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# Searches for $p_T$ dependent fluctuations of flow angle and magnitude in Pb–Pb and p–Pb collisions

You Zhou (for the ALICE Collaboration)<sup>1</sup>

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

you.zhou@cern.ch

# Abstract

Anisotropic azimuthal correlations are used to probe the properties and the evolution of the system created in heavy-ion collisions. Two-particle azimuthal correlations were used in the searches of  $p_T$  dependent fluctuations of flow angle and magnitude, measured with the ALICE detector. The comparison of hydrodynamic calculations with measurements will also be presented in this proceedings.

Keywords: flow angle, flow fluctuations, factorization

#### 1. Introduction

The primary goal of ultra relativistic heavy-ion collisions is to understand the properties of the quark-gluon plasma (QGP), a new state of matter whose existence under extreme conditions is predicted by quantum chromodynamics. An important experimental observable toward this goal is the study of anisotropic flow using a Fourier expansion of the azimuthal anisotropy [1],

$$E\frac{d^{3}N}{d^{3}\mathbf{p}} = \frac{1}{2\pi} \frac{d^{2}N}{p_{\mathrm{T}}dp_{\mathrm{T}}d\eta} (1 + 2\sum_{n=1}^{\infty} v_{n} \cos[n(\varphi - \Psi_{n})])$$
(1)

where *E* is the energy, **p** the momentum,  $p_T$  the transverse momentum,  $\varphi$  the azimuthal angle,  $\eta$  the pseudorapidity of the particle. The  $v_n$  coefficients and  $\Psi_n$  represent the magnitude and angle (symmetry plane) of the  $n^{th}$ -order harmonic, respectively. The elliptic flow  $v_2$ , triangular flow  $v_3$ , quadrangular flow  $v_4$ , and pentagonal flow  $v_5$  have been measured at the CERN Large Hadron Collider (LHC). It provides compelling evidence that strongly interacting matter appears to behave like an almost perfect fluid [2]. Recent hydrodynamic simulations predict the  $p_T$  dependent fluctuations of flow angle and magnitude. Two new observables,  $v_n\{2\}/v_n[2]$  and  $r_n$  were proposed in hydrodynamic calculations [3, 4]. They are used to check whether the factorization of two-particle correlations into the product of single particle anisotropy harmonics is valid, which probes the  $p_T$  dependent flow angle and magnitude fluctuations.

In this proceeding, we present the measurements of  $v_2\{2\}/v_2[2]$  and factorization ratio  $r_n$  in Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV and p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV in ALICE.

<sup>&</sup>lt;sup>1</sup>A list of members of the ALICE Collaboration and acknowledgements can be found at the end of this issue.

### 2. Analysis Details

The data sample collected by ALICE in the first Pb–Pb run and p–Pb run at the Large Hadron Collider were used in this analysis. For more details of ALICE detector, refer to [5]. About 16 million Pb–Pb events and 97 million p–Pb events were recorded with a minimum-bias trigger, based on signals from two VZERO detectors (-3.7< $\eta$ <-1.7 for VZERO-C and 2.8< $\eta$ <5.1 for VZERO-A) and on the Silicon Pixel Detector. The VZERO detectors were also used for the determination of the collision centrality in Pb–Pb collisions while VZERO-A was taken for the determination of the multiplicity classes in p–Pb collisions. Charged particles are reconstructed using the Inner Tracking System and the Time Projection Chamber with full azimuthal coverage for pseudo-rapidity range  $|\eta|$ <0.8. The two-particle correlations are measured using the Q-Cumulant method [6] with a pseudorapidity gap  $|\Delta\eta| > 0.8$ , which is expected to suppress the non-flow effects (azimuthal correlations not related to the symmetry plane) as much as possible but still allow good statistical precision within the TPC acceptance.

### 3. Results



Figure 1. The ratio  $v_2\{2, |\Delta\eta| > 0.8\}/v_2[2, |\Delta\eta| > 0.8]$  for various centralities of Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. The error bars correspond to statistical uncertainties, while the shaded color bands correspond to the systematic uncertainties. Hydrodynamic calculations with MC-Glauber initial condition and  $\eta/s = 0.08$  and with MC-KLN initial condition and  $\eta/s = 0.20$  are shown in green and orange lines.



Figure 2. The ratio  $v_3\{2, |\Delta \eta| > 0.8\}/v_3\{2, |\Delta \eta| > 0.8\}$  for various centralities of Pb–Pb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV.

Figure 1 presents the ratio  $v_2\{2, |\Delta\eta| > 0.8\}/v_2[2, |\Delta\eta| > 0.8]$  as a function of  $p_T$  in different centrality classes. It is observed that the ratio is consistent with unity up to  $p_T \approx 2 \text{ GeV}/c$  in most central collisions and up to  $p_T \approx 3 \text{ GeV}/c$  in the non-central collisions. The deviations from unity become weaker but occur at higher  $p_T$  range toward peripheral collisions. The result indicates that if  $p_T$  dependent flow angle ( $\Psi_2$ ) and magnitude ( $v_2$ ) fluctuations exist, such effect is within 10% in non-central collisions in the presented  $p_T$  range. The comparison to hydrodynamic calculations shows that both calculations overestimate the deviation of  $v_2\{2, |\Delta\eta| > 0.8\}/v_2[2, |\Delta\eta| > 0.8]$  in most central collisions, and the data is better described by the one with MC-KLN initial condition and  $\eta/s = 0.20$ .

