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D meson elliptic flow in non-central Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV

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Abstract

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 centre-of-mass energy $\sqrt{s_{\rm NN}} = 2.76$ 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 $p_{\rm T}$, in the range 2–16 GeV/c. The measured v_2 of D mesons is comparable in magnitude to that of light-flavour hadrons. It is positive in the range $2 < p_{\rm T} < 6$ GeV/c with 5.7 σ significance, based on the combination of statistical and systematic uncertainties.

*See Appendix A for the list of collaboration members

The experimental study of heavy-ion collisions at ultra-relativistic energies is aimed at exploring the structure and dynamics 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) state occurs [1].

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

Two mechanisms are expected to generate a non-zero v_2. The first mechanism, dominant at low ($p_{\rm T} < 3$ GeV/c) and intermediate (3–6 GeV/c) transverse momentum, is the build-up of a collective expansion through interactions among the medium constituents. An anisotropic component in this collective expansion develops mainly in the early stages of the lifetime of the system, when the spatial anisotropy is large [4–6]. 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 transverse momenta [7, 8].

The v_2 values measured for light-flavour hadrons at RHIC and LHC energies can be described for the low-$p_{\rm T}$ region in terms of collective expansion of a strongly-interacting fluid [2, 9–11], and for the high-$p_{\rm T}$ region ($p_{\rm T} >$6–8 GeV/c) in terms of path-length dependent parton energy loss [12–15].

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 small [16]. Hence, the final state heavy-flavour hadrons at all transverse momenta originate from heavy quarks that experienced all stages of the system evolution. At low $p_{\rm T}$, charmed hadron v_2 offers a unique opportunity to test whether also quarks with large mass ($m_{\rm c} \approx 1.5$ GeV/c^2) participate in the collective expansion dynamics and possibly thermalize in the medium [17, 18]. 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 [19]. At low and intermediate $p_{\rm T}$, 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 [20, 21], thus enhancing the v_2 of D mesons with respect to that of charm quarks [18]. In this context, the measurement of D meson v_2 is also relevant for the interpretation of the results on J/ψ anisotropy [22], because J/ψ's formed from $\rm c\overline{c}$ (re)combination would inherit the azimuthal anisotropy of their constituent quarks [23, 24]. At high $p_{\rm T}$, the D meson v_2 can constrain the path-length dependence of parton energy loss, complementing the measurement of the suppression of particle yields with respect to the expectation from proton–proton collisions. The latter is quantified by the nuclear modification factor $R_{\rm AA}$ [25], defined as the ratio of the yield measured in nucleus–nucleus to that observed in pp collisions scaled by the number of binary nucleon–nucleon collisions.

Theoretical models of heavy-quark interactions with the medium constituents enable the calculation of both v_2 and $R_{\rm AA}$ of heavy-flavour mesons in a wide $p_{\rm T}$ range [26–30]. For semi-central collisions at the LHC, they predict a large elliptic flow ($v_2 \approx$ 0.1–0.2) for D mesons at $p_{\rm T} \approx$ 2–3 GeV/c and a decrease to a constant value $v_2 \approx 0.05$ at high $p_{\rm T}$.

The azimuthal anisotropy in heavy-flavour production was measured in Au–Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV at RHIC using electrons from heavy-flavour decays. The resulting v_2 values are as large as 0.13 [31, 32]. A large suppression of the inclusive D meson yield is observed in central Pb–Pb collisions at the LHC for $p_{\rm T} > 5$ GeV/c, where the dominant effect is expected to be the in-medium energy loss of heavy quarks [33].

In this Letter we present the first measurement of v_2 for $\rm D^0$, $\rm D^+$, and $\rm D^{*+}$ mesons and their anti-particles reconstructed from their hadronic decays at mid-rapidity ($|y| < 0.8$) in non-central Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV.

The measurement was carried out with the ALICE detector at the LHC [36]. Particle reconstruction and identification for this analysis were based on the detectors of the central barrel, located inside a solenoid magnet, which generates a 0.5 T magnetic field parallel to the LHC beam direction (z-axis in the ALICE reference frame).

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 [34], and the Time Projection Chamber (TPC) [35]. The reconstructed particles are identified on the basis of their specific energy deposition $\mathrm{d}E/\mathrm{d}x$ 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 for charged particles in the pseudorapidity interval $|\eta| < 0.9$.

