Directed Flow of Charged Particles at Midrapidity Relative to the Spectator Plane in Pb-Pb Collisions at sqrt[s_{NN}]=2.76 TeV.

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Directed Flow of Charged Particles at Midrapidity Relative to the Spectator Plane in Pb-Pb Collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV

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The directed flow of charged particles at midrapidity is measured in Pb-Pb collisions at $\sqrt{s_{\rm NN}} =$ 2.76 TeV relative to the collision symmetry plane defined by the spectator nucleons. A negative slope of the rapidity-odd directed flow component with approximately 3 times smaller magnitude than found at the highest RHIC energy is observed. This suggests a smaller longitudinal tilt of the initial system and disfavors the strong fireball rotation predicted for the LHC energies. The rapidity-even directed flow component is measured for the first time with spectators and found to be independent of pseudorapidity with a sign change at transverse momenta p_T between 1.2 and 1.7 GeV/c. Combined with the observation of a vanishing rapidity-even p_T shift along the spectator deflection this is strong evidence for dipolelike initial density fluctuations in the overlap zone of the nuclei. Similar trends in the rapidity-even directed flow and the estimate from two-particle correlations at midrapidity, which is larger by about a factor of 40, indicate a weak correlation between fluctuating participant and spectator symmetry planes. These observations open new possibilities for investigation of the initial conditions in heavy-ion collisions with spectator nucleons.

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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), with a positive (in-plane) elliptic flow as first observed at the Alternating Gradient Synchrotron (AGS) [4,5]. A much stronger flow was subsequently measured at the Super Proton Synchrotron (SPS) [6], Relativistic Heavy Ion Collider (RHIC) [7–9], and recently at the LHC [10–12]. Elliptic flow at RHIC and the LHC is reproduced by hydrodynamic model calculations with a small value of the ratio of shear viscosity to entropy density [13–16]. 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 determination of the initial conditions. Significant triangular flow measured recently at RHIC [17,18] and LHC [12,19,20] energies has demonstrated [21,22] that initial energy fluctuations play an important role in the development of the final momentum-space anisotropy of the distribution of produced particles.

The collision geometry is illustrated in Fig. 1, which depicts the participant overlap region and spectators as viewed in (a) the reaction plane and (b) the plane perpendicular to the beam. Figure 1(a) shows the projectile and target spectators repelled in the reaction (xz) plane from the center of the colliding system along the impact parameter (x) direction. An alternative scenario where spectators

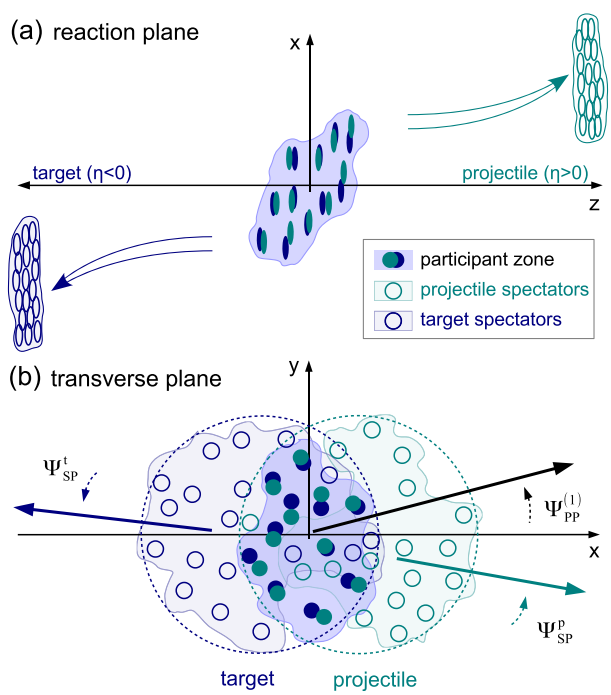

FIG. 1 (color online). Sketch of a noncentral heavy-ion collision. See text for description of the figure.

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are attracted towards the center of the system is discussed in [23].