The ratios of  $v_3\{2, |\Delta\eta| > 0.8\}/v_3[2, |\Delta\eta| > 0.8]$  and  $v_4\{2, |\Delta\eta| > 0.8\}/v_4[2, |\Delta\eta| > 0.8]$  together with various hydrodynamic calculations are shown in Fig. 2. It is found that both ratios agree with unity over a wider  $p_T$  range than  $v_2\{2, |\Delta\eta| > 0.8\}/v_2[2, |\Delta\eta| > 0.8]$ . The  $p_T$  dependent fluctuations of flow angle  $\Psi_3$  (and  $\Psi_4$ ) and magnitude  $v_3$  (and  $v_4$ ) are not significant in the presented  $p_T$  range. Meanwhile it's still difficult to conclude which hydrodynamic calculations describe the measurements better, due to limited statistics.



Figure 3. The factorization ratio  $r_2$ , as a function of  $p_T^a$  in bins of  $p_T^t$  for 0-5 %, 20-30 % and 40-50 % in Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, is presented by solid circles. CMS measurements [7] are presented by open squares, hydrodynamic calculations with MC-Glauber initial condition and  $\eta/s = 0.08$  and with MC-KLN initial condition and  $\eta/s = 0.20$  are shown in green and orange curves.

Figure 3 shows the factorization ratio  $r_2$  for three  $p_T$  of triggle particles (denoted as  $p_T^t$ ), as a function of  $p_T$  of associate particles (denoted as  $p_T^a$ ) for centrality classes 0-5 %, 20-30 % and 40-50 % in Pb–Pb collisions. It significantly deviates from unity as the collisions become more central, this effect becomes stronger with an increase of  $|p_T^t - p_T^a|$ . The deviation is within 10 % for the lowest  $p_T^a$  in the 0-5 % for 2.5<  $p_T^t < 3.0 \text{ GeV}/c$ . This can be due to  $p_T$  dependent fluctuations of flow angle ( $\Psi_2$ ) and magnitude ( $v_2$ ) generated by initial event-by-event geometry fluctuations, and possible remaining non-flow effects. Various hydrodynamic calculations are compared to data for the presented centrality classes. Both hydrodynamic calculations with MC-Glauber initial condition and  $\eta/s = 0.08$  and MC-KLN initial condition and  $\eta/s = 0.20$  qualitatively predict the trend of  $r_2$ , while the latter agrees better with data. In addition, recent CMS measurements [7], which are based on  $|\Delta \eta| > 2.0$  (asymmetry cuts in pseudorapidity), are consistent with our measurements. Notice that the ALICE analysis focus on the mid-pseudorapidity range and the selected two correlated particles are always from symmetric sub-events in pseudorapidity dependent fluctuations of flow angle ( $\Psi_2$ ) and magnitude ( $v_2$ ) is not accessible in the presented pseudorapidity range. The factorization of  $r_3$  (not shown here) in Pb–Pb collisions is valid over a wider range of  $p_T^a$ ,  $p_T^a$  and centrality ranges, compared to  $r_2$ . The

factorization is broken within 10 % for  $p_T^a$ ,  $p_T^t$  below 4 GeV/c. CMS measurements quantitatively agree with our  $r_3$  measurements, additional pseudorapidity dependent fluctuations of flow angle ( $\Psi_3$ ) and magnitude ( $v_3$ ) might be negligible in the presented pseudorapidity range.



Figure 4. The  $v_2\{2, |\Delta \eta| > 0.8\}$  and  $v_2[2, |\Delta \eta| > 0.8]$  for various multiplicity classes of p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. Hydrodynamic calculations (MUSIC) of  $v_2\{2\}$  and  $v_2[2]$  are shown by solid and dash lines.

The  $v_2\{2, |\Delta\eta| > 0.8\}$  and  $v_2[2, |\Delta\eta| > 0.8]$  are also measured in p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV in ALICE. It is found that  $v_2\{2, |\Delta\eta| > 0.8\}$  and  $v_2[2, |\Delta\eta| > 0.8]$  deviate at  $p_T \sim 3$  GeV/*c* for the presented multiplicity classes. Hydrodynamic calculation [8] show a similar trend as a function of  $p_T$  but shows better agreement in central than in peripheral p–Pb collisions. Due to limited statistics, the  $v_3\{2, |\Delta\eta| > 0.8\}$  and  $v_3[2, |\Delta\eta| > 0.8]$  are investigated up to  $p_T \sim 3$  GeV/*c*. The difference of this two measurements are not observed for the the presented multiplicity and  $p_T$ range.

# 4. Summary

In summary, searches of  $p_T$  dependent flow angle and magnitude fluctuations are performed by measuring  $v_n\{2\}/v_n[2]$ and  $r_n$ . It is found that  $v_2\{2, |\Delta\eta| > 0.8\}/v_2[2, |\Delta\eta| > 0.8]$  is consistent with unity up to  $p_T \approx 2$  GeV/c in most central Pb–Pb collisions, the deviation becomes weaker but occur at higher transverse momenta towards peripheral collisions. A significant deviation of  $v_3\{2, |\Delta\eta| > 0.8\}/v_3[2, |\Delta\eta| > 0.8]$  and  $v_4\{2, |\Delta\eta| > 0.8\}/v_4[2, |\Delta\eta| > 0.8]$  from unity is not observed. The factorization ratio  $r_2$  significantly deviates from unity as the collisions become more central, such effect becomes stronger as  $|p_T^t - p_T^a|$  is increasing. The comparison to hydrodynamic calculations shows that the one with MC-KLN initial condition and  $\eta/s = 0.20$  has better agreement to the data than with MC-Glauber initial condition and  $\eta/s = 0.08$ , but none of them can quantitatively describe the data. The  $v_n\{2\}/v_n[2]$  has been measured also in p–Pb collisions, it deviates from unity for  $p_T > 3$  GeV/c and is under predicted in hydrodynamic calculations.

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