

ALICE MEASUREMENT OF DIRECTED FLOW OF HADRONS IN Pb–Pb COLLISIONS*

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Directed flow is one of the key observables used for studying the properties of the hot and dense matter produced in relativistic heavy-ion collisions. Hereby we are reporting the recent results on the directed flow measurements performed by the ALICE Collaboration for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in a wide rapidity range, $|\eta| < 5.1$. Directed flow is studied as a function of pseudorapidity, η , transverse momentum, p_t , and collision centrality. The results are compared with RHIC data and with the model predictions available for CERN LHC energies.

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1. Directed flow in heavy-ion collisions

A collective motion of particles produced in heavy-ion collisions reflects the bulk properties of created matter. The collective flow is quantified by the coefficients in the Fourier decomposition of the particles invariant distribution

$$E \frac{d^3 N}{d^3 p} \sim 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\varphi - \Psi_{RP})),$$

where φ is the azimuthal angle of the particle and Ψ_{RP} is the angle of collision reaction plane. Directed flow v_1 describes the sideward motion of nuclear fragments and newly produced particles and carries information about the very early stages of the collision. The rapidity dependence and sign of directed flow at midrapidity has been of special interest at lower energies (SPS, AGS, RHIC [1]). According to hydrodynamical models the changing of v_1

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sign at certain colliding energy was considered as a signature of a phase transition from normal nuclear matter to a quark-gluon plasma (QGP) [2]. On the other hand, the directed flow magnitude and its energy dependence can be explained in transport models without phase transition by a smooth shift from baryon rich matter to meson rich matter [3].

Charged particle v_1 measured at RHIC energies has negative slope at midrapidity [4] which is decreasing with collision energy. Recent calculations within quark-gluon string model with parton recombination [5], and fluid dynamical predictions [6] suggest much stronger signal at LHC energies with a positive slope of v_1 versus rapidity. In these proceedings, we present the directed flow measurements of charged particles and identified pions made by the ALICE experiment [7] in Pb–Pb collisions at LHC at $\sqrt{s_{NN}} = 2.76$ TeV during the 2010 data taking. The measurement is performed in both central and forward rapidity regions with different detectors.

2. Experimental method

In the present analysis, we have used about about 8 million 0–80% centrality Pb–Pb collisions which passed the standard ALICE minimum bias event selection criteria. Particle tracking was performed by the time projection chamber (TPC) in combination with the silicon inner tracking system (ITS). Tracks with pseudorapidity $|\eta| < 0.8$ and transverse momentum $p_t > 0.15$ GeV/ c are used in current analysis. The particle identification is based on the Time-of-Flight (TOF) measurements in addition to the energy loss measurement in the TPC. The purity was estimated to be better than 95% at $p < 5$ GeV/ c for pions and protons. Charged particle multiplicity at forward rapidity is measured by the pair of forward scintillator arrays (VZERO), which cover rapidity ranges of $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$. They have 2π -coverage in azimuth, being segmented into 8 sectors. This detector is also used to define the centrality of the interaction. First order reaction plane is reconstructed by the two neutron Zero Degree Calorimeters (ZDC) symmetrically centered about midrapidity, conventionally defined as side A and side C, located 114 meters apart from the interaction point ($|\eta| \approx 8.8$). Each ZDC has a 2×2 tower geometry thus providing an estimate of the spectators deflection direction.

The scalar product and the event plane methods are used for the v_1 measurement. Both approaches give the consistent results. Scalar product method employs the flow vector $Q = \{X, Y\}$ and the event plane method employs the angle $\Psi_{EP} = \tan^{-1}(Y/X)$ derived from the flow vector components. The spectator deflection coordinates measured by a given ZDC are

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

where weight w_i is obtained from the measured tower energy as E_i^α , x_i and y_i are centers of each tower and α, β are parameters. The recentering procedure is applied before calculating the event plane angle: $Q' = Q - \langle Q \rangle$, where $\langle Q \rangle$ is the value averaged over many events. In general, it depends on time, event multiplicity (centrality), and beam crossing parameters (3D vertex position). Fig. 1 shows the ZDC event plane resolution components. The resolution decreases as a function of centrality for the most central and most peripheral collisions. Consistent correlations in the same direction for A- and C-sides of ZDCs ($\langle \cos \Psi^A \cos \Psi^C \rangle$, $\langle \sin \Psi^A \sin \Psi^C \rangle$) reflect directed flow of spectators. A negligible correlations in orthogonal directions, $\langle \cos \Psi^A \sin \Psi^C \rangle$, $\langle \sin \Psi^A \cos \Psi^C \rangle$ indicate that recentering removes correlations originating from beam parameter variations.

