EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP-2019-241
28 October 2019

Probing the effects of strong electromagnetic fields with charge-dependent directed flow in Pb–Pb collisions at the LHC

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Abstract

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 $\sqrt{s_{\rm NN}}$ = 5.02 TeV. Results are reported for charged hadrons and $\rm D^0$ mesons for the transverse momentum intervals $p_{\rm T} > 0.2$ GeV/c and $3 < p_{\rm T} < 6$ GeV/c in the 5–40% and 10–40% centrality classes, respectively. The difference between the positively and negatively charged hadron v_1 is found to have a positive slope as a function of pseudorapidity η, $\mathrm{d}\Delta v_1/\mathrm{d}\eta$ =[1.68 ± 0.49 (stat.) ± 0.41 (syst.)] $\times 10^{-4}$, with a 2.6σ significance. The same measurement for $\rm D^0$ and $\overline{\rm D}{}^0$ mesons yields a positive value $\mathrm{d}\Delta v_1/\mathrm{d}\eta$= [4.9 ± 1.7 (stat.) ± 0.6 (syst.)]$\times 10^{-1}$, which is about three orders of magnitude larger than the one of the charged hadrons, and is larger than zero with significance of 2.7σ. These measurements can provide new insights into the effects of the strong electromagnetic field and the initial tilt of matter created in non-central 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 $\rm D^0$ 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 of the recent theoretical calculations incorporating effects of the strong electromagnetic field, which predicted a negative and an order of magnitude smaller value of $\mathrm{d}\Delta v_1/\mathrm{d}\eta$ for both light-flavour and charmed hadrons.

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Quantum Chromo-dynamic (QCD) calculations on the lattice [1–6] predict at very high temperatures and energy densities 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 ultra-relativistic heavy-ion collisions at the Large Hadron Collider (LHC). Measurements of the anisotropic transverse flow [7–11] at the LHC, quantified by the second (elliptic flow) and higher order ($n > 2$) harmonic coefficients v_n, allowed one to characterize the different phases of a heavy-ion collision and to 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 pre-equilibrium early time dynamics in the evolution of the heavy-ion collision. The space-momentum correlations in particle production from a longitudinally tilted source results in a finite v_1. The tilt arises from the asymmetries in the number of forward and backward moving 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 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 does not have a tilt 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 the charm quark production in the transverse plane is shifted with respect to that of the light quarks and gluons. This results 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 directed flow of hadrons containing charm quarks as compared to light-flavour 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 matter produced in a heavy-ion collision.

Ultra-relativistic heavy-ion collisions are also characterized by extremely strong electromagnetic fields primarily induced by the spectator protons, which do not undergo inelastic collisions. There is a strong interest in measuring and understanding the time evolution of these fields, which are estimated to reach $10^{18} - 10^{19}$ Gauss in the very early stages (< 0.5 fm) of Pb–Pb collisions at LHC energies [27, 28]. Several phenomena are predicted to occur in the presence of this strong electromagnetic field, such as 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 the experimental results for charge-dependent correlations are in qualitative agreement with theoretical expectations for the CME [33–35], the 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 a 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 directed flow of the produced particles relative to the collision-spectator plane is directly sensitive to the presence of the 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. In the center-of-mass system of two colliding nuclei the charge dependence of the directed flow comes from two competing effects. The first one is the Lorentz force experienced by a charged particle propagating in the magnetic field. The second one, opposite to the first, is generated by the electric field induced by the rapidly decreasing magnetic field. In an electrically conducting plasma, the induced electric field creates charged currents that might greatly slow down the decay of the magnetic field [27]. The measurement of charge-dependent directed flow may also provide constraints to the QGP electric conductivity.

First estimates of the electromagnetic field effects on the directed flow of charged particles were presented in [37, 38]. Using the electric conductivity from lattice QCD calculations [39, 40], the difference between the directed flow 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 have a value not larger than 10^{-5} for $|\eta| < 1$ [38]. Recently, it has been noticed that charm quarks, which are produced in the early stages of the heavy-ion collision when the magnetic field attains its maximum magnitude, should be more strongly affected by the electromagnetic fields than light quarks [26, 41]. The difference Δv_1 between the directed flow of $\rm D^0$ and $\rm \overline{D}^0$ mesons, containing a c and $\bar{c}$ quark, respectively, could therefore provide better sensitivity to this initial magnetic field. An estimate of v_1 of charmed mesons in the rapidity interval $|y| < 1$ based on the same space-time dependent solutions of the electromagnetic fields as in [38] gives a value $\Delta v_1(D) \sim 10^{-2}$ [41], which is three orders of magnitude larger than the one expected for pions. Recently, the STAR Collaboration published a measurement of directed flow of $\rm D^0$ and $\rm \overline{D}^0$ mesons in 10–80% central Au–Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV [42]. The slope of v_1 of $\rm D^0$ and $\rm \overline{D}^0$ mesons as a function of pseudorapidity, $\mathrm{d}\Delta v_1/\mathrm{d}y$, is observed to be negative and about a factor of 25 times larger than that for charged kaons.

