D Meson Elliptic Flow in Noncentral Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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Azimuthally anisotropic distributions of D^0, D^+, and D^{*+} mesons were studied in the central rapidity region ($|y| < 0.8$) in Pb-Pb collisions at a center-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV per nucleon-nucleon collision, with the ALICE detector at the LHC. The second Fourier coefficient v_2 (commonly denoted elliptic flow) was measured in the centrality class 30%–50% as a function of the D meson transverse momentum p_T, in the range 2–16 GeV/c. The measured v_2 of D mesons is comparable in magnitude to that of light-flavor hadrons. It is positive in the range $2 < p_T < 6$ GeV/c with 5.7σ significance, based on the combination of statistical and systematic uncertainties.

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Heavy-ion collisions at ultrarelativistic energies are aimed at exploring the structure of nuclear matter at extremely high temperatures and energy densities. Under these conditions, according to quantum chromodynamics (QCD) calculations on the lattice, the confinement of quarks and gluons inside hadrons is no longer effective and a phase transition to a quark-gluon plasma (QGP) occurs [1].

The measurement of anisotropy in the azimuthal distribution of particle momenta provides insight into the properties of the QGP medium. Anisotropy in particle momenta originates from the initial anisotropy in the spatial distribution of the nucleons participating in the collision. The anisotropy of produced particles is characterized by the Fourier coefficients $v_n = \langle \cos[n(\varphi - \Psi_n)] \rangle$, where φ is the azimuthal angle of the particle, and Ψ_n is the azimuthal angle of the initial state symmetry plane for the nth harmonic. For noncentral collisions the overlap region of the colliding nuclei has a lenticular shape and the anisotropy is dominated by the second coefficient v_2, commonly denoted elliptic flow [2,3].

The v_2 values measured at RHIC and LHC can be described by the combination of two mechanisms [2,4–12]. The first one, dominant at low ($p_T < 3$ GeV/c) and intermediate (3–6 GeV/c) transverse momentum, is the buildup of a collective expansion through interactions among the medium constituents. Elliptic flow develops mainly in the early stages of this collective expansion, when the spatial anisotropy is large [13–15]. The second mechanism is the path-length dependence of in-medium parton energy loss, due to medium-induced gluon radiation and elastic collisions. This is predicted to give rise to a positive v_2 for hadrons up to large p_T [16,17].

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The measurement of the elliptic flow of charmed hadrons provides further insight into the transport properties of the medium. In contrast to light quarks and gluons that can be produced or annihilated during the entire evolution of the medium, heavy quarks are produced predominantly in initial hard scattering processes and their annihilation rate is expected to be small [18]. Hence, the final state heavy-flavor hadrons at all transverse momenta originate from heavy quarks that experienced all stages of the system evolution. At low p_T, charmed hadron v_2 offers a unique opportunity to test whether also quarks with large mass ($m_c \approx 1.5$ GeV/c^2) participate in the collective expansion dynamics and possibly thermalize in the medium [19,20]. Because of their large mass, charm quarks are expected to have a longer relaxation time, i.e., time scale for approaching equilibrium with the medium, with respect to light quarks [21]. At low and intermediate p_T, the D meson elliptic flow is expected to be sensitive to the heavy-quark hadronization mechanism. In case of substantial interactions with the medium, a significant fraction of low- and intermediate-momentum heavy quarks could hadronize via recombination with other quarks from the bulk of thermalized partons [22,23], thus enhancing the v_2 of D mesons with respect to that of charm quarks [20]. In this context, the measurement of D meson v_2 is also relevant for the interpretation of the results on J/ψ anisotropy [24], because J/ψ's from $c\bar{c}$ (re)combination would inherit the anisotropy of their constituent quarks [25,26]. At high p_T, the D meson v_2 can constrain the path-length dependence of parton energy loss, complementing the measurement of the nuclear modification factor R_{AA} [27], defined as the ratio of the yield in nucleus-nucleus to that observed in pp collisions scaled by the number of binary nucleon-nucleon collisions. A large suppression of the inclusive D meson yield ($R_{AA} \approx 0.25$) is observed in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for $p_T > 5$ GeV/c [28].

Theoretical models of heavy-quark interactions with the medium constituents predict, for semicentral collisions at the LHC, a large v_2 (0.1–0.2) for D mesons at

$p_T \approx 2$–3 GeV/c and a decrease to about 0.05 at high p_T [29–33]. The elliptic flow of electrons from heavy-flavor decays was measured to be as large as 0.13 in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [34,35].

