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Directed flow of charged particles at mid-rapidity relative to the spectator plane in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

The ALICE Collaboration*

Abstract

The directed flow of charged particles at mid-rapidity was measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV relative to the collision plane defined by the spectator nucleons. Both the rapidity-odd (v_1^{odd}) and even (v_1^{even}) directed flow components are reported. The v_1^{odd} component has a negative slope as a function of pseudorapidity similar to that observed at the highest RHIC energy, but with about a three times smaller magnitude. The v_1^{even} component is found to be non-zero and independent of pseudorapidity. Both components show little dependence on the collision centrality and change sign at transverse momenta around $1.2 - 1.7$ GeV/c for midcentral collisions. The shape of v_1^{even} as a function of transverse momentum and a vanishing transverse momentum shift along the spectator deflection for v_1^{even} are consistent with dipole-like initial density fluctuations in the overlap zone of the nuclei.

*See Appendix A for the list of collaboration members

The goal of the heavy-ion program at the Large Hadron Collider (LHC) is to explore the properties of deconfined quark-gluon matter. Anisotropic transverse flow is sensitive to the early times of the collision, when the deconfined state of quarks and gluons is expected to dominate the collision dynamics (see reviews [1–3] and references therein). A positive (in-plane) elliptic flow was first observed at the Alternating Gradient Synchrotron (AGS) [4]. A much stronger flow was then measured at the Super Proton Synchrotron (SPS) [5], Relativistic Heavy Ion Collider (RHIC) [6–8] and recently at the LHC [9–11]. Elliptic flow at RHIC and the LHC is reproduced by hydrodynamic model calculations with a low value of the ratio of shear viscosity to entropy density [12–15]. Despite the success of hydrodynamics in describing the equilibrium phase of matter produced in a relativistic heavy-ion collision, there are still large theoretical uncertainties in determining its initial conditions. Significant triangular flow measured recently at RHIC [16, 17] and LHC [11, 18] energies has demonstrated [19, 20] that initial energy fluctuations play an important role in the development of the final momentum-space anisotropy in the distribution of produced particles.

The directed flow is least sensitive to transport properties of the created matter than the other flow harmonics [21]. As a function of rapidity it has two components. The rapidity odd component ($v_1^{\rm odd}$) results from flow development along the geometrical reaction plane spanned by the impact parameter and the beam directions. The rapidity even component ($v_1^{\rm even}$) which does not vanish at mid-rapidity, originates from the event-by-event fluctuations of the initial energy density in the collision [21–24].

The slope of $v_1^{\rm odd}$ as a function of rapidity at the AGS [4, 25] and SPS [26, 27] energies is mainly driven by the difference between baryon and meson production and the shadowing by the nuclear remnants. At higher (RHIC) energies a zig-zag structure (multiple zero crossing as a function of rapidity) of $v_1^{\rm odd}$ outside of the nuclear fragmentation regions was predicted as a signature of the deconfined phase transition [28, 29], although the RHIC measurements [30–33] did not reveal such a structure.

The magnitude of the directed flow can be related to the amount of baryon stopping in the nuclear overlap zone [34], which makes it a unique experimental probe of the initial conditions in a heavy-ion collision. The set of initial conditions assumed in model calculations of $v_1^{\rm odd}$ at relativistic energies ranges from incomplete baryon stopping [34] with a positive space-momentum correlation to full nucleon stopping with a tilted [29, 35] or rotating [36] source of matter produced in the overlap zone of the nuclei. Model calculations generally reproduce the negative slope of $v_1^{\rm odd}$ as a function of pseudorapidity measured at RHIC [30–33], while expectations differ for the LHC energies. In comparison to the measurement at the highest RHIC energy, the model predictions for $v_1^{\rm odd}$ at the LHC vary from the same slope but with smaller magnitude [35] to an opposite (positive) slope with significantly larger magnitude [36, 37].

The $v_1^{\rm even}$ estimated from the two-particle azimuthal correlations at mid-rapidity for RHIC [38] (also discussed in [23]) and LHC [11, 18, 39] energies is in approximate agreement with ideal hydrodynamic model calculations [21, 24] for dipole-like [22] energy fluctuations in the overlap zone of the nuclei. Interpretation of the two-particle correlations is complicated due to a possibly large bias from correlations unrelated to the initial geometry (non-flow) and due to the model dependence of the correction procedure for effects of momentum conservation [24]. The directed flow measured relative to the spectator deflection is free from such biases and provides a cleaner probe of the initial conditions in a heavy-ion collision. It also allows for a study of the main features of the dipole-like energy fluctuations such as a vanishing transverse momentum shift of the created system along the direction of the spectator deflection.

