HIGHER HARMONIC ANISOTROPIC FLOW MEASUREMENTS OF CHARGED PARTICLES AT $\sqrt{s_{NN}} = 2.76$ TeV WITH THE ALICE DETECTOR*

YOU ZHOU

for the ALICE Collaboration

Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands
and
Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands

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We report the measurements of elliptic flow $v_2$, as well as higher harmonics triangular flow $v_3$ and quadrangular flow $v_4$, in $\sqrt{s_{NN}} = 2.76$ TeV Pb–Pb collisions, measured with the ALICE detector. We show that the measured elliptic and triangular flow can be understood from the initial spatial anisotropy and its event-by-event fluctuations. The resulting fluctuations of $v_2$ and $v_3$ are also discussed.

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1. Introduction

Anisotropic flow is an good observable to study hot and dense matter created in heavy-ion collisions. The second order harmonic anisotropic flow $v_2$ [1], was studied from SPS to LHC energies [2,3,4] as summarized in [5]. Recently, it has been argued that due to initial event-by-event geometry fluctuations the third harmonic $v_3$, called triangular flow, is finite [6]. In these proceedings, we will discuss the anisotropic flow and its fluctuations measured for charged particles in $\sqrt{s_{NN}} = 2.76$ TeV Pb–Pb collisions.

2. Data sample and analysis

For this analysis in these proceedings the ALICE Inner Tracking System (ITS) and the Time Projection Chamber (TPC) were used to reconstruct charged particle tracks within $|\eta| < 0.8$ and $0.2 < p_t < 5.0$ GeV/$c$. The

VZERO counters and the Silicon Pixel Detector (SPD) were used for the trigger. Only the events whose primary vertex was found within 7 cm from the centre of the detector along the beam direction were selected. The tracks are required to have at least 70 reconstructed points in the TPC and a $\langle \chi^2 \rangle$ per TPC cluster $\leq 4$. The collision centrality determination utilized the VZERO detectors. From the study of the collision centrality determined by different detectors [7], i.e. ZDC, TPC, SPD and VZERO, the centrality resolution is found to be $< 0.5\%$ r.m.s. for the most central collisions, while it increases to $2\%$ r.m.s. for peripheral collisions.

3. Results and discussion

Figure 1 shows the centrality dependence of $v_2$, $v_3$ and $v_4$ integrated over the interval $0.2 < p_t < 5.0$ GeV/c. To suppress non-flow effects on the 2-particle cumulant analysis, a minimum $|\Delta \eta|$ gap of one unit was used between the correlated particles. We correct for the estimated remaining non-flow contributions by using HIJING [8]. We observe that the magnitude of $v_3$ is much smaller than $v_2$ (except for the most central collisions) and does not show a strong centrality dependence. These measurements are described by hydrodynamic calculations based on Glauber initial conditions and $\eta/s = 0.08$, while they are underestimated by hydrodynamic calculations with MC–KLN initial conditions and $\eta/s = 0.16$ [9]. The comparison suggests a small value of $\eta/s$ for the produced matter. The $v_3$ measured from the 4-particle cumulant is about a factor 2 smaller than the 2-particle cumulant estimate, which can be understood if $v_3$ originates from the initial stage of the collision.
predominantly from event-by-event fluctuations of the initial spatial geometry [11]. At the same time, we evaluate the correlation between $\Psi_3$ and the reaction plane $\Psi_{\text{RP}}$ via $v_3/\Psi_{\text{RP}} = \langle \cos(3\phi - 3\Psi_{\text{RP}}) \rangle$. In addition, the correlation of $\Psi_3$ and $\Psi_2$ also can be studied by a 5-particle correlator $v_3^2/\Psi_2 = \langle \cos(3\phi_1 + 3\phi_2 - 2\phi_3 - 2\phi_4 - 2\phi_5) \rangle/v_2^2$. In Fig. 1 we observe that $v_3/\Psi_{\text{RP}}$ and $v_3^2/\Psi_2$ are consistent with zero within uncertainties. Based on these results, we conclude that $v_3$ develops as a correlation of all particles with respect to the third order participant plane $\Psi_3$, while there is no (or very weak) correlations between the $\Psi_{\text{RP}}$ (also for $\Psi_2$) and the $\Psi_3$. Finally, from the comparison of AMPT model calculations with our measurements, we find that this model can describe the experimental data very well; there is only a slight overestimation of $v_2\{2\}$ in the most central collisions [12].

