Probing the Effects of Strong Electromagnetic Fields with Charge-Dependent Directed Flow in Pb-Pb Collisions at the LHC

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The first measurement at the LHC of charge-dependent directed flow (v_1) relative to the spectator plane is presented for Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Results are reported for charged hadrons and D^0 mesons for the transverse momentum intervals $p_{\mathrm{T}} > 0.2$ GeV/c and $3 < p_{\mathrm{T}} < 6$ GeV/c in the 5%–40% and 10%–40% centrality classes, respectively. The difference between the positively and negatively charged hadron v_1 has a positive slope as a function of pseudorapidity η, $\mathrm{d}\Delta v_1/\mathrm{d}\eta = [1.68 \pm 0.49(\mathrm{stat}) \pm 0.41(\mathrm{syst})] \times 10^{-4}$. The same measurement for D^0 and $\bar{\mathrm{D}}^0$ mesons yields a positive value $\mathrm{d}\Delta v_1/\mathrm{d}\eta = [4.9 \pm 1.7(\mathrm{stat}) \pm 0.6(\mathrm{syst})] \times 10^{-1}$, which is about 3 orders of magnitude larger than the one of the charged hadrons. These measurements can provide new insights into the effects of the strong electromagnetic field and the initial tilt of matter created in noncentral heavy ion collisions on the dynamics of light (u, d, and s) and heavy (c) quarks. The large difference between the observed Δv_1 of charged hadrons and D^0 mesons may reflect different sensitivity of the charm and light quarks to the early time dynamics of a heavy ion collision. These observations challenge some recent theoretical calculations, which predicted a negative and an order of magnitude smaller value of $\mathrm{d}\Delta v_1/\mathrm{d}\eta$ for both light flavor and charmed hadrons.

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Quantum chromodynamic (QCD) calculations on the lattice [1–6] predict at high temperatures the existence of a deconfined state of quarks and gluons, known as the quark–gluon plasma (QGP). Characterizing the QGP properties is among the main goals of the experimental program with ultrarelativistic heavy ion collisions at the Large Hadron Collider (LHC). Measurements of the anisotropic transverse flow [7–11], quantified by the second (v_2) and higher order ($n > 2$) harmonic coefficients v_n, allow one to characterize the different phases of a heavy ion collision and constrain the properties of the QGP [12–16].

The directed flow, v_1, has a special role due to its sensitivity to the three-dimensional spatial profile of the initial conditions and the preequilibrium early time dynamics in the evolution of the collision. The space momentum correlations in particle production from a longitudinally tilted source result in a nonzero v_1. The tilt arises from the asymmetries in the number of forward and backward moving participant nucleons at different positions in the transverse plane [17–19]. The directed flow of charged hadrons at the LHC [20] has significantly smaller magnitude compared to that at lower relativistic heavy ion collider (RHIC) energies [21], which can be interpreted as a smaller initial tilt at the LHC [22–24].

Charm quarks are produced early in the collision via hard scattering processes. Their emission region is not tilted in the longitudinal direction [19] unlike the one of light quarks, which are predominantly produced in soft processes at later stages of the collision [18,25]. Consequently, the region of charm quark production in the transverse plane is shifted with respect to that of light quarks and gluons, resulting in an enhanced dipole asymmetry in the charm quark distribution [19]. During the system expansion, charm quarks would be dragged by the flow of the light quarks in the transverse direction of the shift, which is predicted to result in a larger v_1 of charm hadrons compared to light flavor hadrons [19,26]. Consequently, the measurements of the charge-integrated directed flow of hadrons containing light (u, d, and s) and heavy (c) quarks together with their difference in magnitude are of great interest and allow one to probe the three-dimensional space-time evolution of the produced matter.