In this Letter, the ALICE Collaboration reports on the measurement of the charged particle directed flow relative to the deflection of spectator neutrons in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The directed flow is characterized by the first harmonic coefficient v_1 in a Fourier decomposition of the particle azimuthal distribution with respect to the collision symmetry plane, Ψ,

$$v_1(\eta, p_{\rm T})\{\Psi\} = \langle \cos(\phi - \Psi) \rangle \,, \tag{1}$$

where $\eta = -\ln[\tan(\theta/2)]$, $p_{\rm T}$, θ and ϕ are the particle pseudo-rapidity, transverse momentum, polar

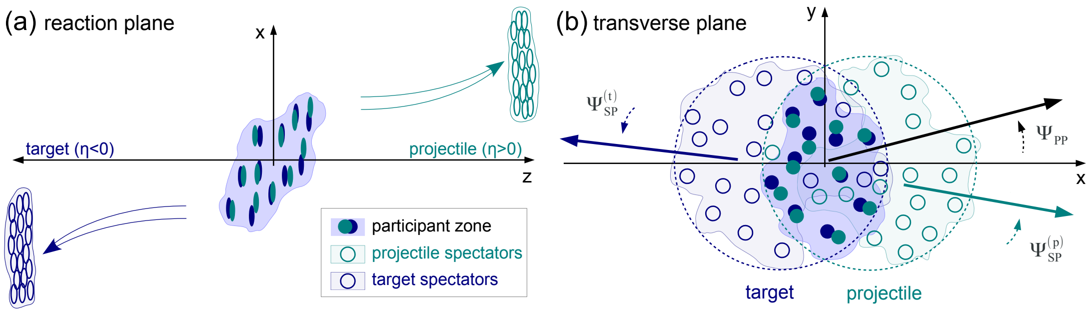

Fig. 1: (color online) Sketch of non-central heavy-ion collision. See text for description of the figure.

and azimuthal angles, respectively. The brackets ”⟨...⟩” indicate an average over produced particles for a large ensemble of events. The collision geometry is illustrated in Fig. 1 which depicts (a) the reaction plane and (b) the transverse to the beam plane views of the system produced in the overlap (participant) zone, as well as the projectile and target spectators. The sign of the projectile fragments directed flow at positive pseudo-rapidity, $\eta > 0$, is by convention positive [30]. It is usually assumed that the projectile and target spectators are deflected away from the collision (z) axis along the impact parameter direction (x-axis) in directions opposite to each other as indicated by the double arrows in Fig. 1(a).

For a non-fluctuating nuclear matter distribution, the directed flow in the participant zone develops along the impact parameter direction. The collision symmetry requires the directed flow to be an anti-symmetric function of pseudo-rapidity, $v_1^{\rm odd}(\eta) = -v_1^{\rm odd}(-\eta)$. As illustrated in Fig. 1(b), due to event-by-event fluctuations in the initial energy density of the collision, the participant plane angle ($\Psi_{\rm PP}^{(1)}$) defined by the dipole asymmetry of the initial energy density [22,23] and that of projectile ($\Psi_{\rm SP}^{\rm p}$) and target ($\Psi_{\rm SP}^{\rm t}$) spectators, in which the flow develops, are different from the geometrical reaction plane angle $\Psi_{\rm RP}$ (coincides with the x-axis). As a consequence, the directed flow can develop [21–24] a rapidity-symmetric component, $v_1^{\rm even}(\eta) = v_1^{\rm even}(-\eta)$, which does not vanish at mid-rapidity.

A sample of about 13 million minimum-bias trigger [9] Pb–Pb collisions at $\sqrt{s_{\rm NN}} =$ 2.76 TeV in the 5-80% centrality range was analyzed. For the most central (0-5%) collisions, the small number of spectators does not allow for a reliable reconstruction of their deflection. Standard ALICE event selection criteria [9] were applied in the analysis. The amplitude measured by the two forward scintillator arrays (VZERO) [40] was used to determine the collision centrality. Charged particles reconstructed in the Time Projection Chamber (TPC) [41] with transverse momentum $p_{\rm T} > 0.15$ GeV/c and pseudorapidity $|\eta| < 0.8$ were selected for the analysis.

