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Charged particle directed flow in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV measured with ALICE at the LHC

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Abstract. Directed flow, v_1, is measured over a wide range of pseudo-rapidity, $|\eta| < 5.1$, in Pb-Pb collisions at 2.76 TeV with ALICE at the LHC. v_1 is reported as a function of the pseudo-rapidity, the transverse momentum and collision centrality. Using the neutral spectator deflection at beam rapidity we investigate both the rapidity asymmetric v_1 which is sensitive to the collision reaction plane, and the rapidity symmetric v_1 which is sensitive to the energy fluctuations in the initial geometry. The results are compared with those at RHIC, and the model calculations.

1 Introduction

The collective sideward motion of spectators and produced particles arises in non-central heavy-ion collisions. This effect is called the directed flow v_1. Directed flow is considered to have origin at the early stage of the collision, when nuclei passing each other. At RHIC and LHC energies it could be established before the system reaches local equilibrium, hence it carries information on early collision dynamics and is sensitive to the system thermalization time [1]. Directed flow, v_1, is defined as first Fourier coefficient in an angular distribution of particles produced in collisions with respect to the collision symmetry plane Ψ_{RP}, $v_1 = \langle cos(\varphi - \Psi_{RP})\rangle = \langle p_x/p_T\rangle$. For the symmetric nuclei collision, due to momentum conservation, $v_1(\eta)$ is an odd function of pseudorapidity and is zero at $\eta = 0$.

At RHIC energies directed flow at midrapidity has been measured to have a negative slope. It was found that v_1 doesn't depend on the size of colliding nuclei and it decreases with increase of the collision energy [2]. If plotted as a function of rapidity shift from the beam rapidity, the directed flow at different energies exhibits universal behaviour [2, 3].

At RHIC and LHC energies, a "wiggle" structure of $v_1(\eta)$ may appear. In the microscopic model calculations such as RQMD and UrQMD, this could come from baryon stopping [4]. In hydro models, this can be a signature that the matter evolved via the phase of deconfined quarks and gluons [5]. Still, data don't support a wiggle structure at midrapidity in the observed charged particle directed flow [2].

There is a number of model predictions for the directed flow at the LHC energies. The fluid dynamic calculations for Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV predicted a very large positive $v_1(\eta)$ at mid-rapidity with a presence of wiggle structure [6]. Introducing initial center of mass rapidity fluctuation was shown to smear the magnitude of the v_1, still keeping the slope positive. The quark gluon string model (QGSM) with parton rearrangement predicts the positive $v_1(\eta)$ for charged hadrons with wiggle

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structure at $\sqrt{s_{NN}} = 5.5$ TeV [7]. A suggested explanation of the positive slope is a very low viscosity of the created medium at mid-rapidity. The different viscosity at mid and forward rapidities causes the wiggle structure in this model.

In these proceedings, the directed flow of charged particles is reported as a function of centrality, pseudorapidity and transverse momentum in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

2 Data set and experimental methods

About 8 millions Pb-Pb events collected by ALICE experiment [8] within 0-80% centrality range are used for the current analysis. Centrality estimation is done with the VZERO detector. A reconstructed primary vertex position along the beam direction is set to be within ± 10 cm of the nominal interaction point. Reconstruction of charged particle tracks was performed with the Time Projection chamber (TPC) in rapidity range $|\eta| < 0.8$. Good track quality was ensured by requiring the tracks to have at least 70 clusters out of 159 in the TPC, a χ^2 per TPC cluster < 4 (with two degrees of freedom per cluster) and to point back to the primary interaction vertex within 3 cm. A cut to the transverse momentum $p_T > 0.15$ GeV/c is imposed on all charged particle tracks. As a cross check the analysis was also performed using TPC and the Inner Tracking System (ITS). The Inner Tracking System is composed of six cylindrical layers of silicon detectors. The additional requirements for these tracks are at least two matching hits in the ITS and the distance of closest approach to the primary interaction vertex below 0.3 cm. The results for (TPC+ITS)-tracks and TPC standalone tracks agree very well.