Heavy ion collisions are also characterized by extremely strong electromagnetic fields primarily induced by spectator protons, which do not undergo inelastic collisions. There is strong interest in characterizing the time evolution of these fields, which are estimated to reach 10^{18}–10^{19} Gauss in the early stages (<0.5 fm) of Pb-Pb collisions at

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LHC energies [27,28]. Phenomena predicted to occur in the presence of this strong electromagnetic field include the chiral magnetic effect (CME), which is driven by the generation of an electric current along the magnetic field in a medium with chiral imbalance [29–32]. While experimental results for charge-dependent correlations are in qualitative agreement with theoretical expectations for the CME [33–35], possible background contributions, such as effects of local charge conservation coupled with the anisotropic flow, prevent their unambiguous interpretation [36] and have led to upper limits on the CME at LHC energies. Thus, it is fundamental to use other observables with direct sensitivity to the electromagnetic fields in order to constrain their magnitudes and time evolution in heavy ion collisions.

The charge dependence of the produced particle directed flow relative to the spectator plane is directly sensitive to the presence of electromagnetic fields. The spectator plane is defined by the deflection direction of the collision spectators. On average, its orientation is perpendicular to the direction of the magnetic field generated by the positively charged spectators. The charge dependence of v_1 comes from two competing effects acting in opposite directions: the Lorentz force and the Coulomb force, both induced by the rapidly decreasing magnetic field. In an electrically conducting plasma, the induced charged currents might slow down the decay of the magnetic field [27]. The measurement of charge-dependent v_1 can therefore constrain the QGP electric conductivity.

First estimates of these effects on the v_1 of charged particles were presented in [37,38]. Using the electric conductivity from lattice QCD calculations [39,40], the difference between the v_1 of positively and negatively charged pions, $\Delta v_1(\pi) = v_1(\pi^+) - v_1(\pi^-)$, in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV was estimated to be not larger than 10^{-5} for $|\eta| < 1$ [38]. Charm quarks, which are produced in the early stages when the magnetic field is maximal, should be more strongly affected by the electromagnetic fields than light quarks [26,41]. The difference Δv_1 between the v_1 of D^0 ($c\bar{u}$) and $\bar{\mathrm{D}}^0$ ($\bar{c}u$) mesons should therefore provide better sensitivity to this initial magnetic field. A calculation of v_1 of charmed mesons in the rapidity interval $|y| < 1$ gives a value $\Delta v_1(D) \sim 10^{-2}$ [41], which is 3 orders of magnitude larger than the one expected for pions. Recently, STAR Collaboration published a measurement of directed flow of D^0 and $\bar{\mathrm{D}}^0$ mesons in 10%–80% central Au–Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV [42]. The slope of v_1 of D^0 and $\bar{\mathrm{D}}^0$ mesons as a function of rapidity is negative and about a factor of 25 times larger than that of charged kaons.

This Letter reports the first measurements at the LHC of the charge dependence of v_1 relative to the spectator plane for charged hadrons and D^0 mesons as a function of pseudorapidity in midcentral Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV.

About $23(19) \times 10^6$ Pb-Pb collisions in the 5%–40% (10%–40%) centrality interval are used for the charged hadron (D^0 and $\bar{\mathrm{D}}^0$ meson) v_1 measurements. Only events with a primary vertex reconstructed within ± 10 cm from the detector center along the beam direction are analyzed. Two forward scintillator arrays (V0A and V0C) [43] are used to determine the collision centrality. For the most central (0%–5%) collisions, the small number of spectators prevents an accurate reconstruction of their deflection. In the 5%–10% centrality interval, the large combinatorial background does not allow the measurement of the D^0 and $\bar{\mathrm{D}}^0$ v_1.

The deflection direction of the collision spectators is reconstructed from spectator neutrons detected using two zero degree calorimeters (ZDCs) [44,45]. The ZDCs have a 2×2 segmentation in the plane transverse to the beam direction and are installed at 112.5 m distance from the detector center on both sides of the interaction point, covering the "projectile" ($\eta > 8.78$) and the "target" ($\eta < -8.78$) spectator regions. For each ZDC, a flow vector is constructed following the procedure described in [20]:

$$\mathbf{Q}^{t,p} \equiv (\mathrm{Q}_x^{t,p}, \mathrm{Q}_y^{t,p}) = \sum_{i=1}^{4} \mathbf{n}_i E_i^{t,p} \Big/ \sum_{i=1}^{4} E_i^{t,p}, \qquad (1)$$

where p and t denote the ZDC on the projectile and target side, E_i is the measured signal, and $\mathbf{n}_i = (x_i, y_i)$ are the coordinates of the center of the ith ZDC segment.