The event-by-event deflection of the projectile and target neutron spectators is reconstructed with a pair of Zero Degree Calorimeters (ZDC) [42]. Each ZDC has a 2×2 segmentation in the transverse plane and is installed on each side, 114 meters from the interaction point covering the $|\eta| > 8.78$ (beam rapidity) region. The spectator deflection in the transverse plane was quantified with a pair of two-dimensional vectors

$$\mathbf{Q}^{\rm t,p} \equiv \left(\mathrm{Q}_x^{\rm t,p}, \mathrm{Q}_y^{\rm t,p}\right) = \sum_{i=1}^{4} \mathbf{r}_i E_i^{\rm t,p} \Bigg/ \sum_{i=1}^{4} E_i^{\rm t,p}, \tag{2}$$

where “p” (“t”) denotes the ZDC on the $\eta > 0$ ($\eta < 0$) side of the interaction point, E_i is the measured signal and $\mathbf{r}_i = (x_i, y_i)$ are the coordinates of the i-th ZDC segment. An event-by-event correction (re-centering) [3] of the $\mathbf{Q}^{\rm t,p}$ vectors for their event averages ($\mathbf{Q}^{\rm t,p} \to \mathbf{Q}^{\rm t,p} - \langle \mathbf{Q}^{\rm t,p} \rangle$) is applied as a function of collision centrality to compensate for the run-dependent variation of the LHC beam crossing position and the spread of the collision vertices with respect to its nominal position. The directed flow is then determined with the scalar product method [3,43] independently from correlation of either x or y component of the $\mathrm{Q}_r^{\rm t,p}$ vectors ($r = x,y$) and that of a unit vector $\mathbf{u}(p_{\rm T},\eta) \equiv (u_x,u_y) = (\cos\phi, \sin\phi)$ defined for charged particles

$$v_1^{(r)}\{\Psi_{\rm SP}^{\rm p}\} = \sqrt{2}\frac{\langle {\rm u}_r {\rm Q}_r^{\rm p}\rangle}{\sqrt{|\langle {\rm Q}_r^{\rm t}{\rm Q}_r^{\rm p}\rangle|}},\; v_1^{(r)}\{\Psi_{\rm SP}^{\rm t}\} = -\sqrt{2}\frac{\langle {\rm u}_r {\rm Q}_r^{\rm t}\rangle}{\sqrt{|\langle {\rm Q}_r^{\rm t}{\rm Q}_r^{\rm p}\rangle|}}. \tag{3}$$

The $v_1^{\rm odd}$ and $v_1^{\rm even}$ components of the directed flow relative to the spectator plane ($\Psi = \Psi_{\rm SP}$ in Eq. (1)) are calculated from the equations

$$v_1^{\rm odd}\{\Psi_{\rm SP}\} = \left[v_1\{\Psi_{\rm SP}^{\rm p}\} + v_1\{\Psi_{\rm SP}^{\rm t}\}\right]/2 \tag{4}$$

and

$$v_1^{\rm even}\{\Psi_{\rm SP}\} = \left[v_1\{\Psi_{\rm SP}^{\rm p}\} - v_1\{\Psi_{\rm SP}^{\rm t}\}\right]/2, \tag{5}$$

where $v_1\{\Psi_{\rm SP}^{\rm t,p}\} = \left[v_1^{(x)}\{\Psi_{\rm SP}^{\rm t,p}\} + v_1^{(y)}\{\Psi_{\rm SP}^{\rm t,p}\}\right]/2$. Equation (4) defines the sign of $v_1^{\rm odd}$ according to the same convention as used at RHIC [30, 31] and implies a positive directed flow (or deflection along the positive x-axis direction in Fig. 1(a)) of the projectile spectators ($\eta > 0$).

