellent tool for studying the Quark–Gluon Plasma (QGP). The QGP is a strongly-interacting nuclear matter formed in ultra-relativistic heavy-ion collisions. It exhibits hydrodynamical properties of a nearly perfect fluid with very low viscosity. The initial interaction region, where the QGP developed, is non-isotropic due to initial geometry of a collision. Extreme conditions inside the collision zone lead to plasma expansion. Thus, the initial spatial anisotropy is translated into the final spatial anisotropy observed in the momentum space. As a result, particles

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produced in a collision exhibit anisotropic particle distribution. This feature is commonly studied using the azimuthal angles of produced particles: $\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + \sum_n 2\nu_n \cos[n(\phi - \Psi_n)]$ [2], where ϕ is an azimuthal angle of particle, Ψ is a reaction plane angle and n is the number of harmonic. The ν_n coefficients are known as flow harmonics of n^{th} order. The 2^{nd} flow harmonic (*elliptic flow*) provides the information about the initial shape of the interaction region, while higher order ν_n describe initial state fluctuations.

This report presents the ATLAS measurements of ν_n harmonics obtained using Pb+Pb and Xe+Xe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [3] and $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV [4], respectively. Furthermore, the correlations of flow harmonics and mean event p_{T} in 5.02 TeV Pb+Pb and p+Pb collisions are discussed using the modified Pearson's correlation coefficient [5].

2. Azimuthal anisotropy measurements in heavy-ion collisions

The ν_n results shown in the report are obtained using the scalar-product (SP) [6] and two-particle correlations (2PC) [2] measurement techniques. The SP and 2PC methods are based on correlations of two particles taken from the same event but with different pseudorapidity or transverse momentum range, and measure the same quantity, which is $\sqrt{\langle \nu_n^2 \rangle}$ [7]. In both methods, any non-flow correlations are suppressed by requiring large separation in pseudorapidity, $\Delta\eta$, between correlating particles. In 2PC, the $\Delta\eta$ is usually chosen to be $|\Delta\eta| > 2$, while it is even higher for the SP method and is within $|\Delta\eta| > 3.2$.

Figure 1 shows ν_n harmonics obtained with the SP method as a function of p_{T} up to $p_{\mathrm{T}} = 60$ GeV in two collision centrality intervals: 0–0.1% and 30–40% corresponding to the ultra-central and mid-central $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV Pb+Pb collisions, respectively. Results are integrated over $|\eta| < 2.5$ range. All measured harmonics (ν_2–ν_7) exhibit similar trend over different centralities: at low p_{T}, the ν_n increase almost linearly with p_{T} reaching its maximum at $p_{\mathrm{T}} = 2$–4 GeV, then the gradual fall of ν_n value is observed. The ν_2 is a dominant anisotropy in mid-central collisions as the geometrical shape of the collision region is elliptical. The magnitudes of higher order flow coefficients significantly decrease indicating the harmonics ordering of $\nu_n > \nu_{n+1}$. In the ultra-central Pb+Pb collisions, the interaction region is almost spherical, which reflects in small value of elliptic flow. Thus, higher order ν_n harmonics are more pronounced and the ν_n ordering is changed to $\nu_3 > \nu_4 > \nu_5 \approx \nu_2$ for $p_{\mathrm{T}} = 3$–5 GeV implying that in these collisions the azimuthal anisotropy arises from the initial state fluctuations. The flow coefficients are measured up to 7^{th} harmonic, which is found to be non-zero for centrality range of 0–50%, and is most prominent in the central and mid-central collisions at $p_{\mathrm{T}} = 2$–4 GeV.

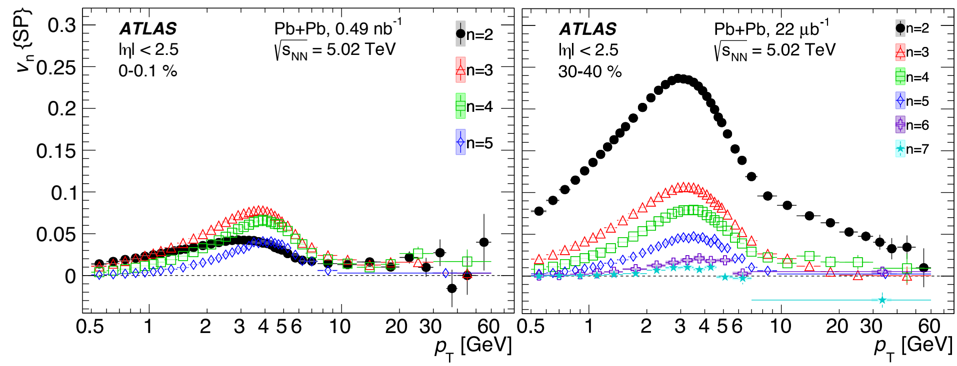

Fig. 1. The v_n harmonics as a function of p_T integrated over $|\eta| < 2.5$ obtained using SP method in ultra-central (left) and mid-central (right) Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [3].