In this Letter, the first measurements at the LHC of the charge dependence of the directed flow v_1 relative to the spectator plane are reported. The v_1 is reported for charged hadrons and $\rm D^0$ mesons as a function of pseudorapidity in mid-central Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV.

About 23 (19) million Pb–Pb collisions in the 5–40% (10–40%) centrality interval are used for the charged hadron ($\rm D^0$ and $\rm \overline{D}^0$ meson) directed flow measurements. Only the events with a primary vertex reconstructed within ± 10 cm from the detector centre along the beam direction are analysed. 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, a strong increase of the combinatorial background does not allow the measurement of the $\rm D^0$ and $\rm \overline{D}^0$ v_1.

The deflection direction of the collision spectators is reconstructed from the spectator neutrons detected using two Zero Degree Calorimeters (ZDC) located on both sides of the interaction point [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 centre 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]

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

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 i-th ZDC segment.

To compensate for the run-dependent variation of the LHC beam crossing position, a correction [46] is applied to the $\mathbf{Q}^{t,p}$ vectors as a function of the collision centrality and the transverse position of the collision vertex relative to the nominal center of ALICE. The deflection direction of the spectator neutrons is estimated event-by-event with the corrected $\mathbf{Q}^{t,p}$ vectors. It is expected to be opposite (anti-correlated) 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 greater than 40%, is observed even after the flow-vector correction procedure is applied. These residual variations are used in the estimation of the systematic uncertainty as discussed below.

The directed flow is measured using the scalar-product method [47]

$$v_1^{t,p} = \frac{\langle \mathbf{u}\mathbf{Q}^{t,p}\rangle}{\sqrt{\left|\langle \mathbf{Q}^t\mathbf{Q}^p\rangle\right|}} = \frac{\left\langle \mathrm{u_x} \mathrm{Q}_x^{t,p} + \mathrm{u_y} \mathrm{Q}_y^{t,p}\right\rangle}{\sqrt{\left|\left\langle \mathrm{Q}_x^t \mathrm{Q}_x^p + \mathrm{Q}_y^t \mathrm{Q}_y^p\right\rangle\right|}}, \tag{2}$$

where $\mathbf{u} = (\cos\varphi, \sin\varphi)$ is the unit flow vector of the charged hadron or D^0 meson candidate with azimuthal momentum angle φ. The directed flow relative to the spectator plane is then 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 ($\eta > 8.78$). This definition corresponds to the rapidity-odd component of the directed flow discussed in [20] which in this paper is denoted as v_1.

The v_1 of charged hadrons is measured from tracks reconstructed with the Inner Tracking System (ITS) [48] and the Time Projection Chamber (TPC) [49]. Tracks with $p_\mathrm{T} > 0.2$ GeV/c, $|\eta| < 0.8$, at least 70 (out of a maximum of 159) TPC space points, and with a χ^2/ndf in the TPC momentum fit smaller than 2 are selected for the analysis. In order to reduce the contamination from secondary particles, produced either in interactions with the detector material or from weak decays of strange hadrons, 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. An average transverse momentum of the selected charged hadrons is $\langle p_\mathrm{T}\rangle \approx 0.7$ GeV/c.