The observed non-zero negative correlations $\langle {\rm Q}_x^{\rm t}{\rm Q}_x^{\rm p}\rangle$ and $\langle {\rm Q}_y^{\rm t}{\rm Q}_y^{\rm p}\rangle$ [44] indicate deflection of the projectile and target spectators in opposite directions. Correlations between $\langle {\rm Q}_x^{\rm t}{\rm Q}_y^{\rm p}\rangle$ and $\langle {\rm Q}_y^{\rm t}{\rm Q}_x^{\rm p}\rangle$ in orthogonal directions, which can be non-zero only due to residual detector effects are measured [44] to be less than 5% of the correlations in the aligned directions. The extracted difference between the correlations $\langle {\rm Q}_x^{\rm t}{\rm Q}_x^{\rm p}\rangle$ and $\langle {\rm Q}_y^{\rm t}{\rm Q}_y^{\rm p}\rangle$ for mid-central collisions is about 10-20% [44], which is mainly due to a different offset of the beam spot from the center of the ZDCs in-plane and perpendicular to the LHC accelerator ring. This asymmetry is the dominant source of systematics in the directed flow measurement. The corresponding systematic uncertainty is evaluated from the spread of results calculated with different $\mathbf{Q}^{\rm t,p}$-vector components according to Eq. (3) and estimated to be below 20%. The results obtained with Eq. (3) were compared with calculations using the event plane method [3] and are consistent within the statistical precision of the measurement. The variation of the results obtained for the nominal ±10 cm range of the collision vertex along the beam direction from the center of the ALICE detector and for the range reduced to ±7 cm are within 5%. The results with opposite polarity of the magnetic field of the ALICE detector are consistent within 5%. Variation of the results with the collision centrality estimated with the TPC, VZERO, and Silicon Pixel Detectors [42] is less than 5%. Altering the selection criteria for the tracks reconstructed with the TPC resulted in a 3-5% variation of the directed flow results. The systematic error evaluated for each of the sources listed above were added in quadrature to obtain the total systematic uncertainty of the measurement.

Figure 2(a) shows the charged particle directed flow as a function of pseudorapidity measured in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The $v_1^{\rm odd}(\eta)$ component has a negative slope as a function of pseudorapidity. The $v_1^{\rm even}(\eta)$ component is found to be negative and independent of pseudo-rapidity within the statistical and systematic uncertainties of the measurement. The STAR data [31] for $v_1^{\rm odd}$ in Au-Au collisions at $\sqrt{s_{\rm NN}} = 200$ (62) GeV in Fig. 2(c) are downscaled with a factor 0.37 (0.12) which is the value of the ratio of $v_1^{\rm odd}(\eta)$ slope at the LHC to that at RHIC energy. Compared to the measurement at the highest RHIC energy presented in Fig. 2(c), $v_1^{\rm odd}(\eta)$ has the same sign of the slope and a factor of three smaller magnitude. This is in contrast to the positive slope of $v_1^{\rm odd}(\eta)$ expected from the model calculations [36, 37] with stronger rotation of the participant zone at the LHC than at RHIC. A smaller value of $v_1^{\rm odd}$ at the LHC is consistent with the model prediction [35] where a smaller tilt of the participant zone in x–z plane (see Fig. 1(a)) is predicted for the LHC compared to RHIC energies. The ratio of 0.37 (0.12) of $v_1^{\rm odd}$ slope at the LHC to that in Au-Au collisions at $\sqrt{s_{\rm NN}} = 200$ (62) GeV indicates a factor of 1.82 (4.55) deviation from the beam rapidity scaling ($v_1/y_{\rm beam}$) discussed in [33].

Figure 2(b) shows the relative momentum shift $\langle p_x\rangle / \langle p_{\rm T}\rangle \equiv \langle p_{\rm T}\cos(\phi - \Psi_{\rm SP})\rangle / \langle p_{\rm T}\rangle$, along the spectator symmetry plane as a function of pseudorapidity. It is obtained based on Eq. (3) by introducing a