The deflection direction of the spectator neutrons is estimated event by event with the $\mathbf{Q}^{t,p}$ vectors corrected for the run-dependent variation of the LHC beam crossing position [46]. In midcentral collisions, this deflection direction is strongly correlated with the magnetic field orientation. The deflection is expected to be opposite (anticorrelated) for the projectile and the target sides, i.e., $\langle \mathrm{Q}_x^p \mathrm{Q}_x^t \rangle = \langle \mathrm{Q}_y^p \mathrm{Q}_y^t \rangle < 0$ and $\langle \mathrm{Q}_y^p \mathrm{Q}_x^t \rangle$ and $\langle \mathrm{Q}_x^p \mathrm{Q}_y^t \rangle = 0$. A deviation from these expectations, mostly for peripheral collisions with centrality above 40%, is observed even after applying the flow vector correction. These residual variations are used in the estimation of the systematic uncertainty as described in [20] and discussed below.

The directed flow is measured using the scalar product method [47] as follows:

$$v_1^{t,p} = \frac{\langle \mathbf{u} \mathbf{Q}^{t,p} \rangle}{\sqrt{|\langle \mathbf{Q}^t \mathbf{Q}^p \rangle|}} = \frac{\langle \mathrm{u}_x \mathrm{Q}_x^{t,p} + \mathrm{u}_y \mathrm{Q}_y^{t,p} \rangle}{\sqrt{|\langle \mathrm{Q}_x^t \mathrm{Q}_x^p + \mathrm{Q}_y^t \mathrm{Q}_y^p \rangle|}}, \qquad (2)$$

where $\mathbf{u} = (\cos\varphi, \sin\varphi)$ is the unit flow vector of the charged hadron or D^0 meson candidate with azimuthal angle φ. The directed flow is calculated as $v_1 = (v_1^p - v_1^t)/2$. The sign of v_1 is defined relative to the deflection of the projectile spectators, corresponding to the rapidity odd component of the v_1 discussed in [20]. The measurement of v_1 using spectators does not require any treatment of the momentum conservation unlike the measurements based on correlations between particles produced at midrapidity [48]. This is justified by the observation of a vanishing relative momentum shift along the spectator plane at $\eta = 0$ [20].

The charged hadron v_1 is measured from tracks reconstructed with the Inner Tracking System (ITS) [49] and the time projection chamber (TPC) [50] and selected requiring $p_{\rm T} > 0.2$ GeV/c, $|\eta| < 0.8$, at least 70 (out of a maximum of 159) TPC space points and $\chi^2/\mathrm{ndf} < 2$ for the momentum fit in the TPC. In order to reduce the contamination from secondary particles, only tracks with a maximum distance of closest approach (DCA) to the reconstructed primary vertex in both the transverse ($\mathrm{DCA}_{xy} < 2.4$ cm) and the longitudinal direction ($\mathrm{DCA}_z < 3.2$ cm) are accepted.

The D^0 and $\bar{\mathrm{D}}^0$ mesons are reconstructed using the decay channel $\mathrm{D}^0 \to K^-\pi^+$ and its charge conjugate for $3 < p_{\rm T} < 6$ GeV/c. Pions and kaons are reconstructed in the TPC and ITS detectors. Tracks are selected requiring $|\eta| < 0.8$, $p_{\rm T} > 0.4$ GeV/c, at least 70 hits in TPC, and at least two hits (out of a maximum of six) in the ITS, out of which at least one has to be in the two innermost layers. Particle identification is based on measurements of the specific ionization energy loss $\mathrm{d}E/\mathrm{d}x$ in the TPC and the flight time from the interaction point to the time of flight (TOF) detector [51]. The charge of the identified pions and kaons allows one to distinguish between the $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ and $\bar{\mathrm{D}}^0 \to \mathrm{K}^+\pi^-$ candidates. Geometrical selections on the displaced decay vertex topology are applied to reduce the combinatorial background [52].

