PROCEEDINGS OF SCIENCE

Directed, elliptic and triangular flow of D mesons in ALICE

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Heavy flavour quarks, like charm and beauty, are sensitive probes to investigate the colour-deconfined medium created in high-energy heavy-ion collisions, the quark-gluon plasma (QGP). The ALICE Collaboration measured the production of strange and non-strange D mesons in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. The measurement of elliptic (v_2) and triangular (v_3) flow of D mesons gives insight into the participation of the charm quark in the collective motion of the medium at low transverse momentum (p_{T}), while it constrains the path-length dependence of in-medium energy loss. Furthermore, the coupling of the charm quark to the light quarks in the underlying medium is investigated with the event-shape engineering (ESE) technique to the non-strange D-meson elliptic flow. Finally, the effect of the magnetic field created in the early stage of the collisions is studied via the first measurement at LHC energies of the charge-dependent directed flow of D^0 as a function of pseudorapidity.

HardProbes2020
1-6 June 2020
Austin, Texas

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PoS(HardProbes2020)071

1. Introduction

In ultra-relativistic heavy-ion collisions, heavy quarks are largely produced via hard-scattering processes on a timescale shorter than the quark-gluon plasma (QGP) formation time. Therefore they experience the full system evolution and interact with the medium constituents via elastic and inelastic processes. In particular, the measurement of the azimuthal anisotropies can provide insights into the interaction of heavy quarks with the QGP and the initial condition of the system. They are characterised by the magnitude of 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 symmetry plane angle relative to the n^{th} harmonic.

The first harmonic coefficient v_1, known as directed flow, is suggested to be a useful probe of the strong initial magnetic field created in the collision that induces electromagnetic currents in the QGP. Indeed, the early production of charm quarks and their relaxation time are similar to the QGP lifetime and therefore charmed hadrons experience the evolution of the magnetic field. The expected consequence of these currents is a charge-dependent contribution to the pseudorapidity-odd component of v_1 for c and $\bar{c}$ quarks. The second order flow coefficient v_2, called elliptic flow, is the dominant component in non-central collisions and, at low p_T is sensitive to the coupling of heavy quarks with the underlying medium, while at high p_T can constrain the path-length dependence of the in-medium energy loss. The third coefficient v_3, called triangular flow, originates from event-by-event fluctuations in the initial distribution of gluons and nucleons in the overlap region of the collision and therefore it is sensitive to the initial conditions of the system. Further insights into the dynamics of heavy quarks in the medium is reached with the application of the event-shape engineering (ESE) technique, which allows to investigate the coupling between charm quarks and light flowing quarks of the bulk.

Charmed mesons were reconstructed in ALICE at midrapidity ($|y| < 0.8$) via the decay channels $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^{*+} \to D^0\pi^+$, and $D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$ and their charge conjugates. The combinatorial background was reduced by applying geometrical selections on the decay-vertex topology and particle identification on the daughters tracks. A simultaneous fit to the

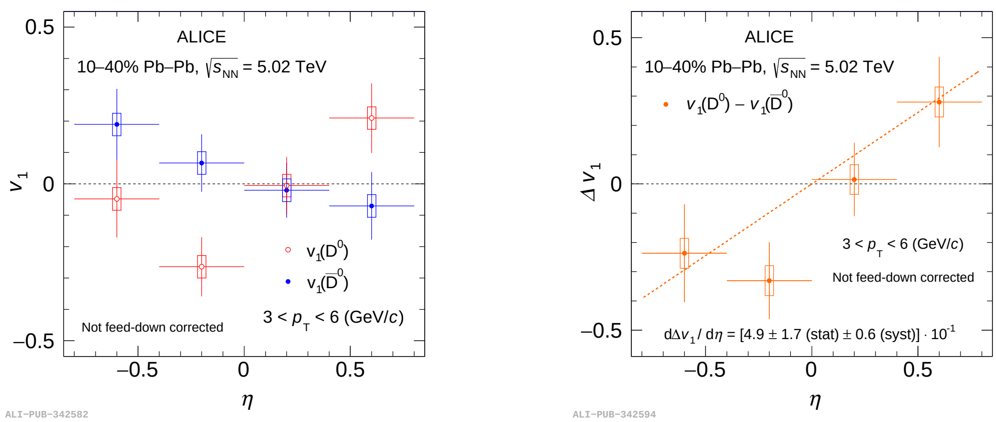

Figure 1: D^0 and $\overline{D}^0$ v_1^{odd} (left) and their difference Δv_1^{odd} (right) as a function of pseudorapidity in the 10–40% centrality class.