The analysis was performed on a data sample of Pb–Pb collisions collected 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 offline to remove background from beam-gas interactions, based on the time information provided by the VZERO and the neutron Zero-Degree Calorimeters (ZDC). Only events with a vertex reconstructed within ± 10 cm from the centre of the detector along the beam line were considered in the analysis. Collisions were classified according to their centrality, which was determined from the VZERO summed amplitudes and defined in terms of percentiles of the total hadronic Pb–Pb cross section [37].

The measurement of D meson v_2 reported here was performed using 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 analyzed events in the 30–50% centrality class passing the offline selection cuts was 9.5×10^6. Using the Pb-Pb hadronic cross section from [37], this corresponds to an integrated luminosity of $(6.2 \pm 0.2)\ \mu\mathrm{b}^{-1}$.

The analysis was performed by reconstructing the decays $\rm D^0 \to K^- \pi^+$, $\rm D^+ \to K^- \pi^+ \pi^+$ and $\rm D^{*+} \to D^0 \pi^+$, and their charge conjugates, following the procedure described in [33, 39]. These weak decays of $\rm D^0$ ($c\tau \approx 123\ \mu$m) and $\rm D^+$ ($c\tau \approx 312\ \mu$m) have branching ratios of $3.88 \pm 0.05\%$ and $9.13 \pm 0.19\%$, respectively. The strong decay $\rm D^{*+} \to D^0 \pi^+$ has a branching ratio of $67.7 \pm 0.5\%$ [38]. $\rm D^0$ and $\rm D^+$ candidates were formed using pairs and triplets of tracks with $|\eta| < 0.8$, $p_{\rm T} > 0.4$ 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. $\rm D^{*+}$ candidates were formed by combining $\rm D^0$ candidates with tracks with $|\eta| < 0.8$, $p_{\rm T} > 0.1$ 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 $p_{\rm T}$, varies from $|y| < 0.7$ for $p_{\rm T} = 2$ GeV/c to $|y| < 0.8$ for $p_{\rm T} > 5$ GeV/c.

D meson candidates were selected with the same strategy as used in [33], in order to increase the statistical significance of the signal with respect to the large background of all possible track combinations. The high spatial precision of the ITS enables a D meson selection 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. In order to further reduce the background, 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 $\mathrm{d}E/\mathrm{d}x$ and time-of-flight.

The measurement of v_2 was performed by correlating the D meson azimuthal angle, $\varphi_{\rm D}$, with the angle ψ_2 of the so-called event plane [40], 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: $\psi_2\ =\frac{1}{2}\tan^{-1}(Q_{2,y}/Q_{2,x})$, 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, $\vec{Q}_2=\left(\sum_{i=1}^{N} w_i\cos 2\varphi_i\,,\sum_{i=1}^{N} w_i\sin 2\varphi_i\right)$. The weights w_i correct for non-uniformities in the acceptance and efficiency of the detector, and optimize the event-plane resolution [40]. They are defined as the product of the track $p_{\rm T}$ 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, pseudorapidity $0<\eta<0.8$, and distance of closest approach to the primary vertex smaller than 3.2 cm in z 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 non-flow, 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 with the VZERO detector. In this case, the contribution of short-range non-flow correlations is reduced by the presence of an η gap between the D mesons and the particles used for the event plane determination.

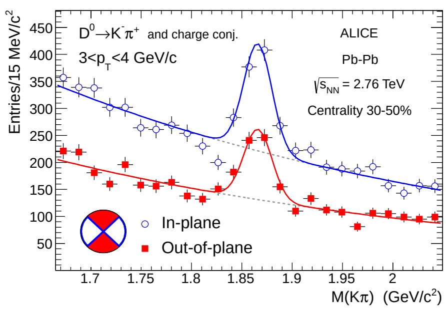

Figure 1: Invariant mass distributions for $\mathrm{D^0}$ candidates and their charge conjugates with $3<p_{\rm T}<4$ GeV$/c$ for 9.5×10^6 Pb–Pb collisions in the 30–50% centrality class. The distributions are shown separately for the in-plane (open symbols) and out-of-plane (closed symbols) intervals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

D meson candidates were classified in two groups according to their azimuthal angle relative to the event plane ($\Delta\varphi=\varphi_{\rm D}-\psi_2$): in-plane ($-\frac{\pi}{4}<\Delta\varphi\leq\frac{\pi}{4}$ and $\frac{3\pi}{4}<\Delta\varphi\leq\frac{5\pi}{4}$) and out-of-plane ($\frac{\pi}{4}<\Delta\varphi\leq\frac{3\pi}{4}$ and $\frac{5\pi}{4}<\Delta\varphi\leq\frac{7\pi}{4}$).