In this Letter we present the measurement of v_2 for D^0, D^+, and D^{*+} mesons and their antiparticles reconstructed from their hadronic decays at midrapidity ($|y| < 0.8$) in noncentral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

The measurement was carried out with the ALICE detector at the LHC [36]. Particle reconstruction and identification were based on the detectors of the central barrel, located inside a solenoid magnet, which generates a 0.5 T field parallel to the beam direction.

The detectors used for the reconstruction of the trajectories of candidate D meson decay particles are the inner tracking system (ITS), composed of six cylindrical layers of silicon detectors [37], and the time projection chamber (TPC) [38]. The reconstructed particles are identified on the basis of their specific energy deposition dE/dx in the TPC gas and of their time of flight from the interaction point to the time of flight (TOF) detector. The ITS, TPC, and TOF detectors provide full azimuthal coverage in the pseudorapidity interval $|\eta| < 0.9$.

The analysis was performed on a sample of Pb-Pb collisions collected in 2011 with an interaction trigger that required coincident signals in both scintillator arrays of the VZERO detector, covering the full azimuth in the regions $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$. Events were further selected off-line to remove background from beam-gas interactions, using the time information provided by the VZERO and the neutron zero-degree calorimeters. Only events with a vertex reconstructed within ± 10 cm from the center of the detector along the beam line were considered in the analysis. Collisions were classified according to their centrality, determined from the VZERO summed amplitudes and defined in terms of percentiles of the total hadronic Pb-Pb cross section [39].

The D meson v_2 was measured for events in the centrality range 30%–50%, where the initial geometrical anisotropy and the medium density are large. In this range, the trigger and event selection are fully efficient for hadronic interactions. The number of selected events in the 30%–50% centrality class was 9.5×10^6, corresponding to an integrated luminosity of (6.2 ± 0.2) μb^{-1}.

The decays $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D^{*+} \to D^0\pi^+$, and their charge conjugates, were reconstructed as described in [28,40]. D^0 and D^+ candidates were formed using pairs and triplets of tracks with $|\eta| < 0.8$, $p_T > 0.4$ GeV/c, at least 70 associated space points in the TPC, and at least two hits in the ITS, of which at least one should be in either of the two innermost layers. D^{*+} candidates were formed by combining D^0 candidates with tracks with $|\eta| < 0.8$, $p_T > 0.1$ GeV/c, and at least three associated hits in the ITS. The selection of tracks with $|\eta| < 0.8$ limits the D meson acceptance in rapidity, which, depending on p_T, varies from $|y| < 0.7$ for $p_T = 2$ GeV/c to $|y| < 0.8$ for $p_T > 5$ GeV/c.

D meson candidates were selected with the same strategy as used in [28], in order to increase the statistical significance of the signal with respect to the large background of all possible track combinations. The selection of the decay topology was based on the displacement of the decay tracks from the interaction vertex, the separation between the secondary and primary vertices, and the pointing of the reconstructed D meson momentum to the primary vertex. The pion and kaon identification in the TPC and TOF detectors was utilized by applying cuts in units of resolution (at $\pm 3\sigma$) around the expected mean values of dE/dx and time of flight.

The measurement of v_2 was performed by correlating the candidate D meson azimuthal angle, φ_D, with the angle ψ_2 of the so-called event plane [41], which is an estimator of the direction Ψ_2 of the second-order initial-state symmetry plane. The event plane angle ψ_2 was determined from the second harmonic of the azimuthal distribution of the detected charged particles: $\psi_2 = (1/2)\tan^{-1}(Q_{2,y}/Q_{2,x})$, where $Q_{2,x}$ and $Q_{2,y}$ are the transverse components of the second order flow vector, $\vec{Q}_2$, defined event by event from the azimuthal angles φ_i of a sample of N tracks, $\vec{Q}_2 = (\sum_{i=1}^{N} w_i \cos 2\varphi_i, \sum_{i=1}^{N} w_i \sin 2\varphi_i)$. The weights w_i correct for nonuniformities in the acceptance and efficiency of the detector, and optimize the event-plane resolution [41]. They are defined as the product of the track p_T and the inverse of the probability of reconstructing a particle with azimuthal angle φ_i. The tracks used to compute $\vec{Q}_2$ were required to have at least 50 associated space points in the TPC, $0 < \eta < 0.8$, $p_T > 150$ MeV/c, and distance of closest approach to the primary vertex smaller than 3.2 cm along the beam direction and 2.4 cm in the transverse plane. To avoid auto correlations between the D mesons and the event plane, the angle ψ_2 was recalculated for each candidate after subtracting from the $\vec{Q}_2$ vector the contribution from the tracks used to form that particular candidate. A correlation of D mesons with the tracks used to determine the event plane could also originate from other sources, commonly denoted nonflow, which are not related to the correlation with the initial geometry symmetry plane, such as higher-mass particle decays or jets. Their effect was estimated to be small with respect to the other uncertainties by repeating the analysis using the event plane determined in a different η region with the VZERO detector.