Directed flow at forward rapidity was measured using azimuthal distribution of hits in VZERO detectors. VZERO scintillators measure the signal which is proportional to the number of charged particles hitting the detector. The two VZEROs, each of which consists of four rings, are placed at both sides of the interaction point, located at different pseudorapidities (C-side: η =[-3.7, -3.2, -2.7, -2.2, -1.7] and A-side: η =[5.1, 4.5, 3.9, 3.4, 2.8]). Each ring is segmented into eight 45^o sectors in azimuth, covering 2π in azimuthal direction.

The scalar product and the event plane methods [9] were used for v_1 measurement. Reaction plane was reconstructed using the two neutron Zero Degree Calorimeters (ZDC). They are placed along the beam line at 114 meters apart from the interaction point from A-side ($\eta > 8.8$) and C-side ($\eta < -8.8$) and provide an estimate of the spectators deflection. Each neutron ZDC has a 2×2 tower geometry. Scalar product method employs the centroid coordinates $\{X, Y\}$ of the deflection and the event plane method employs the angle $\Psi_{EP} = tan^{-1}(Y/X)$ derived from the coordinates. The centroid position is defined with four towers event-by-event:

$$\{X, Y\} = \frac{\sum_{i=1}^{4} \{x_i, y_i\} w_i}{\sum_{i=1}^{4} w_i} ,$$

where weight $w_i = E_i^{\alpha}$. E_i is the measured energy in a given tower, $\{x_i, y_i\}$ are centers of each tower and $\alpha = 0.395$ is a parameter. For the C-side the weights are put to be negative which takes into account the opposite sign of spectators deflection with respect to A-side. Ideally, when the spot of spectators is perfectly centered wrt. the center of ZDCs, the centroid position $\{X, Y\}$ averaged over many events should be zero. Experimentally, the average can be shifted from the center of ZDCs what biases the event plane distribution. The average offset can be corrected for by recentering procedure, i.e $X' = X - \langle X \rangle$, $Y' = Y - \langle Y \rangle$, where the mean values can in general depend on time, event multiplicity (centrality), and event vertex position. After recentering a consistent correlations in the same direction for A- and C- sides of ZDCs are observed. As an example, Figure 1 shows measured correlations $\langle X_A X_C \rangle$, $\langle Y_A Y_C \rangle$. These correlations are sensitive to the directed flow of spectators and are used in determination of the reaction plane resolution (Eqs. (1), (2)). The ZDC resolution decreases for the most central and most peripheral collisions. Correlations in orthogonal directions, $\langle X_A Y_C\rangle$, $\langle Y_A X_C\rangle$, which should be zero for a perfect detector, are also shown in Figure 1.

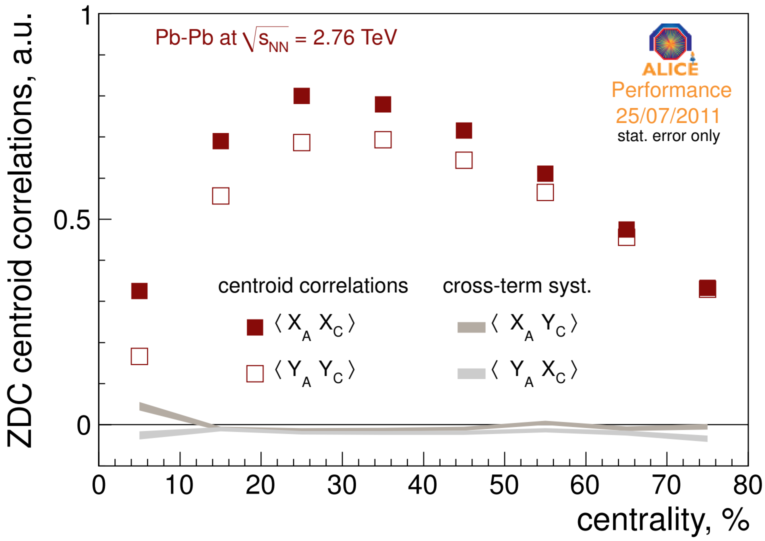

Figure 1. (color online). Correlation between the centroid position reconstructed with the ZDC on A- and C-side for the aligned and orthogonal directions as a function of centrality.

