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Nuclear modification factor and elliptic flow of open heavy-flavour particles in Pb–Pb collisions with ALICE at the LHC

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The latest results on the nuclear modification factor (R_{AA}) and the elliptic flow (v_2) of D mesons and heavy-flavour hadron decay leptons in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 2.76 TeV measured with ALICE are presented for different centrality classes. The results, obtained in a wide transverse momentum (p_{T}) range and in different rapidity regions, provide further information on the properties of the medium. A suppression of a factor of about 3–4 of production yields relative to pp collisions and a positive v_2 for open heavy-flavour particles are observed in $p_{\mathrm{T}} > 5$ GeV$/c$ in most central collisions and in intermediate p_{T} region in semi-central collisions, respectively. The leptons at high p_{T} are dominated by beauty-hadron decays, therefore they are sensitive to transport properties of beauty quarks in the QCD medium. Finally, the results obtained with the Event-Shape Engineering (ESE) technique applied to the D-meson elliptic flow in semi-central Pb–Pb collisions will be discussed.

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†A footnote may follow.

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1. Introduction

The LHC heavy-ion physics program aims at investigating the properties of the Quark-Gluon Plasma (QGP) [1]. Heavy quarks (charm and beauty) are regarded as effective probes to study and characterize the QGP, as they are mainly created on a very short time scale in initial hard processes and subsequently experience the entire system evolution interacting with the medium constituents. Therefore, they allow us to explore transport properties of the hot and dense nuclear matter by investigating their production, propagation and hadronization mechanisms in such color-deconfined medium.

ALICE [2] is the dedicated heavy-ion experiment at the LHC with precision vertexing, tracking and particle identification optimized for the high multiplicity environment. The heavy-flavour particles are measured in ALICE over a wide rapidity range. D mesons are reconstructed via hadronic decays at mid-rapidity ($|y| < 0.5$) using the Inner Tracking System (ITS) and the Time Projection Chamber (TPC). In addition, combining information of ITS, TPC and Electromagnetic Calorimeter (EMCal) allows us to study the open heavy-flavour hadron decay electrons in a wide p_{T} range at mid-rapidity ($|y| < 0.7$). At forward rapidity ($2.5 < y < 4$), open heavy-flavour hadron decay muons are measured in the muon spectrometer where the background of light-flavour hadrons is reduced by the front absorber and the muon filter.

2. Nuclear modification factor of open heavy-flavour particles

When heavy quarks traverse the QCD medium, they interact with medium constituents via both inelastic (radiative energy loss) [3–5] and elastic (collisional energy loss) [6–9] processes. Due to the color-charge effect, gluons are expected to lose more energy than quarks [10]. Moreover, the energy loss is predicted to depend on the mass of the quark [11–15], the radiative energy loss is expected to be smaller for heavy quarks with respect to light quarks. Therefore, the following energy loss hierarchy $\Delta E_{\mathrm{g}} > \Delta E_{\mathrm{light\ quark}} > \Delta E_{\mathrm{c}} > \Delta E_{\mathrm{b}}$ is expected. Experimentally, the parton in-medium energy loss is studied using the nuclear modification factor, R_{AA}, which compares the p_{T}-differential production yields in nucleus–nucleus (AA) collisions ($\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}$) with the production cross section in proton–proton (pp) collisions ($\mathrm{d}\sigma_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}$) scaled by the average nuclear overlap function ($\langle T_{\mathrm{AA}}\rangle$):

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle T_{\mathrm{AA}}\rangle} \cdot \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}. \quad (2.1)$$

The p_{T}-differential R_{AA} of prompt-D mesons (averaged of D^0, D^+ and D^{*+}) in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [16] is shown in the left panel of figure 1, and compared with the same measurements at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [17]. The measurements at the two energies are compatible. Such effect is predicted by models considering the variation of the medium density and the charm-quark p_{T} distribution at the two energies [19, 20]. The uncertainties of the measurements at 5.02 TeV are reduced by a factor of about two and the p_{T} coverage is extended from 16 to 50 (36) GeV/c in the 0–10% (30–50%) centrality class. Larger suppression, by about a factor of two, is observed in the most 10% central collisions compared to the 30–50% centrality class for $p_{\mathrm{T}} > 5$ GeV/c. This can be understood as resulting from the increasing medium density, size and lifetime from