D meson candidates were classified in two groups according to their azimuthal angle relative to the event plane ($\Delta\varphi = \varphi_D - \psi_2$): in-plane ($]-(\pi/4), (\pi/4)]$ and $](3\pi/4), (5\pi/4)]$) and out-of-plane ($]-(\pi/4), (3\pi/4)]$ and $](5\pi/4), (7\pi/4)]$).

The raw signal yields were extracted in each $\Delta\varphi$ and p_T interval by means of a fit to the candidate invariant mass distributions (mass difference $M(\text{K}\pi\pi) - M(\text{K}\pi)$ for D^{*+}). The fitting function was the sum of a Gaussian function to describe the signal and an exponential (for D^0 and D^+) or a power-law (for D^{*+}) function for the background. An example fit is shown in Fig. 1 for D^0 candidates. For each meson and in each p_T interval, the mean and the width of the Gaussian were fixed to those obtained from a fit to the invariant mass distribution integrated over $\Delta\varphi$, whose signal peak has larger statistical significance. The raw yields in the two $\Delta\varphi$ intervals, $N_{\text{in-plane}}$ and $N_{\text{out-of-plane}}$, were obtained as the integrals over the corresponding Gaussian signal functions. v_2 was computed as

$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}. \quad (1)$$

The factor $\pi/4$ results from the integration of the second term, $2v_2\cos(2\Delta\varphi)$, of the $dN/d\varphi$ distribution in the considered $\Delta\varphi$ intervals and the factor $1/R_2$ is the correction for the finite resolution in the estimation of the symmetry plane Ψ_2 via the event plane ψ_2 [41]. R_2 was determined from the correlation between the event plane angles calculated from tracks reconstructed in the two sides of the TPC, namely, $-0.8 < \eta < 0$ and $0 < \eta < 0.8$. The resulting value is $R_2 = 0.8059 \pm 0.0001(\text{stat}) \pm 0.024(\text{syst})$.

The measured D meson yield has a contribution from feed-down from B meson decays, which amounts to about 10%–20% [28,40], depending on the selection cuts and p_T. Indeed, the B feed-down contribution is enhanced by the selection criteria that are more efficient for feed-down D mesons, because their decay vertices are more displaced from the primary vertex. Thus, the measured v_2 is a combination of those of promptly produced and of feed-down D mesons. Considering that the elliptic flow is additive, the value for promptly produced D mesons, v_2^{prompt}, can be obtained from the measured v_2^{all} as

$$v_2^{\text{prompt}} = \frac{v_2^{\text{all}}}{f_{\text{prompt}}} - \frac{1 - f_{\text{prompt}}}{f_{\text{prompt}}} v_2^{\text{feed-down}}, \quad (2)$$

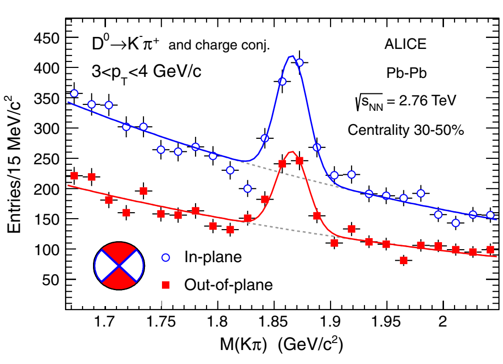

FIG. 1 (color online). Invariant mass distributions for D^0 candidates and their charge conjugates with $3 < p_T < 4$ GeV/c for 9.5×10^6 Pb-Pb collisions in the 30%–50% centrality class. The distributions are shown separately for the in-plane (open symbols) and out-of-plane (closed symbols) intervals of azimuthal angle. The curves show the fit functions as described in the text.

where f_{prompt} is the fraction of promptly produced D mesons in the measured raw yield and $v_2^{\text{feed-down}}$ is the elliptic flow of D mesons from B decays, which depends on the dynamics of beauty quarks in the medium. These two quantities have not been measured. However, as it can be seen in Eq. (2), v_2^{all} coincides with v_2^{prompt}, independent of f_{prompt}, if $v_2^{\text{feed-down}} = v_2^{\text{prompt}}$. The assumption $v_2^{\text{feed-down}} = v_2^{\text{prompt}}$ was used to compute the central value of the results for the prompt D meson elliptic flow. The systematic uncertainty related to this assumption is discussed below.