The D^0 and $\overline{\mathrm{D}}^0$ mesons are reconstructed using the decay channel $\mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+$ and its charge conjugate for $3 < p_\mathrm{T} < 6$ GeV/c, which corresponds to a $\langle p_\mathrm{T}\rangle \approx 4.2$ GeV/c calculated as described in [50]. The $\langle p_\mathrm{T}\rangle$ of the selected D^0 mesons is larger than that of the charged hadrons considered for the v_1 measurement. Pions and kaons are reconstructed in the TPC and ITS detectors. Tracks are selected requiring $|\eta| < 0.8$, $p_\mathrm{T} > 0.4$ GeV/c, at least 70 hits in TPC and at least 2 hits (out of a maximum of 6) 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 ionisation energy loss dE/dx in the TPC and the flight time from the interaction point to the Time-Of-Flight (TOF) detector [51]. Tracks not matched to a hit in the TOF are identified using only the TPC information. The charge of the identified pions and kaons allows one to distinguish between the $\mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+$ and $\overline{\mathrm{D}}^0 \rightarrow \mathrm{K}^+\pi^-$ candidates. Geometrical selections on the displaced decay vertex topology are applied to reduce the combinatorial background as explained in detail in [52]. The main selection variables are the separation between the primary and decay vertices, the displacement of the decay tracks from the primary vertex and the pointing of the reconstructed D-meson momentum to the primary vertex.

The directed flow v_1^D is extracted separately for D^0 and $\overline{\mathrm{D}}^0$ 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 for the D^0 meson candidates in the interval $3 < p_\mathrm{T} < 6$ GeV/c and $-0.4 < \eta < 0$ 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 $\overline{\mathrm{D}}^0$ 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 parametrized by a linear function.

Candidates which satisfy both the $\mathrm{K}^-\pi^+$ and $\mathrm{K}^+\pi^-$ hypotheses (reflected kinematics) and therefore can not be tagged uniquely as D^0 or $\overline{\mathrm{D}}^0$ are rejected. This selection 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 $\overline{\mathrm{D}}^0$ yield. Moreover, the inclusion of the reflected candidates requires to introduce in Eq. 4 an additional fit parameter to account for their v_1 and to use the shape of their invariant mass distribution extracted from the GEANT Monte Carlo simulations of the ALICE detector response [53]. Fits with these additional terms did not yield a stable fit result. The extracted $v_1^{\rm D}$ includes the contributions from both prompt $\rm D^0$ mesons (originating from the hadronization of charm quarks) and feed-down $\rm D^0$ mesons from decays of hadrons containing beauty quarks. The fraction of prompt $\rm D^0$ meson is about 85% for the analysed centrality class and $p_{\rm T}$ interval [54]. The $\rm D^0$ meson contribution from beauty hadron decays is not subtracted from the observed $\rm D^0$.

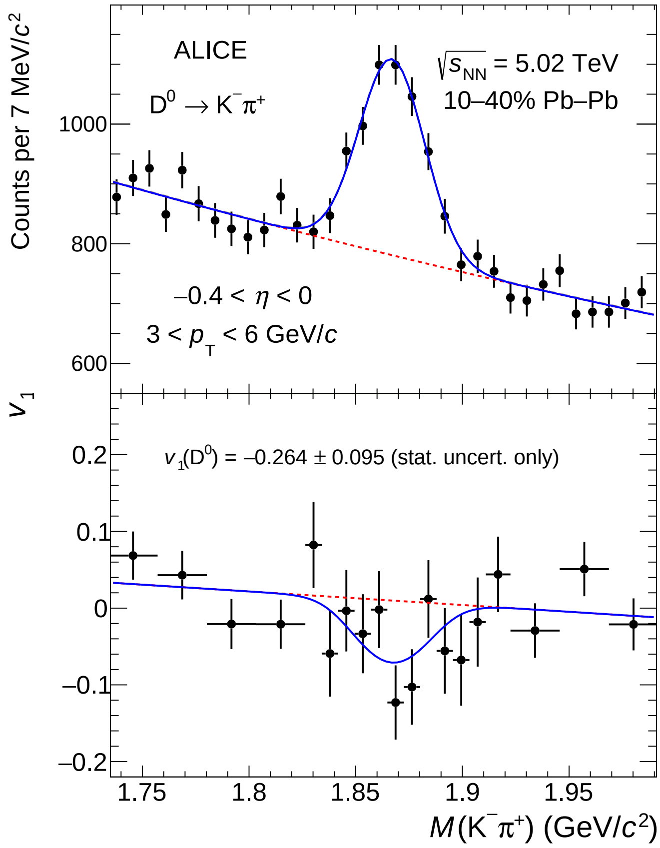

Figure 1: (color online) Illustration of the $\rm D^0$ meson v_1 extraction procedure via a simultaneous fit to the candidate invariant mass distribution (upper panel) and v_1 (lower panel). Results are for $3 < p_{\rm T} < 6$ GeV/c and $-0.4 < \eta < 0$ in the 10–40% centrality interval in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. The blue solid lines correspond to the combined signal and background fit functions, while the red dashed lines represent the background contributions. Coarse invariant mass intervals are used in the lower panel to reduce statistical fluctuations of the background v_1.