The raw signal yields were extracted in each $\Delta\varphi$ and $p_{\rm T}$ interval by means of a fit to the candidate invariant mass distributions (mass difference $M(\mathrm{K}\pi\pi)-M(\mathrm{K}\pi)$ for $\mathrm{D^{*+}}$). The fitting function was the sum of a Gaussian function to describe the signal and an exponential (for $\mathrm{D^0}$ and $\mathrm{D^+}$) or a power-law (for $\mathrm{D^{*+}}$) function for the background. An example fit is shown in Fig. 1 for $\mathrm{D^0}$ candidates with $3<p_{\rm T}<4$ GeV$/c$ in the two considered $\Delta\varphi$ intervals. For each meson and in each $p_{\rm T}$ 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. The second Fourier coefficient, v_2, was then computed according to:

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

The factor $\pi/4$ results from the integration of the second term, $2v_2\cos(2\Delta\varphi)$, of the $\mathrm{d}N/\mathrm{d}\varphi$ 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 [40]. The value of R_2 depends on the multiplicity and the magnitude of v_2 of the particles used for the event plane calculation. It 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 $R_2 = 0.8059 \pm 0.0001$.

The D meson azimuthal distribution may include the contribution from other harmonics than v_2. However, all odd harmonics, as well as v_4 and v_8, induce the same average contribution to $N_{\text{in-plane}}$ and $N_{\text{out-of-plane}}$ by symmetry, and therefore they make no contribution to Eq. (1). The contribution of v_6, v_{10} and higher harmonics is assumed to be negligible on the basis of the values measured for light particles [41, 42].

The measured D meson yield has a contribution from feed-down from B meson decays, which amounts to about 10–20% of the measured raw yield [33, 39], depending on the meson species, the selection cuts and p_{T}. Indeed, the B feed-down contribution is enhanced by the applied selection criteria that are more efficient for feed-down D mesons, because their decay vertices are more displaced from the primary vertex due to the long B meson lifetime. As a consequence, 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:

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

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:

- determination of D meson yields and their anisotropy relative to the event plane (10–30% in $4 < p_{\mathrm{T}} < 6$ GeV/c depending on the meson species);
- non-flow effects and centrality dependence in the event plane resolution (3%);
- 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 with different fit configurations: 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.

Furthermore, the v_2 result obtained using the D meson signal yields and 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

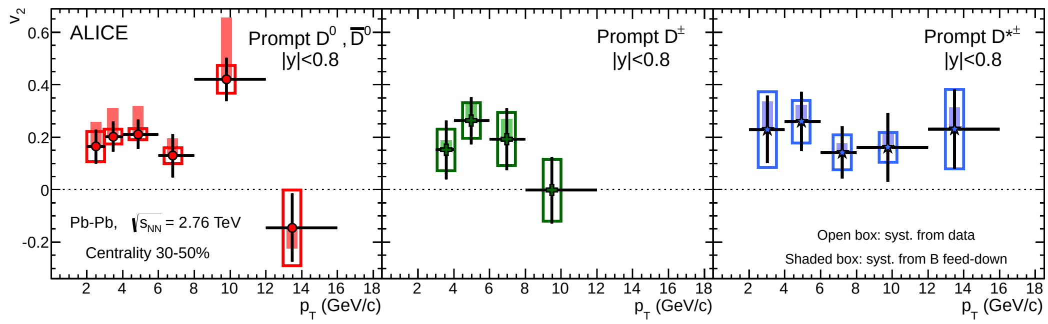

Figure 2: v_2 as a function of $p_{\rm T}$ for prompt $\rm D^0$, $\rm D^+$ and $\rm D^{*+}$ mesons for Pb–Pb collisions in the centrality range 30-50%. The central value was obtained with the assumption $v_2^{\text{feed-down}} = v_2^{\text{prompt}}$. Error bars represent the statistical uncertainty, 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.

invariant mass, M [43]. Here $v_2(M)$ was obtained both with the event plane technique and with methods based on two-particle correlations, namely the scalar product [44] and the Q-cumulants [45].