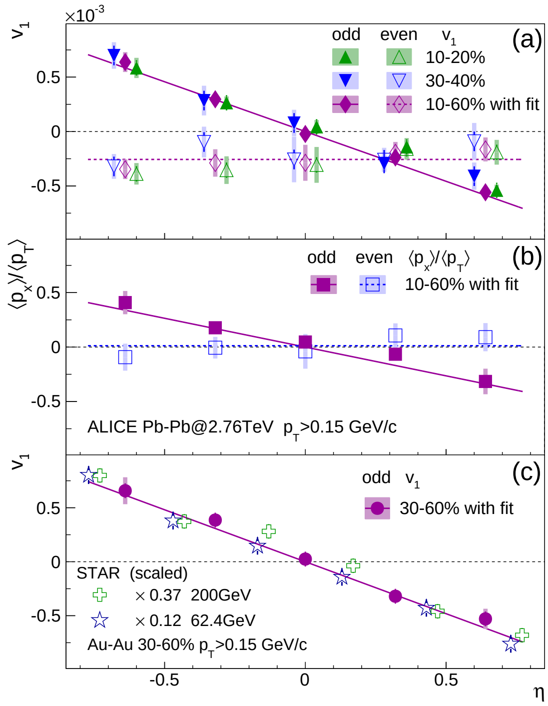

Fig. 2: (color online) (a) v_1 and (b) $\langle p_x \rangle / \langle p_T \rangle$ versus pseudorapidity in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The statistical (systematic) uncertainties are indicated by the error bars (shaded bands). Lines represent fits with linear (constant) function for v_1^{odd} (v_1^{even}). (c) v_1^{odd} in Pb-Pb collisions compared to the STAR data [31] for Au-Au collisions at $\sqrt{s_{NN}} = 200$ (62.4) GeV downscaled with a factor 0.37 (0.12).

$p_T / \langle p_T \rangle$ weight in front of u$_r$. The observed non-zero $\langle p_x \rangle^{odd} / \langle p_T \rangle$ shift has a smaller magnitude than v_1^{odd}, while $\langle p_x \rangle^{even} / \langle p_T \rangle$ is zero in a measured pseudorapidity region. A vanishing $\langle p_x \rangle^{even}$ is consistent with the dipole-like event-by-event fluctuations of the initial energy density in a system with zero net transverse momentum. Disappearance of $\langle p_x \rangle$ at $\eta \approx 0$ indicates that particles produced at mid-rapidity are not involved in balancing the transverse momentum carried away by spectators.

Figures 3(a) and 3(b) present the charged particle v_1 and $\langle p_x \rangle / \langle p_T \rangle$ versus collision centrality. In case of odd components an average in the $|\eta| < 0.8$ range was calculated by taking values at negative η with an opposite sign. Both, v_1^{odd} and v_1^{even} have weak centrality dependence. The $\langle p_x \rangle^{even}$ component is zero at all centralities, while $\langle p_x \rangle^{odd} / \langle p_T \rangle$ is a steeper function of centrality than v_1^{odd}. The magnitude of v_1^{odd} measured at the LHC is significantly smaller than at RHIC (see Fig. 3(c)), while the centrality dependence is very similar at the different energies.

Figure 4(a) presents results for the charged particle directed flow as a function of transverse momentum. The v_1^{odd} and v_1^{even} components change sign around $p_T \sim 1.2 - 1.7$ GeV/c. The observed zero crossing of $v_1^{even}(p_T)$ at a value close to the mean transverse momentum of the produced particles is expected for the dipole-like energy fluctuations when momentum of the low p_T particles is balanced by that of the high p_T particles [21–24]. Compared to the measurements at the highest RHIC energy, in Fig. 4(b), v_1^{odd} shows a similar trend including the sign change around $p_T \sim 1.5$ GeV/c in central collisions and negative value at all p_T for peripheral collisions.

The p_T dependence of $v_1^{even}\{\Psi_{SP}\}$ is similar to that of $v_1^{even}\{\Psi_{PP}^{(1)}\}$ estimated from the Fourier fits of the two-particle correlations [11, 18, 39], while the magnitude of $v_1^{even}\{\Psi_{SP}\}$ is smaller by a factor of forty [24, 45]. The latter can be interpreted as a weak (but non-zero) correlation, $\left\langle \cos\left(\Psi_{PP}^{(1)} - \Psi_{SP}\right)\right\rangle \ll 1$, between the orientation of the participant and spectator collision symmetry planes.