To investigate the role of viscosity on anisotropic flow measurements, we calculate the ratio $v_2/\varepsilon_2$ and $v_3/\varepsilon_3$. Here $\varepsilon_2$ and $\varepsilon_3$ are the eccentricity and triangularity of the initial spatial geometry which are defined by

$$\varepsilon_n = \sqrt{\langle r^2 \sin(n\phi) \rangle^2 + \langle r^2 \cos(n\phi) \rangle^2} / \langle r^2 \rangle. \quad (1)$$

The definition of $\varepsilon_n\{2\}$ (also $\varepsilon_n\{4\}$) can be found in [13].

Figure 2 (left) shows the centrality dependence of the ratio $v_n/\varepsilon_n$. The $\varepsilon_n$ are extracted from the MC–Glauber model (using the number of wounded nucleons) and the MC–KLN CGC model, denoted by $\varepsilon_n^{\text{W}}\{2\}$ and $\varepsilon_n^{\text{CGC}}\{2\}$, respectively. Based on the assumption that $v_n \propto \varepsilon_n$, we get $v_n\{2\} \propto \varepsilon_n\{2\}$ [13]. We observe that the $v_2\{2\}/\varepsilon_2^{\text{W}}\{2\}$ is larger than $v_3\{2\}/\varepsilon_3^{\text{W}}\{2\}$ in

![Fig. 2. Left: The centrality dependence of $v_2/\varepsilon_2$ and $v_3/\varepsilon_3$ for MC–Glauber and MC–KLN CGC initial conditions. Right: $v_n$ and scaled $\varepsilon_n$ as a function of centrality for the most central collisions (0–5%). The $k_1$ and $k_2$ have been used for eccentricities to match the 2% and 3% centrality percentile data. Figure taken from [10].](image-url)
all centrality bins, which indicates significant viscous corrections. However, for the MC–KLN CGC model the magnitude of \( v_2 \langle \rangle / \varepsilon_2^{\text{CGC}} \) equals to \( v_3 \langle \rangle / \varepsilon_3^{\text{CGC}} \) in the most central collisions, which might be expected for an almost ideal fluid [9]. The ratio of \( v_3 \langle \rangle / \varepsilon_3^{\text{CGC}} \) decreases faster than \( v_2 \langle \rangle / \varepsilon_2^{\text{CGC}} \) from central to peripheral collisions, which is consistent with larger viscous corrections to \( v_3 \). The collective flow should be directly sensitive to the change of the initial spatial geometry since the viscous effects do not change too much in the small centrality range. In Fig. 2 (right) we observe that in this centrality range \( v_3 \) does not show a strong centrality dependence while the \( v_2 \langle \rangle \) increases significantly. The comparison of the scaled initial eccentricity shows that \( v_2 \langle \rangle \) and \( v_3 \langle \rangle \) can only be simultaneously described by \( \varepsilon_2 \langle \rangle \) and \( \varepsilon_3 \langle \rangle \) from the MC–KLN model.

In order to reduce the event-by-event fluctuations within a centrality bin, we plot the integrated \( v_2 \) as a function of centrality in narrow bins, 1% centrality bins for 0–20% and 2% bins for 20–80% [7]. Elliptic flow estimated from 2-particle azimuthal correlations, \( v_2 \langle \rangle \), was obtained by using two different pseudorapidity gaps (\(|\Delta\eta| > 0\) and \(|\Delta\eta| > 1\)). The difference between the two measurements can be understood as resulting from non-flow effects. At the same time, the results of 4-, 6- and 8-particle cumulants estimates are shown in Fig. 3 (left). The good agreement of the multi-particle cumulants indicates that with 4-particle cumulants non-flow is strongly suppressed, so that there is little gain in suppressing it further by higher order cumulants (like 6- and 8-particle).