The directed flow is characterized by the first harmonic coefficient v_1 in a Fourier decomposition of the particle azimuthal distribution with respect to one of the collision symmetry planes, Ψ, as illustrated in Fig. 1(b) and discussed below

$$v_1(\eta, p_T)\{\Psi\} = \langle \cos(\phi - \Psi) \rangle. \quad (1)$$

Here $\eta = -\ln[\tan(\theta/2)]$, p_T, θ, and ϕ are the particle pseudorapidity, transverse momentum, polar, and azimuthal angles, respectively. The brackets "$\langle \ldots \rangle$" indicate an average over measured particles in all recorded events.

For a nonfluctuating nuclear matter distribution, the directed flow in the participant zone develops along the impact parameter direction. The collision symmetry requires that the directed flow be an antisymmetric function of pseudorapidity, $v_1^{\rm odd}(\eta) = -v_1^{\rm odd}(-\eta)$. Because of 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 [24,25] and that of projectile ($\Psi_{\rm SP}^{p}$) and target ($\Psi_{\rm SP}^{t}$) spectators are different from the geometrical reaction plane angle $\Psi_{\rm RP}$ [x axis in Fig. 1(b)]. As a consequence, the directed flow can develop [24–27] a rapidity-symmetric component, $v_1^{\rm even}(\eta) = v_1^{\rm even}(-\eta)$, which does not vanish at midrapidity.

The slope of $v_1^{\rm odd}$ as a function of rapidity at AGS [5,28] and SPS [29,30] energies is driven by the difference between baryon and meson production and shadowing by the nuclear remnants. At higher (RHIC) energies a multiple zero crossing of $v_1^{\rm odd}$ with rapidity outside the nuclear fragmentation regions was predicted as a signature of the deconfined phase transition [31,32]. However, the RHIC measurements [33–36] did not reveal such a structure. The magnitude of the directed flow depends on the amount of baryon stopping in the nuclear overlap zone [37]. The two can be related via realistic model calculations, making $v_1^{\rm odd}$ an important experimental probe of the initial conditions in a heavy-ion collision. The initial conditions assumed in model calculations of $v_1^{\rm odd}$ range from incomplete baryon stopping [37], with a positive space-momentum correlation, to full nucleon stopping with a tilted [32,38] or rotating [39] source of matter produced in the overlap zone of the nuclei. Model calculations generally agree on the negative sign of the $v_1^{\rm odd}$ slope as a function of pseudorapidity at RHIC [33–36]. The model predictions for $v_1^{\rm odd}$ at the LHC vary from having the same slope as at RHIC but with smaller magnitude [38] to an opposite (positive) slope with significantly larger magnitude [39,40].

The $v_1^{\rm even}$ estimated from the two-particle azimuthal correlations at midrapidity for RHIC [41] (see also [25]) and LHC [12,20,42] energies is in approximate agreement with ideal hydrodynamic model calculations [26,27] for dipolelike [24] 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 (nonflow) and due to the model dependence of the correction procedure for effects of momentum conservation [27]. 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 dipolelike energy fluctuations such as a vanishing transverse momentum shift of the created system along the direction of the spectator deflection. Directed flow and its fluctuations also play an important role in understanding effects due to the strong magnetic field in heavy-ion collisions [24] and interpretation of the observed charge separation relative to the reaction plane [43] in terms of the chiral magnetic effect [44].

In this Letter, we report the charged particle directed flow measured relative to the deflection of spectator neutrons in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. About 13×10^6 minimum-bias [10] collisions in the 5%–80% centrality range were analyzed. For the most central (0%–5%) collisions, the small number of spectators does not allow for a reliable reconstruction of their deflection. Two forward scintillator arrays (VZERO) [45] were used to determine the collision centrality. Charged particles reconstructed in the time projection chamber (TPC) [46] with $p_T > 0.15$ GeV/c and $|\eta| < 0.8$ were selected for the analysis.