The contributions to the systematic uncertainty on the measured v_2 originate from (i) determination of D meson yields and their anisotropy relative to the event plane (e.g., 10%–30% in $4 < p_T < 6$ GeV/c depending on the meson species), (ii) nonflow effects and centrality dependence in the event plane resolution (3%), and (iii) B feed-down contribution (typically $^{+45}_{-0}$ %).

The first contribution was estimated from the maximum deviation from the central v_2 value obtained by repeating the yield extraction in each p_T and $\Delta\varphi$ interval when varying the fit configuration: different fit functions were used for the background; the Gaussian width and mean were left as free parameters in the fit; the yield was defined by counting the histogram entries in the invariant mass region of the signal, after subtracting the background contribution estimated from a fit to the side bands.

The v_2 result obtained with Eq. (1) was cross-checked by using an independent technique based on fits to the measured v_2 of candidates as a function of their invariant mass, M [42]. Here $v_2(M)$ was obtained with methods based on two-particle correlations, namely, the scalar product [43] and the Q cumulants [44].

It was checked that the results were stable against variations of the cuts applied for the selection of D meson candidates, and that the reconstruction and selection efficiencies from Monte Carlo simulations were compatible for the in-plane and out-of-plane D mesons.

The uncertainty on the correction factor R_2 for the event plane resolution has two contributions. The first one is due to the centrality dependence of R_2. The average R_2 in the 30%–50% centrality interval was computed assuming that the D meson yield is uniformly distributed as a function of centrality. A systematic uncertainty of 2% was assigned by comparing this value with an alternative estimation of the average where the R_2 values in narrow centrality intervals were weighted with the D meson yields measured in the same intervals. The second contribution to the R_2 uncertainty arises from the presence of nonflow correlations between the two subevents used to compute the resolution. The systematic uncertainty was estimated to be of 2.3% on the basis of the difference to the R_2 value obtained using three subevents with a wider pseudorapidity gap, namely, TPC tracks and the signals in the two VZERO detectors.

The systematic uncertainty related to the contribution of D mesons from B decays was assigned by varying the

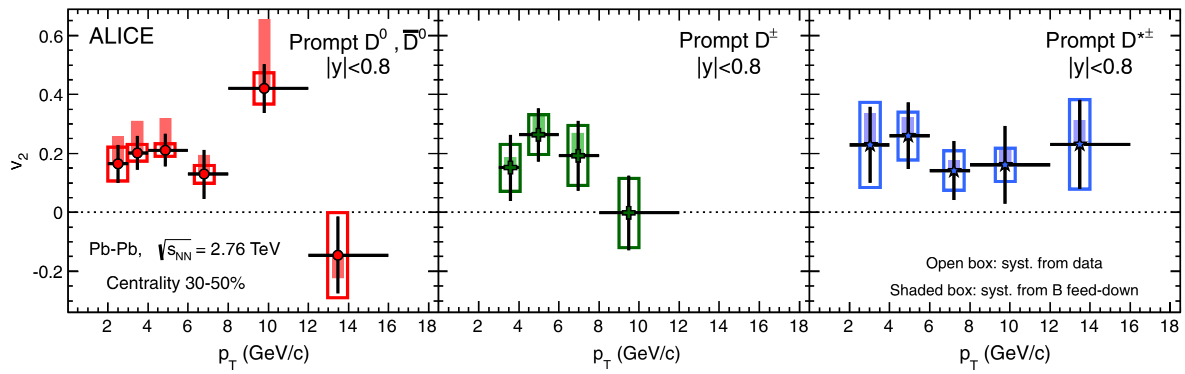

FIG. 2 (color online). v_2 as a function of p_T for prompt D^0, D^+, and D^{*+} mesons for Pb-Pb collisions in the centrality range 30%–50%. The central value was obtained with the assumption $v_2^{\text{feed-down}} = v_2^{\text{prompt}}$. Vertical error bars represent the statistical uncertainty, empty boxes the systematic uncertainty due to the D meson anisotropy measurement and the event-plane resolution, and shaded boxes show the uncertainty from the contribution of D mesons from B feed-down.