![Graph showing centrality dependence of integrated \( v_2 \) in 1–2% bins with different order cumulants.](image)

![Graph showing relative flow (eccentricity) fluctuations versus centrality.](image)

As shown by Gaussian fluctuations studies [14], in the limit of small fluctuations (\( \sigma_v < \bar{v} \)), we can estimate the participant plane flow and its fluctuations with:

\[
\bar{v}_n \approx \sqrt{\frac{v_n^2 \langle \rangle + v_n^4 \langle \rangle}{2}} \quad \text{and} \quad \sigma_{v_2} \approx \sqrt{\frac{v_2^2 \langle \rangle - v_2^4 \langle \rangle}{2}}.
\]
However, in the case of only fluctuations \([14,15]\), we have
\[
\bar{v}_n = \frac{\sqrt{\pi}}{2} v_n \{2\} \quad \text{or} \quad \sigma_{v_n}/\bar{v}_n = \sqrt{4/\pi - 1} \quad \text{and} \quad v_n \{4\} = 0. \quad (3)
\]
Also based on the assumption that \(v_n\) is proportional to \(\varepsilon_n\), the centrality dependence of eccentricity and its fluctuations should show behavior similar to that of flow. In Fig. 4 (left) we indeed observe a similar centrality dependence of \(\varepsilon^2\) with \(v^2\) and the following equations are valid
\[
\varepsilon^2 \{2\} \approx \varepsilon^2 + \sigma_{\varepsilon^2}^2, \quad \varepsilon^2 \{4\} \approx \varepsilon^2 - \sigma_{\varepsilon^2}^2 \quad (4)
\]
with the exception of the most central collisions (for which \(\sigma_v < \bar{v}\) does not hold).

The centrality dependence of the relative flow fluctuations \(\sigma_{v^2}/\bar{v}^2\) are plotted in Fig. 3 (right). We find that the magnitude of relative flow fluctuations is around 40%. Also we show the comparison of the relative flow fluctuations to \(\sigma_{\varepsilon^2}/\varepsilon^2\) (extracted from Eqs. (4)) from both the MC–Glauber model and the MC–KLN model. In mid-central and mid-peripheral collisions, the MC–Glauber model can describe the flow fluctuations while the MC–KLN model underestimates the measurements. In the more central collisions, neither the MC–Glauber nor the MC–KLN can describe the data. At the same time, we notice that \(\sigma_{\varepsilon^2}/\varepsilon^2\) from both the MC–Glauber model and the MC–KLN model reach \(\sqrt{4/\pi - 1}\) in the most central collisions, which is consistent with the predictions if there are only fluctuations \([14]\).
Assuming that \( v_3 \) originates from the initial geometry fluctuations (there are only flow fluctuations), we expect that \( v_n\{2\} = \frac{2}{\sqrt{\pi}} \bar{v}_n \) and \( v_n\{4\} = 0 \). However, as we have shown in Fig. 1, the \( v_3\{4\} \) has a finite magnitude. In order to understand the fluctuations of \( v_3 \), we look at the centrality dependence of triangularity \( \varepsilon_3 \). In Fig. 4 we observe that \( \varepsilon_3\{2\} = \frac{2}{\sqrt{\pi}} \varepsilon_3 \) is still valid (or the ratio \( \sigma_{\varepsilon_3}/\varepsilon_3 \) equals to \( \sqrt{\frac{4}{\pi} - 1} \)), but it seems that \( \varepsilon_3\{4\} \approx \varepsilon_3 - \sigma_{\varepsilon_3} \) in the centrality bins we present here. Whether the fluctuations of \( \varepsilon_3 \) are the dominant contribution to the fluctuations of \( v_3 \) is currently unknown.

4. Summary

In these proceedings we have presented the results on anisotropic flow measured in Pb–Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV by ALICE at the LHC. The measurements of higher harmonic anisotropic flow, in particular \( v_3 \), provide new constraints on the initial anisotropic flow as well as the shear viscosity to entropy density ratio \( \eta/s \).

REFERENCES