The deflection of neutron spectators was reconstructed using a pair of zero degree calorimeters (ZDC) [47] with 2×2 segmentation installed 114 m from the interaction point on each side, covering the $|\eta| > 8.78$ (beam rapidity) region. A typical energy measured by both ZDCs for 30%–40% centrality is about 100 TeV [48]. The spectator deflection in the transverse plane was measured with a pair of two-dimensional vectors

$$\mathbf{Q}^{t,p} \equiv (Q_x^{t,p}, Q_y^{t,p}) = \sum_{i=1}^{4} \mathbf{n}_i E_i^{t,p} \Big/ \sum_{i=1}^{4} E_i^{t,p}, \quad (2)$$

where p (t) denotes the ZDC on the $\eta > 0$ ($\eta < 0$) side of the interaction point, E_i is the measured signal, and $\mathbf{n}_i = (x_i, y_i)$ are the coordinates of the ith ZDC segment. An asymmetry of 0.1% [49] in energy calibration of the two ZDCs and an absolute energy scale uncertainty cancel in Eq. (2). To compensate for the run-dependent variation of the LHC beam crossing position, an event-by-event correction $\mathbf{Q}^{t,p} \to \mathbf{Q}^{t,p} - \langle \mathbf{Q}^{t,p} \rangle$ [3] was applied as a function of collision centrality and transverse position of the collision vertex relative to the center of the ALICE detector. Experimental values of the correction for the 30%–40% centrality class are $\langle Q_{x(y)}^{p} \rangle \approx 2.0(-1.5)$ mm and $\langle Q_{x(y)}^{t} \rangle \approx -1.1(0.01)$ mm.

The directed flow is determined with the scalar product method [3,50]

$$v_1\{\Psi^p_{\rm SP}\} = \frac{1}{\sqrt{2}}\left[\frac{\langle u_x Q^p_x\rangle}{\sqrt{|\langle Q^t_x Q^p_x\rangle|}} + \frac{\langle u_y Q^p_y\rangle}{\sqrt{|\langle Q^t_y Q^p_y\rangle|}}\right],$$
$$v_1\{\Psi^t_{\rm SP}\} = -\frac{1}{\sqrt{2}}\left[\frac{\langle u_x Q^t_x\rangle}{\sqrt{|\langle Q^t_x Q^p_x\rangle|}} + \frac{\langle u_y Q^t_y\rangle}{\sqrt{|\langle Q^t_y Q^p_y\rangle|}}\right], \quad (3)$$

where $u_x = \cos\phi$ and $u_y = \sin\phi$ are defined for charged particles at midrapidity. The odd and even components of the directed flow relative to the spectator plane [$\Psi = \Psi_{\rm SP}$ in Eq. (1)] are then calculated from the equations

$$v_1^{\rm odd}\{\Psi_{\rm SP}\} = [v_1\{\Psi^p_{\rm SP}\} + v_1\{\Psi^t_{\rm SP}\}]/2 \quad (4)$$

and

$$v_1^{\rm even}\{\Psi_{\rm SP}\} = [v_1\{\Psi^p_{\rm SP}\} - v_1\{\Psi^t_{\rm SP}\}]/2. \quad (5)$$

Equation (4) defines the sign of $v_1^{\rm odd}$ using the convention used at RHIC [33,34] and implies a positive directed flow [or deflection along the positive x-axis direction in Fig. 1(a)] of the projectile spectators.