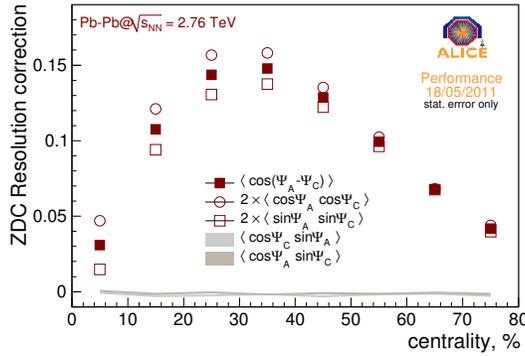


Fig. 1. (Color on line) Components of resolution correction factor *vs.* centrality.

The formula for the event plane method is [8]

$$v_1\{\text{EP}\} = \frac{\langle \cos(\phi - \Psi^{\text{full}}) \rangle}{\sqrt{2} \langle \cos(\Psi^A - \Psi^C) \rangle}, \quad (1)$$

where in case of VZERO detector, multiplicity in a given sector was used as a weight, ϕ is the azimuthal angle of a charged particle (a sector) and angle brackets denote the average over other particles and events. The denominator accounts for event plane resolution. In current analysis, we treat the X- and Y-directions separately and the event plane resolution correction is applied term by term, which gives a better control on systematics. Thus, for the scalar product method the v_1 components are [9]

$$\begin{aligned} v_1^X\{\text{SP}\} &= \sqrt{2} \langle \cos \phi X_{A;C} \rangle / \sqrt{\langle X_A X_C \rangle}; \\ v_1^Y\{\text{SP}\} &= \sqrt{2} \langle \sin \phi Y_{A;C} \rangle / \sqrt{\langle Y_A Y_C \rangle}. \end{aligned} \quad (2)$$

Due to large rapidity gap between two ZDCs there is practically no contribution from non-flow in our measurements. Main sources of the systematic uncertainties considered in this analysis is the ZDC centroid coordinates reconstruction.

3. Results

Directed flow at central rapidity is presented in Fig. 2, where p_t - and η -dependences of directed flow v_1 are shown for different centrality bins. In contrast to mentioned theoretical predictions, the charged particle $v_1(\eta)$ at LHC still has a negative slope, similar to that at RHIC energies. The magnitude of the v_1 at midrapidity decreases further in comparison with top SPS and RHIC energies [4]. At LHC $v_1(p_t)$ changes sign from negative to positive at $p_t \approx 1.5$ GeV/c. The p_t -dependence is similar to that of v_1 obtained from two particle correlation analysis in the ALICE experiments [10]. Zero crossing point can be an indication of transition phenomena from soft to hard physics taking place in that p_t region. Fig. 3 shows a comparison between ALICE and STAR ($\sqrt{s_{NN}} = 200$ GeV) $v_1(p_t)$ for two centrality bins, 0–40% and 40–80%. The zero crossing is present in both experiments for more central events (0–40%), while for peripheral events at LHC and lower energies [1] crossing point moves to higher p_t and is not so pronounced.

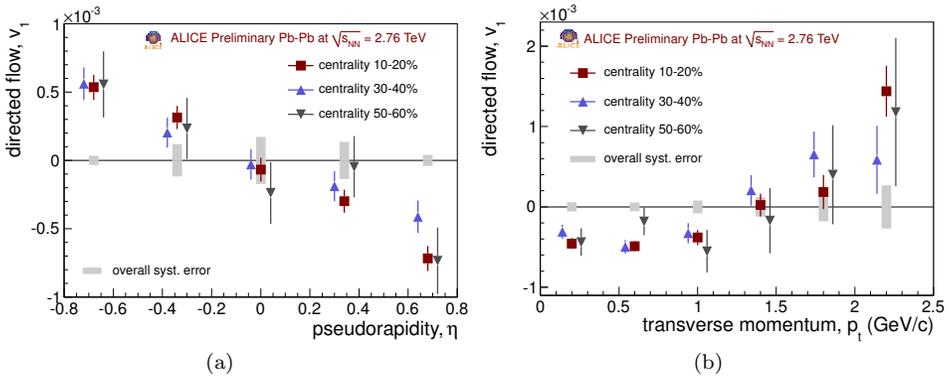


Fig. 2. (Color on line) Directed flow of charged particles at midrapidity for three centrality bins: (a) η -dependence, (b) p_t -dependence.

Fig. 4(a) shows directed flow measured at forward rapidity by VZERO multiplicity counters. In a wide pseudorapidity range $|\eta| < 5$, v_1 has a negative slope with no wiggle structure. Notice, that for spectators (at $y \approx 8$) v_1 is defined to have positive slope by convention. Fig. 4(b) shows $v_1(\eta - y_{\text{beam}})$ -dependence in wide range of energies. Shifted to beam rapidity value, directed flow at LHC is consistent with the longitudinal scaling picture, previously observed at RHIC [4].