A set of independent estimates of v_1 with ZDC A- and C-sides in the scalar product method is given by:

$$v_{1;x}^{A;C} = \frac{\sqrt{2}\langle\cos\phi\cdot X_{A;C}\rangle}{\sqrt{\langle X_A\ X_C\rangle}}\ ,\ v_{1;y}^{A;C} = \frac{\sqrt{2}\langle\sin\phi\cdot Y_{A;C}\rangle}{\sqrt{\langle Y_A\ Y_C\rangle}}. \tag{1}$$

Here ϕ is the azimuthal angle of the charged particle or the azimuthal position of VZERO sector, angle brackets denote the average other all events. In case of VZERO detector multiplicity in a given sector is used as a weight when calculating an average. The average of these four components is used as the final result. The event plane method was used in two forms: the one which uses subevent plane angles $\Psi_{\rm EP}^{A;C}$ from two ZDCs separately, and the other which uses full reaction plane angle, $\Psi_{\rm EP}^{Full}$:

$$v_1 = \frac{\langle\cos(\phi - \Psi_{\rm EP}^{Full})\rangle}{\sqrt{2\langle cos(\Psi_{\rm EP}^{A} - \Psi_{\rm EP}^{C})\rangle}}. \tag{2}$$

Here we use an approximation that the full event plane resolution can be obtained from correlation between independent subevents [9]. The scalar product and the event plane method yield consistent results.

3 Results for directed flow

3.1 Rapidity, transverse momentum and centrality dependence of v_1

Figure 2 shows charged particle directed flow versus pseudorapidity for 0-80% centrality class. A negative slope for $v_1(\eta)$, opposite to that of spectators, is observed in the region $|\eta| < 5$. A mid-rapidity

v_1 is very well approximated with a linear function of η. A turnover point changing the $v_1(\eta)$ slope should occur at some rapidity where the produced particles are predominantly coming from nuclear fragments (fragmentation region). Note, that the beam rapidity at the LHC energy $\sqrt{s_{\rm NN}}$=2.76 TeV is y_{beam} = 7.98. The existing predictions [6], [7] for the LHC energy give a positive slope at mid-rapidity, opposite to that observed in the data. Fluid dynamical model [6] has a positive v_1 slope due to overestimation of the initial tilt of the system. Figure 3 shows the so-called longitudinal scaling of

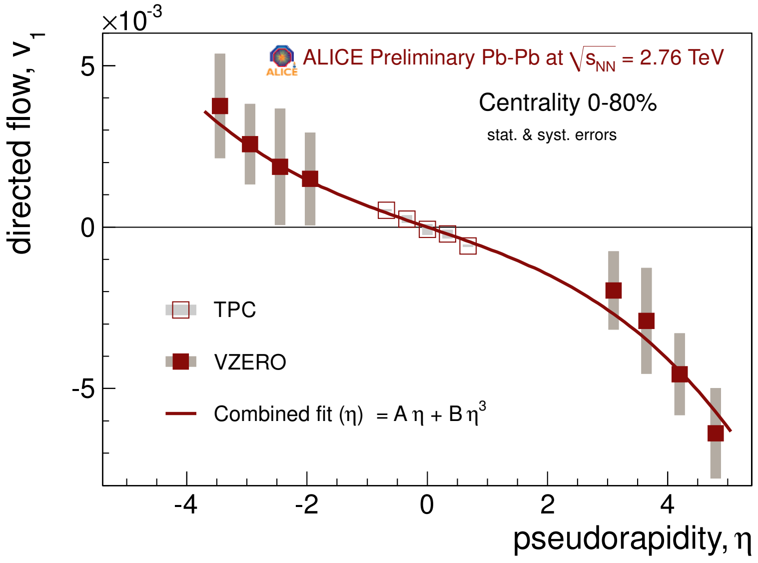

Figure 2. (color online). Charged particle directed flow $v_1(\eta)$ for 0-80% centrality interval in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$=2.76 TeV. The bars represent the statistical errors and the shaded bands are systematic errors.

v_1 when the results at different energies are plotted versus η shifted by the beam rapidity at a given energy. ALICE data is compared with STAR [2](Figure 3 left) and PHOBOS results [3] (Figure 3 right).

Figure 4 shows integrated $sign(\eta) \times v_1(\eta)$ as a function of centrality at LHC $\sqrt{s_{\rm NN}}$=2.76 TeV compared to RHIC Au-Au results at $\sqrt{s_{\rm NN}}$ =200 and 62.4 GeV. The magnitude of v_1 decreases with the collision energy.