The negative correlations $\langle Q^t_x Q^p_x\rangle$ and $\langle Q^t_y Q^p_y\rangle$ [51] indicate a deflection of the projectile and target spectators in opposite directions. These correlations are sensitive to a combination of the spectator's directed flow relative to the reaction plane $\Psi_{\rm RP}$ and an additional contribution due to flow of spectators along the fluctuating $\Psi^p_{\rm SP}$ and $\Psi^t_{\rm SP}$ directions [see Fig. 1(b)]. The two contributions are not separable using current experimental techniques and both should be considered in theoretical interpretations of the results derived from Eqs. (3)–(5). Given that the transverse deflection of spectators [$d_{\rm spec} \approx \sqrt{(\langle Q^t_x Q^p_x\rangle + \langle Q^t_y Q^p_y\rangle)/2}$] is tiny compared to the ZDC detector position $|z_{\rm ZDC}| = 114$ m along the beam direction, one can make a rough estimate of the corresponding transverse momentum carried by an individual spectator: $p_T^{\rm spec} \approx \sqrt{s_{\rm NN}}(d_{\rm spec}/z_{\rm ZDC})$. The measured $d_{\rm spec}$ is about 0.67 (0.92) mm [51] for the 5%–10% (30%–40%) centrality class which yields $p_T^{\rm spec} \sim 16(22)$ MeV/c. Correlations $\langle Q^t_x Q^p_y\rangle$ and $\langle Q^t_y Q^p_x\rangle$ in orthogonal directions, which can be nonzero due to residual detector effects, are less than 5% [51] of those in the aligned directions. The 10%–20% [51] difference between $\langle Q^t_x Q^p_x\rangle$ and $\langle Q^t_y Q^p_y\rangle$ for midcentral collisions 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. The corresponding dominant systematic uncertainty is evaluated from the spread of results for different terms in Eq. (3) and estimated to be below 20%. The results obtained with Eq. (3) are consistent with calculations using the event plane method [3]. 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 [47] and with narrowing the nominal ±10 cm range of the collision vertex along the beam direction from the center of the ALICE detector to ±7 cm is less than 5%. Altering the selection criteria for the tracks reconstructed with the TPC resulted in a 3%–5% variation of the 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 for 10%–20%, 30%–40%, and 10%–60% centrality classes. The $v_1^{\rm even}(\eta)$ component is found to be negative and independent of η. The $v_1^{\rm odd}(\eta)$ component exhibits a negative slope as a function of pseudorapidity. This is in contrast to the positive slope expected from the model calculations [39,40] with stronger rotation of the participant zone at the LHC than at RHIC. The $v_1^{\rm odd}(\eta)$ at the highest RHIC energy [34] has the same sign of the slope and a factor of 3 larger magnitude. This is consistent with a smaller tilt of the participant zone in the x-z plane [see Fig. 1(a)] as predicted in [38] for LHC energies. Figure 2(c) compares $v_1^{\rm odd}$ with the STAR data [34] for Au-Au collisions at $\sqrt{s_{\rm NN}} = 200$ (62) GeV downscaled by the ratio 0.37 (0.12) of the slope at the LHC to

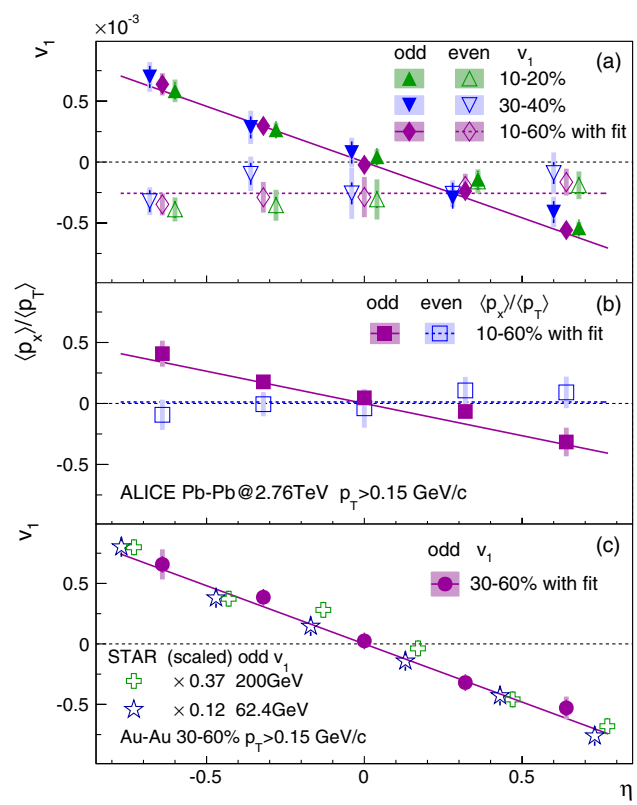

FIG. 2 (color online). (a) v_1 and (b) $\langle p_x\rangle/\langle p_T\rangle$ versus pseudorapidity in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. (c) $v_1^{\rm odd}$ compared to the STAR data [34] for Au-Au collisions at $\sqrt{s_{\rm NN}} = 200$ (62.4) GeV downscaled by a factor 0.37 (0.12). The statistical (systematic) uncertainties are indicated by the error bars (shaded bands). Lines (to guide the eye) represent fits with a linear (constant) function for $v_1^{\rm odd}$ ($v_1^{\rm even}$).

that at RHIC energy. These ratios indicate a strong violation by a factor of 1.82 (4.55) of the beam rapidity scaling discussed in [36].