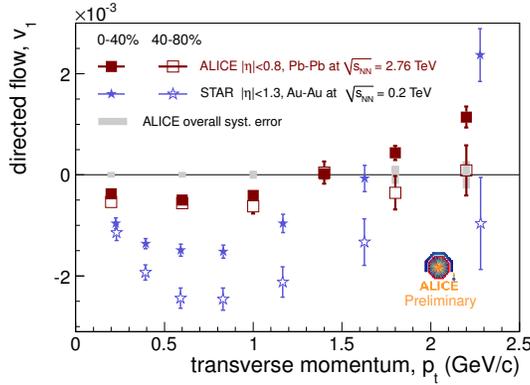


Fig. 3. (Color on line) Comparison with RHIC: $v_1(p_t)$ -dependence *vs.* centrality.

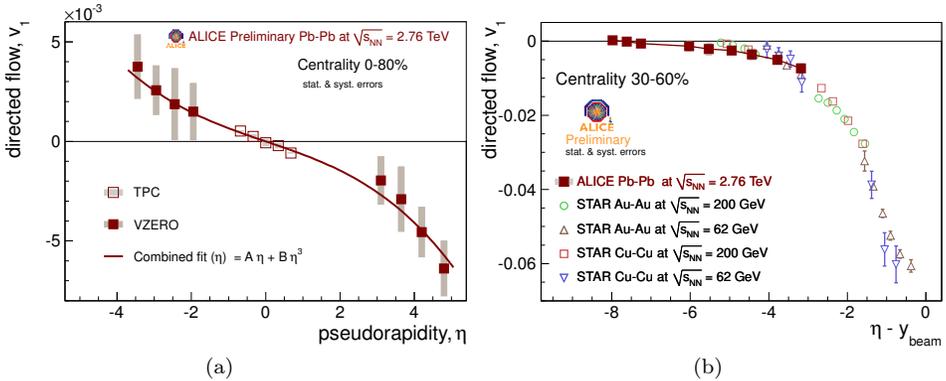


Fig. 4. (Color on line) (a) v_1 over extended rapidity range; (b) longitudinal scaling, $v_1(\eta - y_{\text{beam}})$ with comparison to STAR measurements.

Different behavior of proton and pion flow was observed at lower energies and at top RHIC energy [11]. v_1 for identified particles can reveal different mechanisms of particle production and flow formation. Transport models show a significant difference between flow of protons, which mainly follow the remnants of the nuclei, and flow of newly produced particles, which mostly evolve in spectator-free rapidity regions [3]. A detailed comparison between all charged particles and identified pions was done. Though pions are the dominant fraction of all produced particles, the difference between pion v_1 and all charged v_1 might reveal the admixture of kaon and proton flow. Fig. 5 shows that the pion v_1 follows closely the charged particle flow both for η - and p_t -dependences: it has a negative slope at midrapidity and zero crossing around $p_t \approx 1.5$ GeV/c.

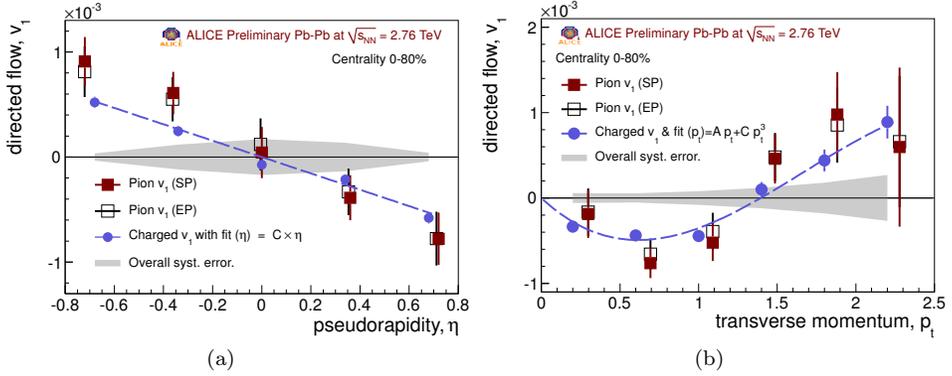


Fig. 5. (Color on line) v_1 for all charged and pions (a) η -dependence, (b) p_t -dependence.

4. Conclusion

Directed flow of charged particles has been measured at midrapidity, $|\eta| < 0.8$, and forward rapidities, $1.7 < |\eta| < 5.1$, for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE at LHC. Magnitude of v_1 is about 3–4 times smaller than at top RHIC energy with a weak centrality dependence. $v_1(p_t)$ crosses zero at $p_t \approx 1.5$ GeV/c. $v_1(\eta)$ has a negative slope both at LHC and as at RHIC in contrast to some theoretical expectations. We found also that $v_1(\eta - y_{\text{beam}})$ at LHC is consistent with a picture of longitudinal scaling observed at lower energies. The charged pion v_1 measured at midrapidity shows the same η - and p_t -dependences as the flow of all charged particles.

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