The common sources of systematic uncertainty between charged hadrons and D mesons are the ones related to the resolution of the spectator plane estimated with the ZDCs and to the dependence on the ALICE magnet polarity, which was reversed during the data taking. 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 $\langle {\rm u_x Q}_x \rangle$ and $\langle {\rm u_y Q}_y \rangle$ correlations with the ZDCs in Eq. 2. It is about 3.5×10^{-5} (2×10^{-2}) for the charged hadrons ($\rm D^0$ and $\rm \overline{D}^0$). Effects related to the 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 non-zero beam crossing angle in the vertical plane, which had opposite values (± 60 μrad) for the opposite magnet polarities. The absolute differences between the v_1 values obtained with the two field polarities are found to be 2.5×10^{-5} for charged hadrons and 2×10^{-2} for the $\rm D^0$ and $\rm \overline{D}^0$ mesons. The above mentioned sources of systematic uncertainties resulted in a common (correlated) uncertainty for charged hadrons, while for the D^0 and $\overline{D}^0$ mesons, within large statistical uncertainties, no significant correlation is observed among η intervals.

In the charged hadron v_1 analysis, 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 to the reconstructed primary vertex in the transverse plane, which resulted in a negligible variation of the charged hadron v_1. The contamination due to TPC tracks originating from pile-up collisions occurring 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 about 10^{-5} for the charged hadrons. No systematic uncertainty is assigned for D^0 and $\overline{D}^0$ because the geometrical selections on their topology are effectively removing tracks coming from collision pile-up. The uncertainty due to the D^0 and $\overline{D}^0$ meson signal extraction procedure is estimated by varying (i) the background and the signal fit functions in Eq. (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 $\overline{D}^0$ yield extraction is 2×10^{-2}. The possible bias due to the p_T-dependent efficiency in the D^0 and $\overline{D}^0$ v_1 analysis is tested by re-weighting both signal and background with the inverse value of the signal (D^0 and $\overline{D}^0$ mesons) reconstruction efficiency as a function of p_T. An average p_T for the re-weighted results reduces by less than 6%. The assigned absolute systematic uncertainty is 10^{-2} for both the D^0 and $\overline{D}^0$ v_1.

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 $\overline{D}^0$. In case of $\Delta v_1(h)$ for the charged hadrons all sources are considered as uncorrelated except for the contributions from the asymmetry in the spectator plane estimation with the ZDC and the differences due to the change of the magnet polarity. The correlated sources, which largely cancel in $\Delta v_1(h)$, result in a total systematic uncertainty of 1.5×10^{-5}.

The pseudorapidity dependence of the directed flow of positively and negatively charged hadrons for the 5–40% centrality class in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV is shown in the top 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. Within the systematic uncertainties no significant difference is observed for the charge-integrated directed flow at $\sqrt{s_{NN}}$ = 5.02 TeV compared to the results at $\sqrt{s_{NN}}$ = 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 bottom left panel of Fig. 2. The rapidity slope $d\Delta v_1/d\eta$, extracted with a linear fit function, yields $d\Delta v_1/d\eta = [1.68 \pm 0.49 \text{ (stat.)} \pm 0.41 \text{ (syst.)}] \times 10^{-4}$ with a significance of 2.6σ for having a positive value. The $d\Delta v_1/d\eta$ is expected to have contributions from different effects, including those originating from the early-time magnetic field dynamics [19, 26, 41], the Coulomb interaction with the charged spectators [55], as well as the transport to mid-rapidity via the baryon stopping mechanism [17] of the positive charge carried by the protons from the colliding nuclei. The importance of the baryon stopping on the charge dependence of unidentified hadron v_1 is supported by an observation of a significant difference, even at top RHIC energy, between proton and antiproton v_1 [22, 56, 57]. The baryon stopping effects are expected to decrease with increasing collision energy. This is supported by the observation of a smaller magnitude of v_1 [20] and of a proton-to-antiproton ratio being closer to unity at the LHC as compared to RHIC [58]. 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 role of baryon stopping can be clarified with future high precision measurements at the LHC with identified hadrons.