Figure 2(b) shows the relative momentum shift $\langle p_x\rangle/\langle p_T\rangle \equiv \langle p_T \cos(\phi - \Psi_{SP})\rangle/\langle p_T\rangle$ along the spectator plane as a function of pseudorapidity. It is obtained by introducing a $p_T/\langle p_T\rangle$ weight in front of u_x and u_y in Eq. (3). The nonzero $\langle p_x\rangle^{odd}/\langle p_T\rangle$ shift has a smaller magnitude than v_1^{odd}. The $\langle p_x\rangle^{even}$ vanishes which is consistent with the dipolelike 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 midrapidity are not involved in balancing the transverse momentum carried away by spectators.

Figures 3(a) and 3(b) present v_1 and $\langle p_x\rangle/\langle p_T\rangle$ versus collision centrality. The odd components were calculated by taking values at negative η with an opposite sign. Both v_1 components 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}. This suggests that v_1^{odd} has two contributions. The first contribution has a similar origin as v_1^{even} due to asymmetric dipolelike initial energy distribution. The second contribution grows almost linearly from central to peripheral collisions and represents an effect of sideward collective motion of particles at nonzero rapidity due to expansion of the initially tilted source. This $\langle p_x\rangle$ is balanced by that of the particles produced at opposite rapidity and in very forward (spectator) regions. The magnitude of v_1^{odd} at the LHC is significantly smaller than at RHIC with a similar centrality dependence [see Fig. 3(c)].

Figure 4(a) presents v_1 as a function of p_T. Both components change sign around p_T between 1.2 and 1.7 GeV/c which is expected for the dipolelike energy fluctuations when the momentum of the low p_T particles is balanced by those at high p_T [24–27]. The p_T dependence of v_1^{even} relative to Ψ_{SP} is similar to that of v_1^{even} relative to $\Psi_{PP}^{(1)}$ estimated from the Fourier fits of the two-particle correlations [12,20,42], while its magnitude is smaller by a factor of 40 [27,52]. This can be interpreted as a weak correlation, $\langle\cos(\Psi_{PP}^{(1)} - \Psi_{SP})\rangle \ll 1$, between the orientation of the participant and spectator collision symmetry planes. Compared to the RHIC measurements in Fig. 4(b), v_1^{odd} shows a similar trend including the sign change around p_T of 1.5 GeV/c in central collisions and a negative value at all p_T for peripheral collisions.

According to hydrodynamic model calculations [24,27,53] particles with low p_T should flow in the direction opposite to the largest density gradient. This, together with the negative even and odd v_1 components relative to Ψ_{SP} measured for particles at midrapidity with low transverse momentum ($p_T \lesssim 1.2$ GeV/c) allows one, in principle, to determine if spectators deflect away from or towards the center of the system. However, a detailed