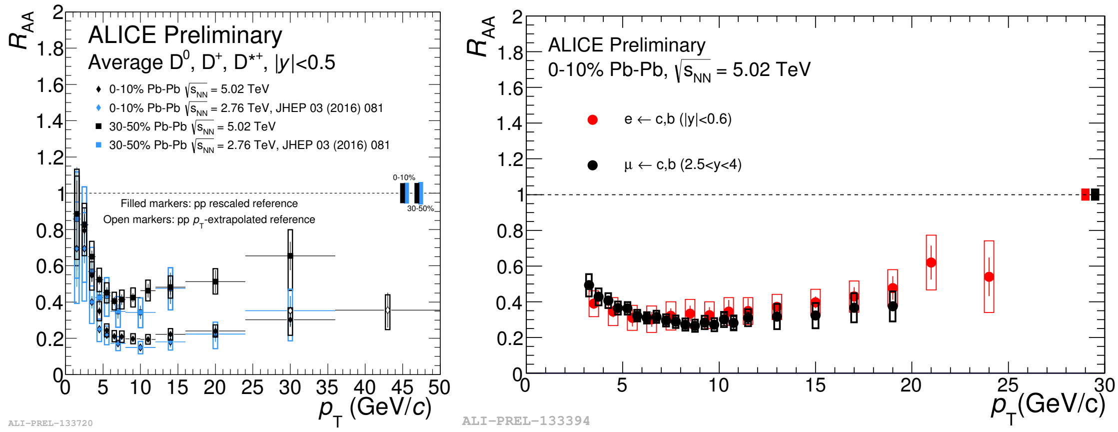

Figure 1: Left: R_{AA} of prompt-D meson (averaged of D^0, D^+ and D^{*+}) as function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (black) [16] and $\sqrt{s_{NN}} = 2.76$ TeV (blue) [17] in the 0–10% and 30–50% centrality classes. Right: p_T-differential R_{AA} of open heavy-flavour hadron decay electrons (red) measured at mid-rapidity ($|y| < 0.6$) and muons (black) measured at forward rapidity ($2.5 < y < 4$) [18] for the most 10% central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

peripheral to central collisions and it indicates that charm quarks undergone strong interactions in the QCD medium in central Pb–Pb collisions.

The right panel of figure 1 shows the R_{AA} of open heavy-flavour hadron decay electrons measured in $|y| < 0.6$ and muons measured in $2.5 < y < 4$ [18] in the 10% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The R_{AA} reaches values smaller than 0.4 in $p_T > 4$ GeV$/c$ for both open heavy-flavour hadron decay electrons and muons. The results are similar with those obtained from the D-meson measurements, although in a different p_T range. The R_{AA} of open heavy-flavour hadron decay electrons is compatible with that of muons within uncertainties. This indicates that the energy loss of heavy quarks in the QCD medium does not vary substantially in the rapidity range $|y| < 4$.

It was also observed that the R_{AA} of prompt-D mesons [21] is significantly lower than that of non-prompt J$/\psi$ from beauty decays [22] in central and semi-central Pb–Pb collisions, indicating the quark-mass dependence of the parton energy loss in the QCD medium. In addition, the suppression of the R_{AA} for electrons from beauty-hadron decays is found about 1.2σ smaller than that from open heavy-flavour hadron decays [23]. This difference is consistent with the ordering of charm and beauty suppression seen in the prompt-D meson and J$/\psi$ from B-meson comparison.