The v_1^{D} is extracted separately for D^0 and $\bar{\mathrm{D}}^0$ mesons via a simultaneous fit to the number $N(M)$ of $K^\mp\pi^\pm$ pairs and their $v_1(M)$ as a function of the invariant mass, M:

$$N(M) = N_D(M) + N_{\mathrm{bg}}(M), \tag{3}$$

$$v_1(M) = [v_1^D N_D(M) + v_1^{\mathrm{bg}}(M) N_{\mathrm{bg}}(M)]/[N_D(M) + N_{\mathrm{bg}}(M)]. \tag{4}$$

An example of the simultaneous fit is shown in Fig. 1. The invariant mass distribution is fitted with the sum of a Gaussian function $N_D(M)$ for the D^0 and $\bar{\mathrm{D}}^0$ signal and an exponential function $N_{\mathrm{bg}}(M)$ for the background. The invariant mass dependence of the directed flow of background candidates $v_1^{\mathrm{bg}}(M)$ is parameterized by a linear function.

Candidates that satisfy both the $\mathrm{K}^-\pi^+$ and $\mathrm{K}^+\pi^-$ hypotheses (reflected kinematics) and therefore cannot be tagged uniquely as D^0 or $\bar{\mathrm{D}}^0$ are rejected. This removes about 35% of the signal and increases the signal to background ratio by about 30%–40%, with a net result of a negligible reduction of the statistical significance of the D^0 and $\bar{\mathrm{D}}^0$ yield. The extracted v_1^{D} includes contributions from both prompt D^0 mesons and feed-down D^0 mesons

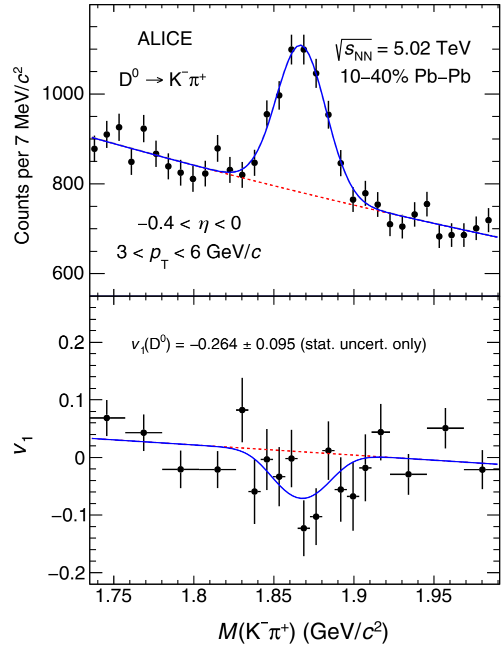

FIG. 1. Illustration of the D^0 meson v_1 extraction procedure via a simultaneous fit to the candidate invariant mass distribution (upper panel) and v_1 (lower panel) for $3 < p_{\rm T} < 6$ GeV/c and $-0.4 < \eta < 0$ in the 10%–40% centrality interval. The blue solid lines correspond to the combined signal and background fit functions, while the red dashed lines represent the background contribution.

from beauty hadron decays. The fraction of prompt D^0 meson is about 85% for the analyzed centrality class and $p_{\rm T}$ interval [53].