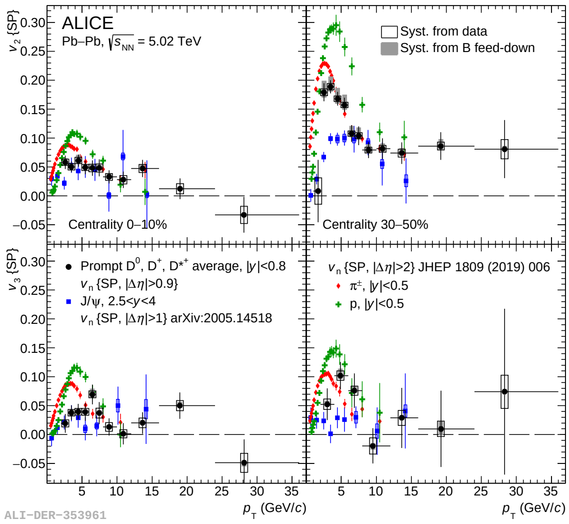

Figure 2: Average v_2 (top) and v_3 (bottom) of prompt D^0, D^+, and D^{*+} in central (left) and mid-central (right) Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV as a function of p_T. The results are compared with v_2 and v_3 of $\pi^{\pm}$, p + $\bar{p}$ [7] and inclusive J/ψ mesons [8] measured at the same centre-of-mass energy

invariant mass distribution and the v_n as a function of the invariant mass is performed in order to obtain the flow coefficient of the signal [2, 3]. The fraction of promptly produced D mesons was estimated with a theory-driven approach based on FONLL calculation [4, 5].
In this proceeding, the most recent results on the azimuthal anisotropy of strange and non strange D mesons, measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, are presented. In particular the v_1 measurement [6] was performed with the data sample collected in 2015, which consisted of 10^8 minimum bias collisions, corresponding to $\simeq 13\ \mu b^{-1}$. The dataset collected in 2018 was used for the v_2 and v_3 measurements [3] and consisted of 100×10^6 and 85×10^6 events in the 0–10% and 30–50% centrality class, corresponding to an integrated luminosity of $\simeq 130\ \mu b^{-1}$ and $\simeq 56\ \mu b^{-1}$ respectively.

2. Directed flow

The directed flow was measured separately for D^0 and $\overline{D}^0$ with the scalar-product method in the 10–40% centrality class. The spectator plane was reconstructed via the transverse asymmetry in the energy deposited in two neutron Zero-Degree Calorimeters (ZDCs) located at η >8.8 (ZDC-A) and η <-8.8 (ZDC-C). The v_1 rapidity-odd component was computed as $v_1^{odd} = \frac{1}{2}[v_1(A) - v_1(C)]$, following the convention of a positive sign of the directed flow of spectator neutrons at positive pseudorapidity. Figure 1 shows the v_1^{odd} of D^0 and $\overline{D}^0$ (left panel) with $3 < p_T < 6$ GeV/c and the related difference Δv_1^{odd} (right panel), as a function of η. A possible hint of signal is observed by fitting the difference with a linear function $\Delta v_1^{odd} = k \times \eta$ and obtaining a positive slope with a significance of 2.7σ, which is also similar to the one measured for the charged hadrons [6].