The $p_{\rm T}$ dependence of v_1 is measured by combining results at positive pseudorapidity with that at negative $\eta < 0$ taken with an opposite sign. Figure 5 presents the $v_1(p_{\rm T})$ at mid-rapidity, $|\eta| < 0.8$ for two centrality classes (0-40% and 40-80%) compared to RHIC $\sqrt{s_{\rm NN}}$=200 GeV results. A similar trend as for RHIC is observed, i.e $v_1(p_{\rm T})$ changes sign from negative to positive value around $p_{\rm T} \approx$ 1.5 GeV/c. The zero crossing point moves towards higher $p_{\rm T}$ for more peripheral events.

3.2 Directed flow fluctuation

Fluctuations in the initial geometry of the collision may result in non-zero even v_1 component at midrapidity [1, 1]. Experimentally we separate η-even and η-odd v_1 by symmetrizing or anti-symmetrizing measured v_1 with spectators in two ZDCs:

$$v_1^{odd} = [v_1^A + v_1^C]/2, \qquad v_1^{even} = [v_1^A - v_1^C]/2.$$

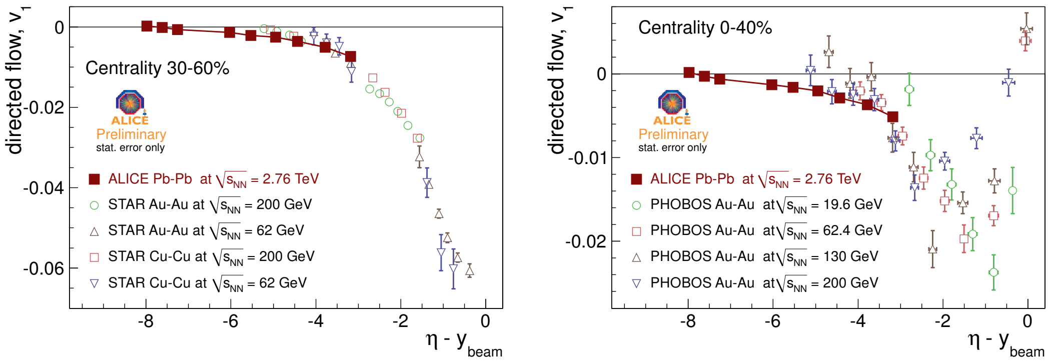

Figure 3. (color online). Charged particle v_1 as a function of $\eta - y_{beam}$ Left: Comparison with STAR for 30-60% centrality events; Right: Comparison with PHOBOS for 0-40% centrality events

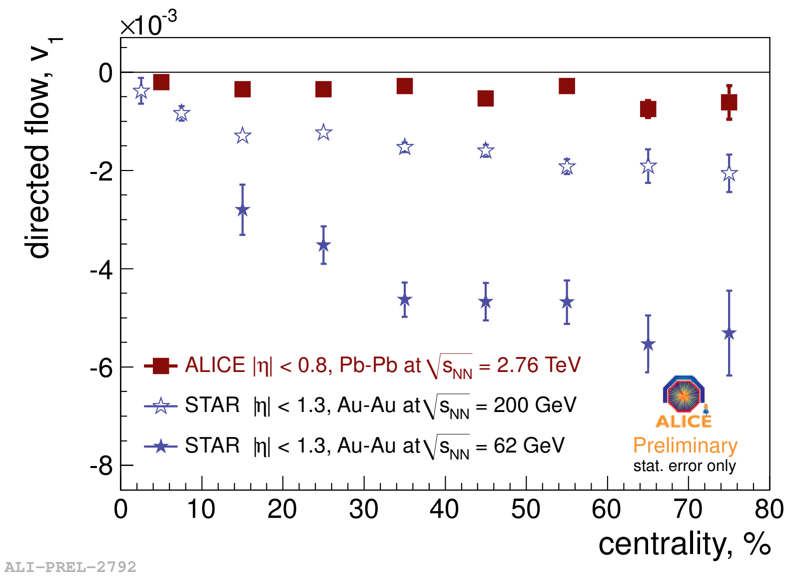

Figure 4. (color online). Integrated charged particle directed flow v_1(centrality) in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV.