Analogous v_n measurements are performed for $\sqrt{s_{NN}} = 5.44$ TeV Xe+Xe collisions and are discussed in Ref. [4]. The differential $v_n\{\text{Xe} + \text{Xe}\}(p_T)$ results resemble the trends observed in Pb+Pb collisions. However, there are differences between flow magnitudes when comparing Pb+Pb and Xe+Xe quantitatively. Left panels in figure 2 show the v_2 and v_3 harmonics ob-

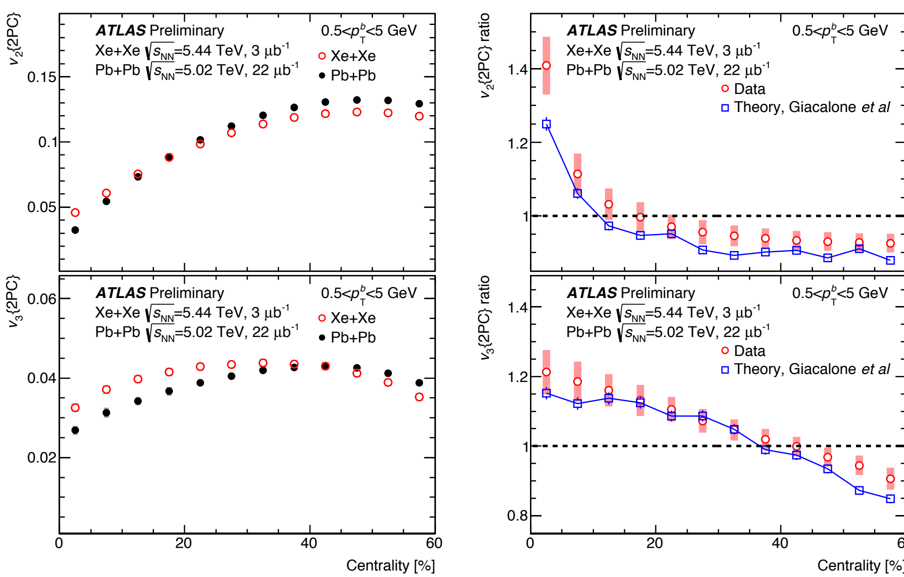

Fig. 2. The v_2 (top left) and v_3 (bottom left) harmonics as a function of centrality obtained with 2PC method in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV integrated over $0.5 < p_T < 5$ GeV [4]. The ratios of the Xe+Xe $v_n\{2\text{PC}\}$ to the Pb+Pb $v_n\{2\text{PC}\}$ (right panels). The ratios are compared with theoretical calculations for $p_T = 0.3$–5 GeV [8].

tained with the 2PC method and integrated over $0.5 < p_{\mathrm{T}} < 5$ GeV as a function of collision centrality in Pb+Pb and Xe+Xe collisions. The ratios of $\nu_n\{\mathrm{Xe}+\mathrm{Xe}\}$ over $\nu_n\{\mathrm{Pb}+\mathrm{Pb}\}$ are presented in right panels of figure 2. The Xe+Xe ν_2 and ν_3 values are significantly larger than those obtained in Pb+Pb collisions in the most central events *i.e.* collision centrality within 0–15(40)% interval for $\nu_2(\nu_3)$. This reflects the fact that Xe ion is twice smaller than Pb ion. The smaller Xe+Xe initial interaction region results in larger fluctuations in the initial nucleons positions, affecting the initial collision geometry, and thus, enhancing ν_n values. On the other hand, in the mid-central and peripheral collisions, the $\nu_n\{\mathrm{Xe}+\mathrm{Xe}\}$ are reduced in comparison to Pb+Pb. This is expected from hydrodynamical predictions as the viscous effects are larger for the lighter collision system. The ratios are consistent with the theoretical calculations obtained by Giacalone *et al.* [8].