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 the value of R_2, which varies by 13% within the centrality interval considered here. The average value of R_2 was computed assuming that the D meson yield is uniformly distributed as a function of centrality. A systematic uncertainty of 2% was assigned on the basis of the difference between this average R_2 and 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 R_2 uncertainty arises from the presence of non-flow correlations between the two sub-events used to compute the resolution. To estimate this uncertainty, the resolution correction factor was re-computed using three sub-events with a pseudorapidity gap. Here the sub-events were defined by the TPC tracks and the signals in the two VZERO detectors. The difference of the resulting R_2 to the value with the default two sub-event method, which was found to be of 2.3%, defines the uncertainty.

The systematic uncertainty related to the contribution of D mesons from B decays was assigned by varying the 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 [26–29]. The maximum variation corresponds to the case $v_2^{\text{feed-down}} = 0$, which gives $v_2^{\text{prompt}} = v_2^{\text{all}} / f_{\text{prompt}}$. The value of f_{prompt} depends on the D meson species, the $p_{\rm T}$ interval, and the applied selections. We estimated f_{prompt} as described in [33] using the following ingredients: (i) FONLL [46] predictions for prompt D and B mesons; (ii) B→D+X decay kinematics from the EvtGen package [47]; (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, $R_{\rm AA}^{\text{feed-down}}$. The latter factor accounts for the medium-induced modification of the $p_{\rm T}$ distribution of B mesons. Its contribution was determined by varying the ratio $R_{\rm AA}^{\text{feed-down}}/R_{\rm AA}^{\text{prompt}}$ in the range 1–3, motivated by the lower value of $R_{\rm AA}$ of prompt D mesons measured by ALICE [33] with respect to preliminary results from the CMS experiment on the $R_{\rm AA}$ of J/ψ from B decays [48]. Since the magnitude of the systematic uncertainty due to the B feed-down is inversely proportional to f_{prompt}, the minimum value of f_{prompt}, which is typically about 0.68, was used for its evaluation, resulting in a relative uncertainty on prompt D meson v_2 of about $^{+45}_{-0}$%.

Fig. 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. This value was determined as the average of the p_T distribution of all candidates in the signal invariant mass region, after subtracting the contribution of the background candidates as estimated from the side-bands of the invariant mass distribution. 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 errors on this average v_2 were calculated by propagating the uncertainties 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. The average of the measured v_2 values in the interval $2 < p_T < 6$ GeV$/c$ is 0.204 ± 0.030 (stat) ± 0.020 (syst) $^{+0.092}_{-0}$ (B feed-down), which is larger than zero with 5.7σ significance. 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 a firm conclusion. The measured D meson v_2 is comparable in magnitude to that of charged particles, which is dominated by light-flavour hadrons [49]. This consistency suggests that the relaxation time of charm quarks in the medium is similar to that of light partons and is short with respect to the time scale for diluting the initial geometrical anisotropy, possibly indicating that low momentum charm quarks take part in the collective motion of the system. The measured v_2 tends to favour the models that predict a larger anisotropy at low p_T [26–29].

In summary, we have presented the first measurement of the D meson elliptic flow coefficient v_2 for semi-central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. A positive elliptic flow, with 5.7σ significance in $2 < p_T < 6$ GeV$/c$, is observed. This indicates that the interactions with the medium constituents transfer to charm quarks information on the azimuthal anisotropy of the system. This v_2 measurement, together with the observed large suppression of D mesons in central collisions [33], provides a stringent constraint to theoretical models describing the interaction of heavy quarks with the medium.

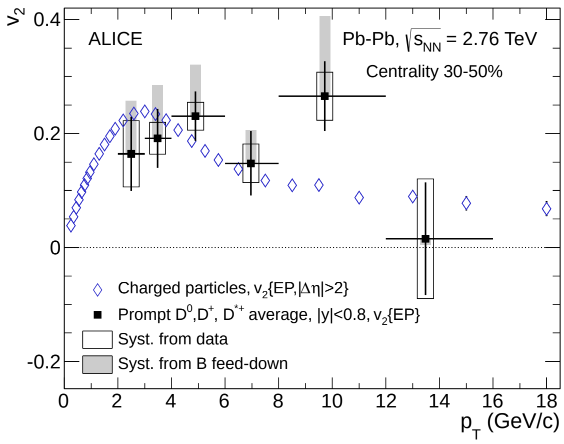

Figure 3: Average of D^0, D^+ and D^{*+} v_2 as a function of p_T, compared to charged-particle v_2 [49] measured with the event plane (EP) method. The symbols are positioned horizontally at the average p_T of the three D meson species.

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