3. Elliptic and triangular flow

Figure 2 shows the average elliptic and triangular flow of prompt D^0, D^+, and D^{*+} measured in central and mid-central Pb–Pb collisions with the scalar-product method [3]. The result is compared to that of charged pions, protons [7] and inclusive J/ψ [8]. The non-strange D-meson v_2 is positive for $p_T > 2$ GeV/c and increases from central to mid-central collisions, reflecting the increasing eccentricity of the interaction region. Similarly the v_3 is positive in the same p_T range, but it is compatible among the two centrality classes, as observed also for light hadrons. The comparison with other particles shows a mass ordering for $p_T < 3$ GeV/c which is explained as an interplay between anisotropic and radial flow. At intermediate p_T, 3–8 GeV/c, $v_n(D) \simeq v_n(\pi) < v_n(p)$ which is consistent with the constituent-quark scaling of v_n. Furthermore, $v_n(D) > v_n(J/\psi)$ in the same range and this confirms the charm-quark coalescence with light quarks. Finally, all v_n coefficients are similar for $p_T > 8$ GeV/c and this is due to a similar path-length dependence of in-medium energy loss for quarks and gluons. The non-strange D-meson v_2 and v_3 was also compared with the predictions of theoretical models and the result is well described by those including both quark coalescence and fragmentation in the hadronisation phase. In addition, it was also possible to constrain the charm spatial diffusion in the range $1.5 < 2\pi T_c D_s < 7$, by evaluating the agreement between the v_n coefficients and the models, and this lead to charm thermalization times τ_{charm} = 3–14 fm/c [3].

The D_s^+ elliptic flow was measured in the 30–50% centrality class with the same analysis technique used for non-strange D-meson v_2 and the results are compatible as shown in Figure 3. Furthermore, the comparison with theoretical predictions shows that models based on the charm-quark transport in an hydrodynamically expanding medium can fairly well describe both strange and non-strange v_2 in mid-central collisions.

4. Event-shape engineering

The v_2 of D^0, D^+, and D^{*+} mesons was further investigated by applying the event-shape engineering technique [11], which allows to classify events with fixed centrality but different

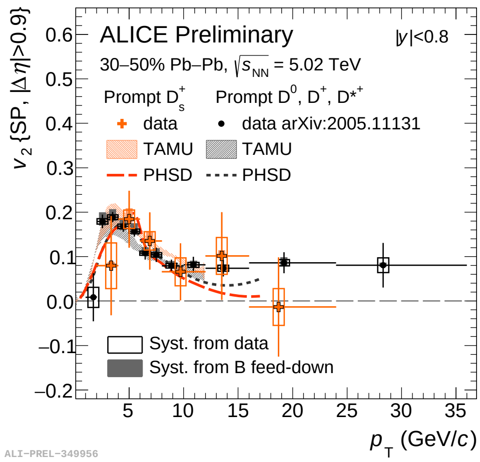

Figure 3: D_s^+ v_2 in mid-central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV as a function of p_T. The result is compared to non-strange D-meson v_2 and theoretical model predictions [9, 10].

average elliptic flow. The latter is quantified via the magnitude of the second-harmonic reduced flow vector $q_2 = |\overrightarrow{Q}_2|/\sqrt{M}$, where M is the event multiplicity and $\overrightarrow{Q}_2$ is the second-harmonic flow vector. The non-strange D-meson v_2 was measured in 20% of events with largest/smallest q_2 in mid-central and, for the first time, central Pb–Pb collsions. The results, described in [3], show a decrease (increase) by about 50% in the 20% small-q_2 (large-q_2) class and this confirms a correlation between the D-meson azimuthal anisotropy and the collective expansion of the medium. In addition, different implementations of theoretical models give a similar description of the measured ratios, suggesting that the ESE effect is more related to the initial geometry rather than to the dynamic evolution of charm quarks in the medium.

5. Conclusions

The ALICE Collaboration has measured the v_2 and v_3 of prompt stange and non-strange D mesons and the charge-dependent v_1^{odd} of D^0 and $\overline{\mathrm{D}}^0$ mesons in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV.

The first measurement at the LHC energies of D^0 and $\overline{\mathrm{D}}^0$ v_1^{odd} as a function η gives a hint of a charge difference and it was quantified with the slope of $\Delta v_1^{\mathrm{odd}}$, which was found to be positive with a significance of 2.7σ. The D-meson v_2 and v_3 are observed to be positive for $p_{\mathrm{T}} > 2$ GeV/c in central and mid-central. The ordering observed for the two harmonics as a function of p_{T} confirms the interplay between charm-quark transport and path-length dependence at different p_{T}. Finally, the usage of the event-shape engineering technique in the v_2 measurement shows a positive correlation between the D-meson azimuthal anisotropy and the collective expansion of the the bulk of light quarks.

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