3. Flow harmonics and mean p_{T} correlations

The dynamics within QGP medium lead to the variation in the mean event p_{T} on the event-by-event basis. As a consequence, it is expected that event-by-event azimuthal flow harmonics should be correlated with the mean p_{T}, $[p_{\mathrm{T}}]$, of the event [9]. Recently, ATLAS performed a ν_n–$[p_{\mathrm{T}}]$ correlation measurement [5] that is based on the new method proposed by Bożek in Ref. [10]. In the standard technique, the strength of the ν_n–$[p_{\mathrm{T}}]$ correlations is studied using a Pearson correlation coefficient, which is dependent on the covariance and variances of the ν_n^2 and $[p_{\mathrm{T}}]$ distributions. However, the finite charged-particle tracks multiplicity in the event introduce statistical fluctuations and as a consequence broadening of the ν_n^2 and $[p_{\mathrm{T}}]$ distributions. It was proposed to modify the Pearson correlation coefficient to be less sensitive to the event track multiplicity and thus, it is defined as

$$\rho = \frac{\mathrm{cov}\left(\nu_n\{2\}^2, [p_{\mathrm{T}}]\right)}{\sqrt{\mathrm{Var}\left(\nu_n\{2\}^2\right)_{\mathrm{dyn}}\sqrt{c_k}}}\,, \tag{1}$$

where the $\nu_n\{2\}$ is the n^{th} order flow harmonic obtained using 2PC method, the $\mathrm{cov}(\nu_n\{2\}^2, [p_{\mathrm{T}}])$ is the covariance between $\nu_n\{2\}^2$ and $[p_{\mathrm{T}}]$, $\mathrm{Var}(\nu_n\{2\}^2)$ and c_k are the dynamical variance of the $\nu_n\{2\}$ and dynamical p_{T} fluctuation magnitude, respectively. The ν_n–$[p_{\mathrm{T}}]$ correlations measurements performed using the modified Pearson's coefficient are detector-independent allowing for the direct comparisons between different results and with theoretical calculations.

Figure 3 shows the ρ coefficient obtained for ν_2 and ν_3 harmonics in three p_{T} intervals as a function of the collision centrality expressed in the number of nucleons participating in the collision, N_{part}. The $\rho(\nu_2\{2\}^2, [p_{\mathrm{T}}])$

increases with $N_{\rm part}$, starting from negative values in the peripheral collisions, then it changes the sign at $N_{\rm part} \approx 40$, gradually rises to the maximum around $N_{\rm part} \approx 380$ and rapidly decreases in the most central collisions. The $\rho(\nu_3\{2\}^2, [p_{\rm T}])$ shows much weaker $N_{\rm part}$ dependence and also the magnitude of the ρ correlation is lower than for ν_2.

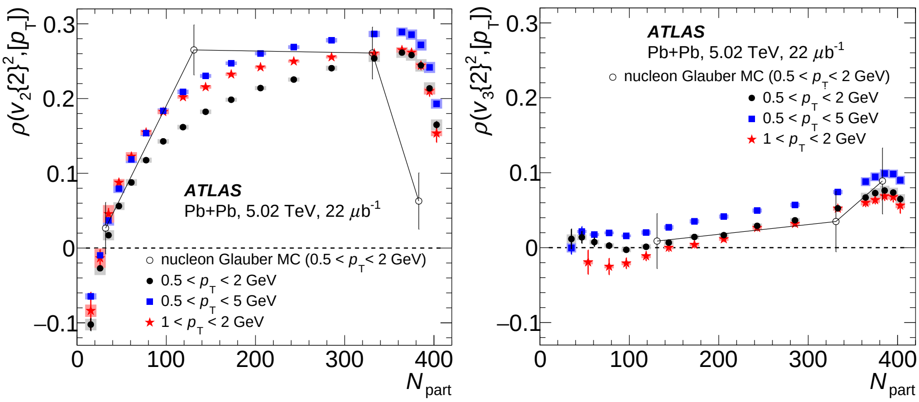

Fig. 3. The modified Pearson's coefficient, ρ, as a function of $N_{\rm part}$ integrated over three $p_{\rm T}$ intervals obtained for ν_2 (left) and ν_3 (right) harmonics in 5.02 TeV Pb+Pb collisions [5]. Results are compared with theoretical predictions.

The results of $\rho(\nu_2\{2\}^2, [p_{\rm T}])$ obtained at $\sqrt{s_{\rm NN}} = 5.02$ TeV p+Pb collisions for three $p_{\rm T}$ intervals as a function of charged-particle multiplicity, $N_{\rm ch}$, which is another estimation of the collision centrality, are shown in figure 4. The ρ coefficient exhibits negative values for the whole range of $N_{\rm ch}$ and is constant within uncertainties.