Common sources of systematic uncertainty between charged hadrons and D mesons are related to the resolution of the spectator plane and to the dependence on the ALICE magnet polarity. The absolute systematic uncertainty related to the residual asymmetry in the spectator plane estimation is given by the difference between the v_1 obtained separately from $\langle \mathrm{u}_x \mathrm{Q}_x \rangle$ and $\langle \mathrm{u}_y \mathrm{Q}_y \rangle$ correlations with the ZDCs in Eq. (2). It is about 3.5×10^{-5} (2×10^{-2}) for charged hadrons (D^0 and $\bar{\mathrm{D}}^0$ mesons). Effects related to track reconstruction and geometrical alignment of the detectors, which could influence positive and negative tracks differently, are estimated by comparing the v_1 results obtained using data taken with opposite magnet polarity. This comparison also probes the bias in the spectator plane estimation due to the nonzero beam crossing angle in the vertical plane, which had opposite values (± 60 μrad) for the opposite magnet polarities. The absolute difference between the v_1 values obtained with the two field polarities is 2.5×10^{-5} (2×10^{-2}) for charged hadrons (D^0 and $\bar{\mathrm{D}}^0$). These systematic uncertainties are correlated in pseudorapidity for charged hadrons, while for D^0 and $\bar{\mathrm{D}}^0$ mesons no significant correlation, beyond statistical uncertainties, is observed.

For charged hadrons, the track quality selections are varied and an absolute systematic uncertainty of 2.5×10^{-5} is assigned. The contribution from secondaries is varied by changing the maximum DCA_{xy}, which resulted in a negligible variation of v_1. The contamination due to TPC tracks originating from pileup collisions during the readout time of the TPC is estimated by varying the selections on the correlations between the event multiplicity (centrality) estimated with detectors with different readout times. The resulting systematic uncertainty is 10^{-5} for the charged hadrons. No systematic uncertainty is assigned for D^0 and $\bar{\mathrm{D}}^0$ because the topological selections effectively remove tracks from pileup. The uncertainty due to the D^0 and $\bar{\mathrm{D}}^0$ signal extraction is estimated by varying (i) the fit functions in Eqs. (3) and (4) for $N(M)$ and $v_1(M)$, (ii) fixing the Gaussian width and mean to the values extracted from Monte Carlo simulations, and (iii) varying the invariant mass fit range. The absolute systematic uncertainty assigned to v_1 due to the D^0 and $\bar{\mathrm{D}}^0$ yield extraction is 2×10^{-2}. The possible bias due to the p_{T}-dependent efficiency in the D^0 and $\bar{\mathrm{D}}^0$ v_1 analysis is tested by reweighting both signal and background with the inverse value of the signal reconstruction efficiency as a function of p_{T}. The assigned absolute systematic uncertainty is 10^{-2}.

The total systematic uncertainty on v_1 is obtained by adding in quadrature the contributions described above. In the calculation of $\Delta v_1(D)$, all individual systematic uncertainties are propagated as fully uncorrelated between D^0 and $\bar{\mathrm{D}}^0$. For charged hadrons, the systematic uncertainties due to the asymmetry in the spectator plane estimation and the magnet polarity are correlated between positive and negative tracks and largely cancel in $\Delta v_1(h)$.

The pseudorapidity dependence of the directed flow of positively and negatively charged hadrons for the 5%–40% centrality class in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV is shown in the upper left panel of Fig. 2. The negative slope of v_1 is usually attributed to the effect of the initial tilt [18] or rotation [25] of the particle-emitting source. The charge-integrated v_1 at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV agrees within uncertainties with the results at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [20].

The difference $\Delta v_1(h)$ between the v_1 of positively and negatively charged hadrons as a function of pseudorapidity is shown in the lower left panel of Fig. 2. The rapidity slope $\mathrm{d}\Delta v_1/\mathrm{d}\eta$, extracted with a linear fit (constrained to $v_1 = 0$ at $\eta = 0$), is $\mathrm{d}\Delta v_1/\mathrm{d}\eta = [1.68 \pm 0.49(\mathrm{stat}) \pm 0.41(\mathrm{syst})] \times 10^{-4}$ with a significance of 2.6σ for having a positive value. The $\mathrm{d}\Delta v_1/\mathrm{d}\eta$ is expected to reflect different effects, including those originating from the early time magnetic field dynamics [19,26,41] and the Coulomb interaction with charged spectators [54], as well as the transport to midrapidity via the baryon stopping mechanism [17] of the positive charge carried by the protons from the colliding