Results for $v_1(\eta)$ obtained from each ZDC separately reveal a shift independent on pseudorapidity, see Figure 6 (left), which corresponds to the even component of v_1.

Figure 6 (right) shows that as a function of p_T even and odd v_1 have a similar shape and magnitude at low and intermediate p_T region.

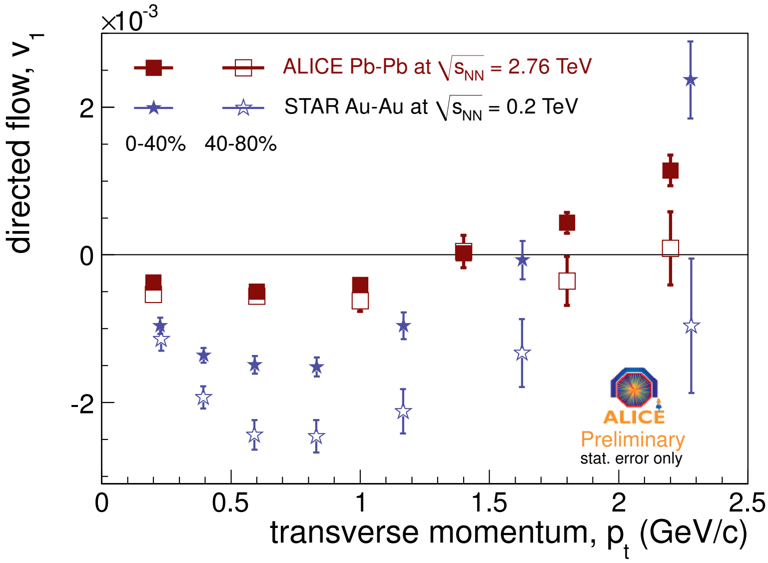

Figure 5. (color online). p_T dependence of charged particle directed flow for $|\eta| < 0.8$ in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV for two centralities: 0-40% and 40-80%. For comparison the STAR results for Au-Au collisions at $\sqrt{s_{NN}}$ =200 GeV collisions with $|\eta| < 1.3$ are shown [2].

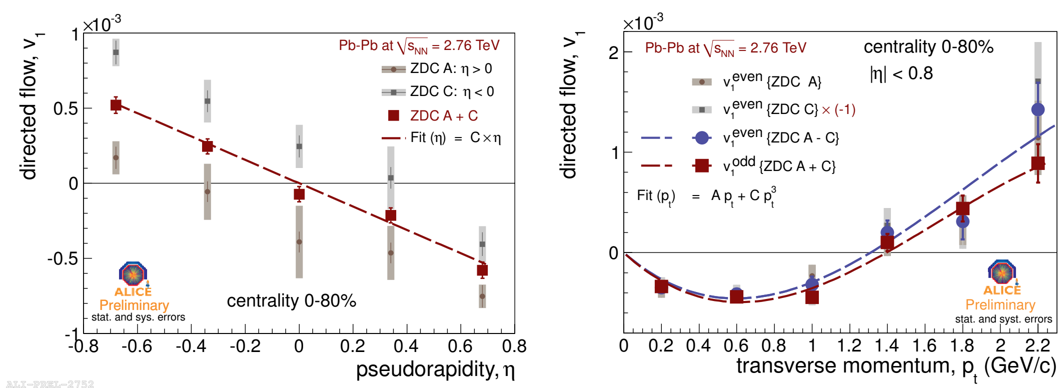

Figure 6. (color online). Left: v_1 measured with ZDC on A- and C-side for centrality 0-80% in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV Right: Even and odd $v_1(p_T)$ for centrality 0-80% in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV.

4 Summary

The ALICE Collaboration has measured the directed flow of charged particles in heavy-ion collisions at the LHC with the reaction plane defined from the deflection of spectators. The observed charged particle v_1 has an opposite sign to that of spectators in the rapidity range $|\eta| < 5.1$. Directed flow has a weak centrality dependence at midrapidity. As a function of transverse momentum, directed flow changes sigh from negative to positive value around $p_T \approx 1.5$ GeV. Compared to the top RHIC energy, about 3 times smaller magnitude of v_1 is observed. Directed flow at the LHC follows the picture of longitudinal scaling. Non-zero even even v_1 component is observed, which has the same order of magnitude and similar p_T-shape as the odd v_1.

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