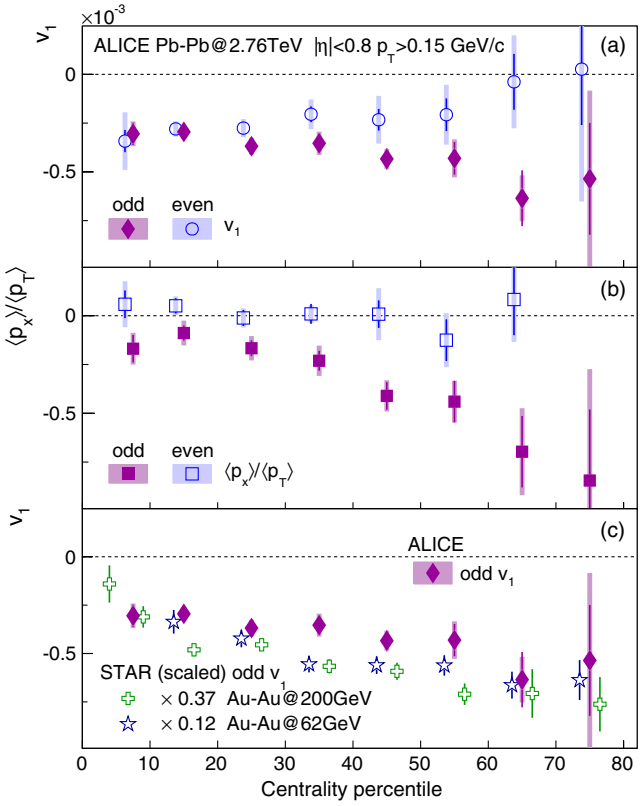

FIG. 3 (color online). (a) v_1 and (b) $\langle p_x\rangle/\langle p_T\rangle$ versus centrality. (c) v_1^{odd} comparison with STAR data [34]. See text and Fig. 2 for description of the data points.

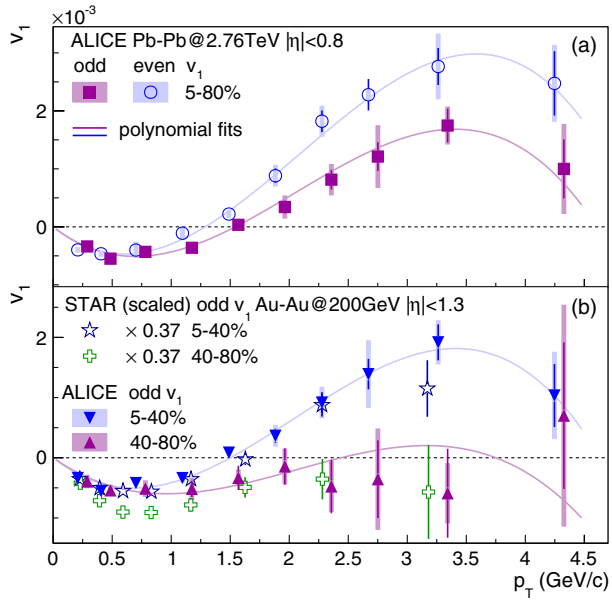

FIG. 4 (color online). (a) v_1 versus transverse momentum. (b) v_1^{odd} comparison with STAR data [34]. See text and Fig. 2 for description of the data points. Lines (to guide the eye) represent fits with a third order polynomial.

theoretical calculation of the correlation between fluctuations in the spectator positions and energy density in the participant zone such as in [23] is required to provide a definitive answer to this question.

In summary, the $v_1^{\rm odd}$ and $v_1^{\rm even}$ components of charged particle directed flow at midrapidity, $|\eta| < 0.8$, are measured relative to the spectator plane for Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The $v_1^{\rm odd}$ has a negative slope as a function of pseudorapidity with a magnitude about 3 times smaller than at the highest RHIC 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 $v_1^{\rm odd}(\eta)$ as predicted in [39,40]. As a function of p_T, $v_1^{\rm odd}$ and $v_1^{\rm even}$ cross zero at p_T between 1.2 and 1.7 GeV/c for semicentral collisions. Disappearance of $\langle p_x \rangle$ for particles produced close to zero rapidity suggest that they do not play a role in balancing the p_T kick of spectators. The shape of $v_1^{\rm even}(p_T)$ and a vanishing $\langle p_x \rangle^{\rm even}$ is consistent with dipolelike fluctuations of the initial energy density in the participant zone. A similar shape but with about 40 times larger magnitude was observed for an estimate of $v_1^{\rm even}(p_T)$ relative to the participant plane from the Fourier fits of the two-particle correlation [12,20,42]. This indicates that fluctuating participant and spectator collision symmetry planes are weakly correlated, which is important experimental input for modeling the ill-constrained initial conditions of a heavy-ion collision. Future studies of the directed flow at midrapidity using identified particles and extension of the v_1 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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