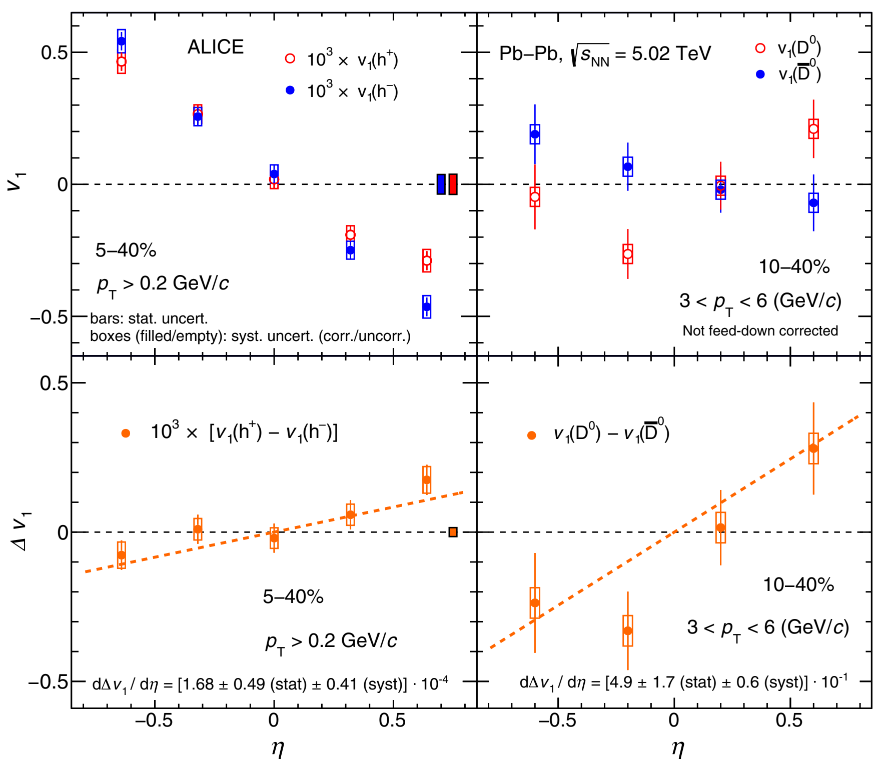

FIG. 2. Upper left: v_1 of positively (red) and negatively (blue) charged hadrons for the 5%–40% centrality interval. Upper right: v_1 of D^0 (red) and $\bar{\mathrm{D}}^0$ (blue) for the 10%–40% centrality interval. Lower left and right: $\Delta v_1(h) = v_1(h^+) - v_1(h^-)$ and $\Delta v_1(\mathrm{D}) = v_1(\mathrm{D}^0) - v_1(\bar{\mathrm{D}}^0)$, respectively. Dashed lines represent fits with a linear function.

nuclei. The importance of baryon stopping for the charge dependence of unidentified hadron v_1 is supported by the observed difference, even at top RHIC energy, between proton and antiproton v_1 [22,55,56]. The baryon stopping effects are expected to decrease with increasing collision energy, as supported by the observation of a smaller magnitude of v_1 [20] and of a proton to antiproton ratio closer to unity at the LHC as compared to RHIC [57]. Despite the overall decrease, the baryon stopping can contribute significantly to the proton and antiproton v_1 difference and, as such, to the charge dependence of the inclusive hadron v_1.

The charged hadron $\mathrm{d}\Delta v_1/\mathrm{d}\eta$ at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV is 1 order of magnitude larger and has an opposite sign with respect to calculations for charged pions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [38] based on the analytic solution of relativistic hydrodynamics [58] with a constant electrical conductivity of the QGP. More recent calculations [54], using viscous hydrodynamic calculations [59], yield an absolute value of $\mathrm{d}\Delta v_1/\mathrm{d}\eta$ of similar magnitude as the one measured for charged hadrons but with opposite sign.