assumption on the elliptic flow of feed-down D mesons in Eq. (2) in the range $0 \leq v_2^{\text{feed-down}} \leq v_2^{\text{prompt}}$, which includes all model predictions [29–32]. The maximum variation corresponds to the case $v_2^{\text{feed-down}} = 0$, which gives $v_2^{\text{prompt}} = v_2^{\text{all}}/f_{\text{prompt}}$. Hence, the magnitude of the systematic uncertainty due to B feed-down is inversely proportional to f_{prompt}. We estimated f_{prompt} as described in [28] using (i) FONLL [45] predictions for prompt D and B mesons, (ii) $B \to D + X$ decay kinematics from EVTGEN [46], (iii) reconstruction and selection efficiencies for prompt and feed-down D mesons from simulations, and (iv) a hypothesis on the nuclear modification factor of the feed-down D mesons, $R_{\text{AA}}^{\text{feed-down}}$. The latter factor accounts for the medium-induced modification of the p_T distribution of B mesons. Its contribution was determined by varying the ratio $R_{\text{AA}}^{\text{feed-down}}/R_{\text{AA}}^{\text{prompt}}$ in the range 1–3, motivated by the lower value of R_{AA} of prompt D mesons measured by ALICE [28] with respect to preliminary results from the CMS experiment on the R_{AA} of J/ψ from B decays [47]. The B feed-down uncertainty was defined by the lower limit of the resulting f_{prompt} range, which depends on the D meson species and p_T. A typical value for this lower limit is 0.68, corresponding to a relative uncertainty on v_2^{prompt} of $^{+45}_{-0}$ %.

Figure 2 shows the measured v_2 as a function of p_T for D^0, D^+, and D^{*+} mesons in the 30%–50% centrality class. The symbols are positioned horizontally at the average p_T of reconstructed D mesons, determined as described in [40]. The elliptic flow of the three D meson species is consistent within uncertainties. An average v_2, and transverse momentum, of D^0, D^+, and D^{*+} was computed using the statistical uncertainties as weights. The systematic uncertainties were propagated through the averaging procedure, treating the contributions from the event-plane resolution and the B feed-down correction as fully correlated among the three D meson species. The resulting D meson v_2 is shown in Fig. 3. It is comparable in magnitude to that of charged particles, dominated by light-flavor hadrons [11]. The average of the measured D meson v_2 values in the interval $2 < p_T < 6$ GeV/c is $0.204 \pm 0.030\,(\text{stat}) \pm 0.020\,(\text{syst})^{+0.092}_{-0}$ (B feed-down), which is larger than zero with 5.7σ significance. This result indicates that the interactions with the medium constituents transfer to charm quarks information on the azimuthal anisotropy of the system, suggesting that low momentum charm quarks take part in the collective motion of the system. A positive v_2 is also observed for $p_T > 6$ GeV/c, which most likely originates from the path-length dependence of the partonic energy loss, although the large uncertainties do not allow for a firm conclusion.

In summary, we have presented the first measurement of the D meson elliptic flow coefficient v_2 for semicentral Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. A positive elliptic flow, with 5.7σ significance in $2 < p_T < 6$ GeV/c, is observed. This v_2 measurement, together with the observed large suppression of D mesons in central

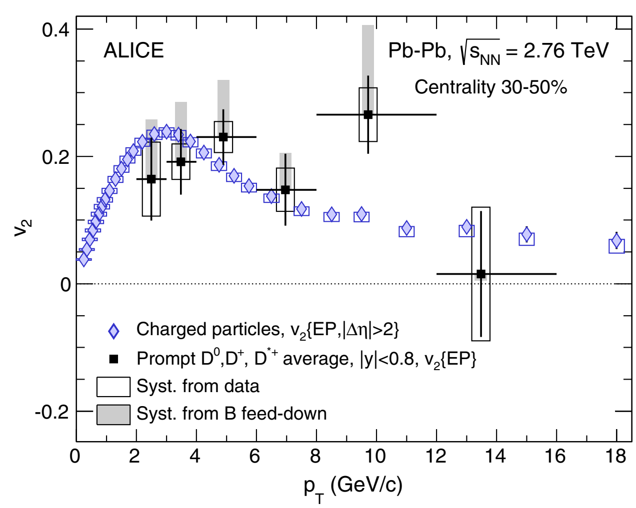

FIG. 3 (color online). Average of D^0, D^+, and D^{*+} v_2 as a function of p_T, compared to charged-particle v_2 [11] measured with the event plane (EP) method. The symbols are positioned horizontally at the average p_T of the three D meson species.

collisions [28], provides a stringent constraint to theoretical models describing the interaction of heavy quarks with the medium.

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