The measured value of the charged-hadron $d\Delta v_1/d\eta$ at $\sqrt{s_{NN}}$ = 5.02 TeV is one order of magnitude larger and has an opposite sign with respect to calculations for charged pions at $\sqrt{s_{NN}}$ = 2.76 TeV [38] based on the analytic solution of the relativistic viscous hydrodynamic calculations [59] with a constant electrical conductivity of the QGP. More recent calculations [55] for the charged pion v_1, using (2+1)-dimensional viscous hydrodynamic calculations coupled to a hadronic cascade model iEBE-VISHNU [60], 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 the opposite sign.

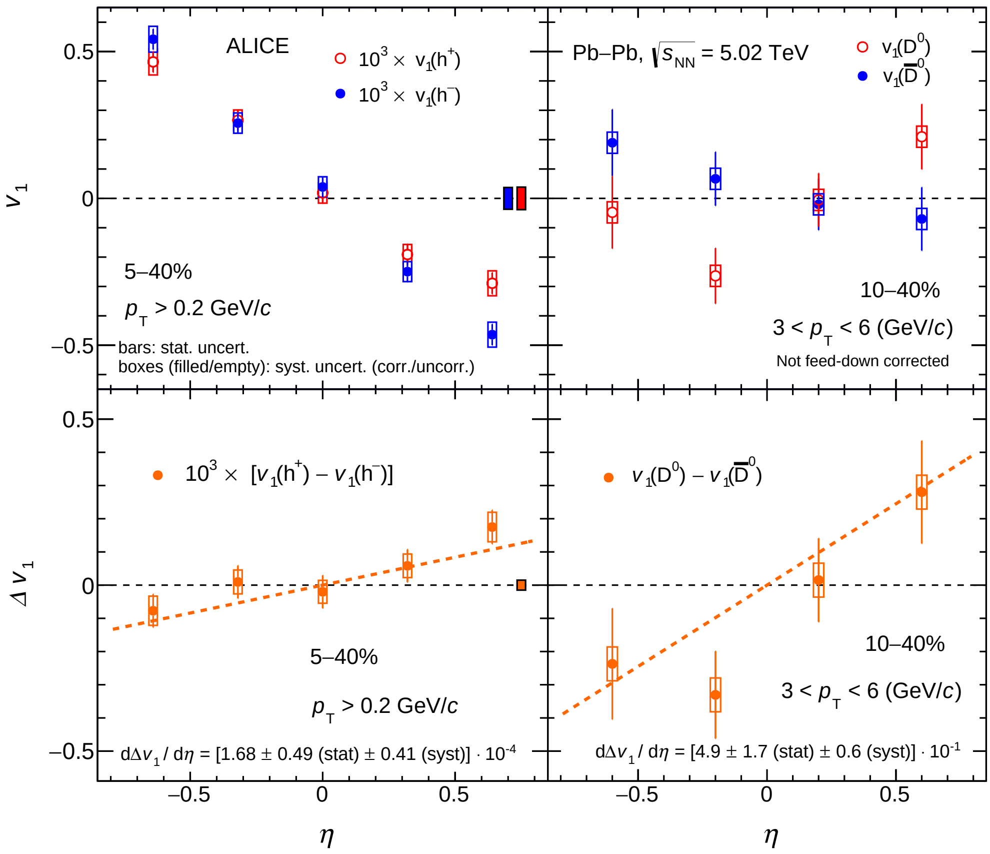

Figure 2: (color online) Top left: v_1 of positively (red) and negatively (blue) charged hadrons for the 5–40% centrality interval in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. Top right: v_1 of D^0 (red) and $\overline{\mathrm{D}}^0$ (blue) for the 10–40% centrality interval in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. Bottom left and right: $\Delta v_1(h) = v_1(h^+) - v_1(h^-)$ and $\Delta v_1(\mathrm{D}) = \mathrm{v}_1(\mathrm{D}^0) - \mathrm{v}_1(\overline{\mathrm{D}}^0)$, respectively. Dashed lines represent fits with a linear function.