The D^0 and $\bar{\mathrm{D}}^0$ v_1 as a function of pseudorapidity is shown in the upper right panel of Fig. 2. The data suggest a positive slope for the rapidity dependence of the v_1 of D^0 and a negative slope for $\bar{\mathrm{D}}^0$, with a significance of about 2σ in both cases. The slopes are different from the measurements in Au–Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV [42], where a negative value is observed for both D^0 and $\bar{\mathrm{D}}^0$. Additionally, the v_1 for D^0 and $\bar{\mathrm{D}}^0$ mesons with $3 < p_{\mathrm{T}} < 6$ GeV$/c$ ($\langle p_{\mathrm{T}}\rangle \approx 4.2$ GeV$/c$) in the 10%–40% centrality interval is about 3 orders of magnitude larger than that of charged hadrons with $p_{\mathrm{T}} > 0.2$ GeV$/c$ ($\langle p_{\mathrm{T}}\rangle \approx 0.7$ GeV$/c$) in the 5%–40% centrality class. The different p_{T} intervals used for the charged hadron and D^0 meson v_1 measurements are imposed by the statistical precision of the data, which simultaneously limits the yield of high p_{T} charged hadrons and results in low significance of the D^0 and $\bar{\mathrm{D}}^0$ meson yield at low p_{T}. The charged hadron v_1 at the LHC has a weak centrality dependence and changes sign around $p_{\mathrm{T}} \approx 1.5$ GeV$/c$ [20]. The differences in centrality and transverse momentum intervals should not be responsible for the observed difference between the magnitude of the v_1 of charged hadrons and D^0 and $\bar{\mathrm{D}}^0$ mesons. The D^0 and $\bar{\mathrm{D}}^0$ v_1 is an order of magnitude larger than the predictions from the transport [41] and hydrodynamic [19,26] model calculations. The difference between the v_1 values of D^0 and $\bar{\mathrm{D}}^0$ mesons $\Delta v_1(D)$ is shown in the lower right panel of Fig. 2. The value of $\mathrm{d}\Delta v_1/\mathrm{d}\eta = [4.9 \pm 1.7(\mathrm{stat}) \pm 0.6(\mathrm{syst})] \times 10^{-1}$ corresponds to a significance of 2.7σ to have a positive slope. A negative value for $\mathrm{d}\Delta v_1/\mathrm{d}\eta$ was predicted in [41] and is observed in Au–Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV [42]. The opposite sign of the measured D^0 meson and charged hadron Δv_1 slope with respect to model calculations might indicate a stronger effect of the Lorentz force relative to the Coulomb one. These results demonstrate the sensitivity of the v_1 to the interplay among the effects of the rapidly decreasing magnetic field and the initial tilt of the source.

In summary, first measurements of the charge dependence of v_1 relative to the spectator plane in midcentral Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV are presented. The v_1 and the difference Δv_1 between positively and negatively charged hadrons and D^0 mesons are sensitive to the effects of the electromagnetic fields induced by spectator protons, baryon number transport, and the initial tilt or rotation of the particle-emitting source for noncentral collisions. An indication of a positive slope $\mathrm{d}\Delta v_1/\mathrm{d}\eta$ of the charge-dependent v_1 at midrapidity for both charged hadrons and D^0 and $\bar{\mathrm{D}}^0$ mesons is observed. The slope $\mathrm{d}\Delta v_1/\mathrm{d}\eta$ is $[1.68 \pm 0.49(\mathrm{stat}) \pm 0.41(\mathrm{syst})] \times 10^{-4}$ for charged hadrons with $p_{\mathrm{T}} > 0.2$ GeV$/c$ and $[4.9 \pm 1.7(\mathrm{stat}) \pm 0.6(\mathrm{syst})] \times 10^{-1}$ for D^0 and $\bar{\mathrm{D}}^0$ mesons with $3 < p_{\mathrm{T}} < 6$ GeV$/c$, with significance of 2.6σ and 2.7σ for having a positive value, respectively. The measured values of v_1 for D^0 and $\bar{\mathrm{D}}^0$ mesons are about 3 orders of magnitude larger than the measured value of charged hadrons. These measurements together with those at RHIC [42] provide new insights and can constrain the theoretical modeling [38,41] of electromagnetic effects. Further constraints will be set by future higher precision measurements at the LHC [60,61].

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