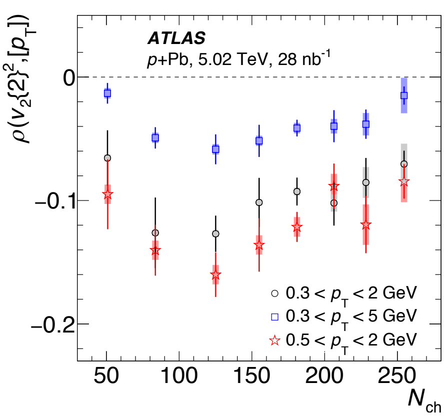

Fig. 4. The charged-particle multiplicity dependence on the $\rho(\nu_2\{2\}^2, [p_{\rm T}])$ obtained in p+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV for three $p_{\rm T}$ intervals [5].

Figure 5 shows the $\rho(v_2\{2\}^2, [p_T])$ correlation as a function of N_{ch} and integrated over $0.5 < p_T < 2$ GeV obtained at $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb and p+Pb collisions. The ρ correlation is negative for both, peripheral Pb+Pb and p+Pb collisions. However, the N_{ch} dependence is different for the two collision systems. In Pb+Pb, the ρ increases with N_{ch}, while in p+Pb, the ρ is constant.

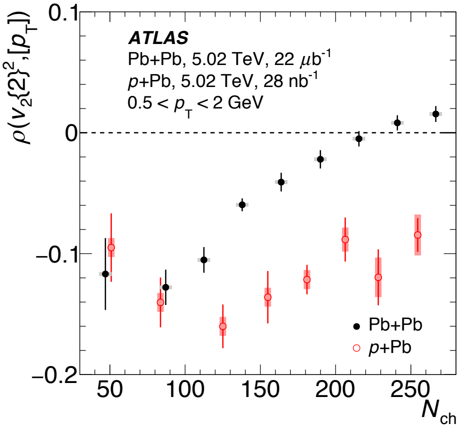

Fig. 5. The $\rho(v_2\{2\}^2, [p_T])$ for the range of $0.5 < p_T < 2$ GeV as a function of N_{ch} obtained for Pb+Pb and p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [5].

4. Summary

One of the QGP properties is azimuthal anisotropy, which is thoroughly studied using data collected in heavy-ion collisions at the ATLAS experiment. The elliptic flow and higher order flow harmonics, v_2–v_7, are measured using several methods up to very high p_T up to 60 GeV, pseudorapidity within detector acceptance $|\eta| < 2.5$, and throughout collision centrality from the ultra-central to the most peripheral 5.02 TeV Pb+Pb and 5.44 TeV Xe+Xe collisions.

ATLAS obtained quantitative estimate of correlation strength between v_n and $[p_T]$ in Pb+Pb and p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the modified Pearsons coefficient ρ. The ρ values are found to be positive for harmonics v_2 and v_3 in the mid-central and central Pb+Pb collisions. In the peripheral Pb+Pb events and p+Pb collisions, the v_2 magnitude is negative. The ρ correlation is dominant and centrality-dependent, while the v_3 harmonic shows much weaker and non-monotonic N_{part} dependence. The hydrodynamic model can qualitatively predict that behaviour. The ρ results provide a quantitative and experimentally unbiased measure of a connection between anisotropic and radial flows.

REFERENCES

[1] ATLAS Collaboration, *JINST* **3**, S08003 (2008).

[2] S.A. Voloshin, A.M. Poskanzer, R. Snellings, *Landolt–Börnstein* **23**, 293 (2010).

[3] ATLAS Collaboration (M. Aaboud *et al.*), *Eur. Phys. J. C* **78**, 997 (2018).

[4] ATLAS Collaboration, Technical Report ATLAS-CONF-2018-011, 2018.

[5] ATLAS Collaboration (G. Aad *et al.*), *Eur. Phys. J. C* **79**, 985 (2019).

[6] C. Adler *et al.*, *Phys. Rev. C* **66**, 034904 (2002).

[7] M. Luzum, J.-Y. Ollitrault, *Phys. Rev. C* **87**, 044907 (2013).

[8] G. Giacalone, J. Noronha-Hostler, M. Luzum, J.-Y. Ollitrault, *Phys. Rev. C* **97**, 034904 (2018).

[9] U. Heinz, R. Snellings, *Annu. Rev. Nucl. Part. Sci.* **63**, 123 (2013).

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