The D^0 and $\overline{\mathrm{D}}^0$ directed flow as a function of pseudorapidity for the 10–40% centrality interval in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV is shown in the top 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 $\overline{\mathrm{D}}^0$, 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 the D^0 and $\overline{\mathrm{D}}^0$. Additionally, the v_1 for D^0 and $\overline{\mathrm{D}}^0$ mesons with $\langle p_\mathrm{T}\rangle \approx$ 4.2 GeV/c in the 10–40% centrality interval is about three orders of magnitude larger than the result obtained for charged particles with $\langle p_\mathrm{T}\rangle \approx$ 0.7 GeV/c in the 5–40% centrality class. The different p_T intervals used for the charged hadron and D 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 $\overline{\mathrm{D}}^0$ 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 $\overline{\mathrm{D}}^0$ mesons. The D^0 and $\overline{\mathrm{D}}^0$ 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 $\overline{\mathrm{D}}^0$ mesons $\Delta v_1(D)$ is shown in the bottom right panel of Fig. 2. The value of $\mathrm{d}\Delta v_1/\mathrm{d}\eta$ = [4.9 $\pm$ 1.7 (stat.) $\pm$ 0.6 (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 the top RHIC energy by the STAR Collaboration [42]. The opposite and large slopes of the Δv_1 of D mesons, as well as for charged hadrons might indicate a stronger effect of the magnetic field relative to the one due to the induced electric field and the initial tilt of the source, demonstrating sensitivity of the charm quark directed flow to the interplay among these effects.

In summary, the first measurements at the LHC of the charge dependence of the directed flow relative to the spectator plane in mid-central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV are presented. The measured directed flow and the difference Δv_1 between positively and negatively charged hadrons and D^0 mesons is sensitive to the effects of the electromagnetic fields induced by the spectator protons, baryon number transport, and the initial tilt or rotation of the particle-emitting source for non-central heavy-ion collisions. An indication of a positive slope $\mathrm{d}\Delta v_1/\mathrm{d}\eta$ of the charge-dependent directed flow at midrapidity for both charged hadrons and D^0 and $\overline{\mathrm{D}}^0$ mesons is observed. The slope $\mathrm{d}\Delta v_1/\mathrm{d}\eta$ is found to be [1.68 $\pm$ 0.49 (stat.) $\pm$ 0.41 (syst.)] $\times 10^{-4}$ for charged hadrons with $p_{\mathrm{T}} > 0.2$ GeV/c and [4.9 $\pm$ 1.7 (stat.) $\pm$ 0.6 (syst.)]$\times 10^{-1}$ for D^0 and $\overline{\mathrm{D}}^0$ 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 $\overline{\mathrm{D}}^0$ meson are about three orders of magnitude larger than the one of charged hadrons. The first measurements of charge dependent directed flow at the LHC together with those at RHIC [42] provide new insights and can constrain the theoretical modelling [38, 41] of electromagnetic effects. However, the limited precision of the current data does not allow for a firm conclusion. Further constraints will be set by the future higher precision measurements at the LHC in Run 3 and Run 4 [61, 62].

Acknowledgements

The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF): [M 2467-N36] and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (Finep), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Universidade Federal do Rio Grande do Sul (UFRGS), Brazil; Ministry of Education of China (MOEC) , Ministry of Science & Technology of China (MSTC) and National Natural Science Foundation of China (NSFC), China; Ministry of Science and Education and Croatian Science Foundation, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research | Natural Sciences, the VILLUM FONDEN and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l'Energie Atomique (CEA), Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS) and Région des Pays de la Loire, France; Bundesministerium für Bildung und Forschung (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial Research (CSIR), India; Indonesian Institute of Science, Indonesia; Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi and Istituto Nazionale di Fisica Nucleare (INFN), Italy; Institute for Innovative Science and Technology , Nagasaki Institute of Applied Science (IIST), Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Society for the Promotion of Science (JSPS) KAKENHI, Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Academico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Commission on Science and Technology for Sustainable Development in the South (COMSATS), Pakistan; Pontificia Universidad Católica del Perú, Peru; Ministry of Science and Higher Education and National Science Centre, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics and Ministry of Research and Innovation and Institute of Atomic Physics, Romania; Joint Institute for Nuclear Research (JINR), Ministry of Education and Science of the Russian Federation, National Research Centre Kurchatov Institute, Russian Science Foundation and Russian Foundation for Basic Research, Russia; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; Suranaree University of Technology (SUT), National Science and Technology Development Agency (NSDTA) and Office of the Higher Education Commission under NRU project of Thailand, Thailand; Turkish Atomic Energy Agency (TAEK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and United States Department of Energy, Office of Nuclear Physics (DOE NP), United States of America.

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