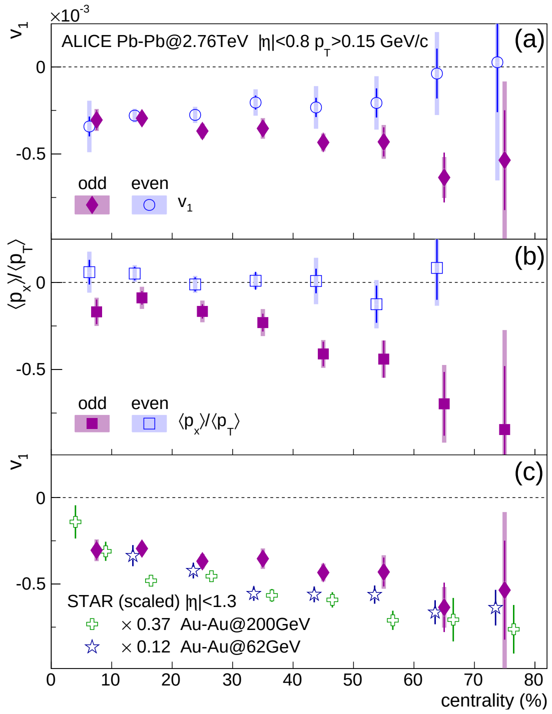

Fig. 3: (color online) (a) v_1 and (b) $\langle p_x \rangle / \langle p_T \rangle$ versus collision centrality in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The statistical (systematic) uncertainties are indicated by the error bars (shaded bands). (c) v_1^{odd} in Pb-Pb collisions compared with the STAR data [31] for Au-Au collisions at $\sqrt{s_{NN}} = 200$ (62.4) GeV downscaled with a factor 0.37 (0.12).

According to hydrodynamic model calculations [22, 24, 46] the particles with low transverse momentum should flow in the direction opposite to the largest magnitude of the density gradient. This, together with the negative even and odd $v_1\{\Psi_{SP}\}$ components measured for particles at mid-rapidity with low transverse momentum ($p_T \lesssim 1.2$ GeV/c) allows one in fact to determine if spectators deflect away from or towards the center of the system. A detailed theoretical calculation of the correlation between fluctuations in the spectator positions and energy density in the participant zone is required to provide a definitive answer on this question.

In summary, the directed flow of charged particles at mid-rapidity, $|\eta| < 0.8$, is reported for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The v_1^{odd} and v_1^{even} directed flow components are measured with respect to the collision symmetry plane defined by spectator neutrons. Both components depend weakly on the collision centrality. The v_1^{odd} has a negative slope as a function of pseudo-rapidity with a magnitude about three times smaller than at the highest RHIC collision energy. This suggests a smaller tilt of the medium created in the participant zone at the LHC, with insufficient rotation to alter the slope of $v_1^{odd}(\eta)$ as predicted in [36, 37]. As a function of transverse momentum, v_1^{odd} and v_1^{even} cross zero at $p_T \sim 1.2 - 1.7$ GeV/c for semi-central collisions. A similar behavior but with about forty times larger magnitude was observed for an estimate of v_1^{even} relative to the participant plane from the Fourier fits of the two-particle correlation [11, 39]. The measured non-zero v_1^{even} indicates that fluctuations of the directed flow of spectators and of particles produced at mid-rapidity are related to each other. The shape of $v_1^{even}(p_T)$ and a vanishing $\langle p_x \rangle^{even}$ is consistent with dipole-like fluctuations of the initial energy density in the participant zone. Disappearance of $\langle p_x \rangle$ for particles produced close to zero rapidity suggest that they do not play a role in balancing the transverse momentum kick of spectators. Further interpretation of the results demands detailed theoretical calculations of the directed flow components relative to the spectator deflection and correlation between the participant and spectator symmetry planes. Future studies of the directed flow at mid-rapidity using identified particles and extension of the v_1

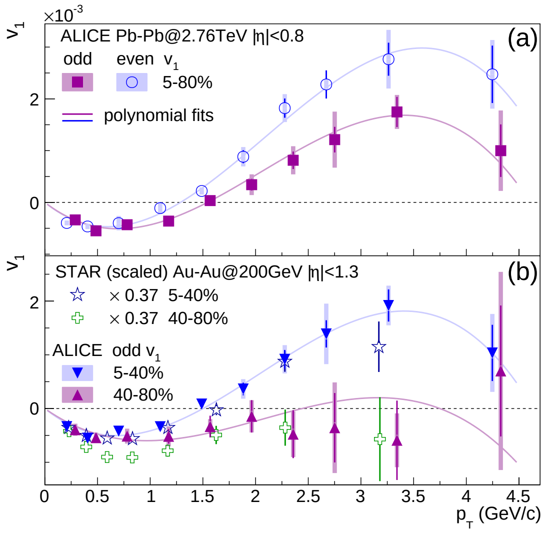

Fig. 4: (color online) v_1 versus transverse momentum in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The statistical (systematic) uncertainties are indicated by the error bars (shaded bands). Lines represent fits with the third order polynomial. (a) v_1 for 5-80% centrality range. (b) $v_1^{\rm odd}$ in Pb-Pb collisions compared with the STAR data [31] for Au-Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV downscaled with a factor 0.37.

measurements to forward rapidities should provide a stronger constraint on the effects of initial density fluctuations in the formation of directed flow.

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