3. D_s^+ meson production

The study of D_s^+-meson production in Pb–Pb collisions can provide additional information for understanding the interactions of charm quarks with the strongly-interacting medium. The D_s^+-meson yield is sensitive to the enhancement of strangeness production in heavy-ion collisions compared to pp interactions, which is viewed as due primarily to the lifting of the canonical suppression [25]. The comparison of the p_T-differential production yields of non-strange D mesons

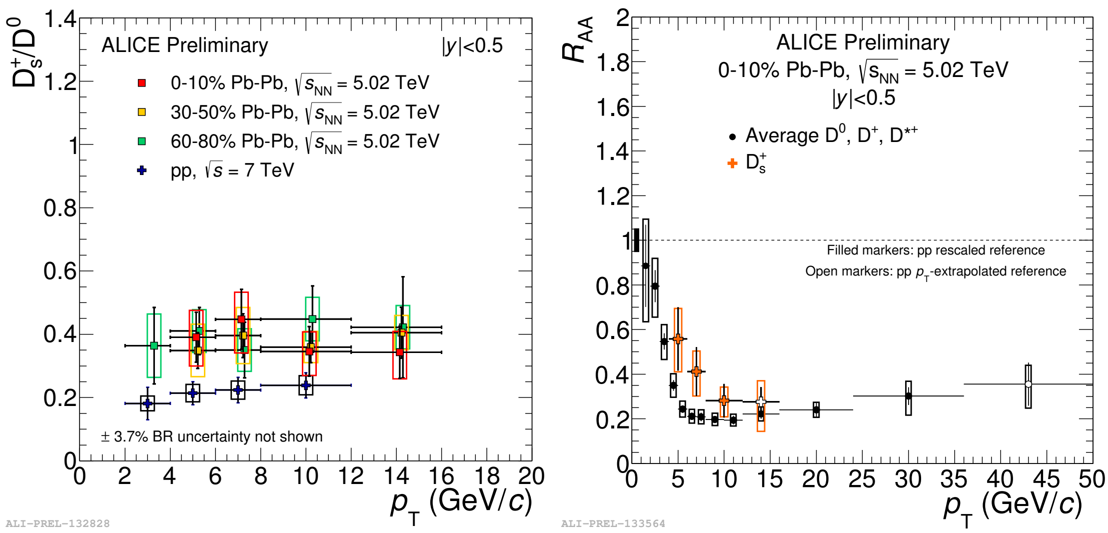

Figure 2: Left: ratios of D_s^+/D^0 meson yields for various centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [16] compared with the values measured in pp collisions at $\sqrt{s} = 7$ TeV [24]. Right: R_{AA} of prompt D_s^+ mesons compared with the average R_{AA} of the three non-strange states for the most 10% Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [16].

and of D_s^+ mesons in Pb–Pb and pp collisions is therefore sensitive to the role of recombination in charm-quark hadronization.

The left panel of figure 2 shows the p_T-dependent ratios of D_s^+/D^0 meson yields in 0–10%, 30–50% and 60–80% centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [16] compared with the values measured in pp collisions at $\sqrt{s} = 7$ TeV [24]. The central values of these ratios are generally larger in Pb–Pb, in all three centrality classes, than in pp collisions. However, the measurements in the two systems are compatible within about 1σ of the combined uncertainties. The right panel of figure 2 shows the R_{AA} of D_s^+ meson compared with the average R_{AA} of the three non-strange states for the most 10% central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [16]. Although the central value of R_{AA} for D_s^+ mesons is generally larger than that of non-strange D mesons, as in the case of the D_s^+/D^0 ratios, the two measurements are compatible within uncertainties. The larger statistics in Pb–Pb data foreseen for 2018 should provide a more firm conclusion towards understanding the contribution from coalescence on charm-quark in-medium hadronization.

4. Elliptic flow of open heavy-flavour particles

The collective dynamics of the expanding QCD medium converts the initial-state spatial anisotropy into final-state particle momentum anisotropy. The latter can be characterized by the Fourier coefficients v_n of the distribution of the particle azimuthal angle φ relative to the initial-state symmetry plane angle Ψ_R [30]. The measurement of the second coefficient $v_2 = \langle\cos[2(\varphi - \Psi_R)]\rangle$ (called elliptic flow) at low p_T (< 5 GeV/c) provides insight into the possible collective flow imparted by the medium to heavy quarks [31], while at high p_T it can constrain the path-length dependence of parton energy loss [32]. In addition, at low and intermediate p_T, the v_2 of open

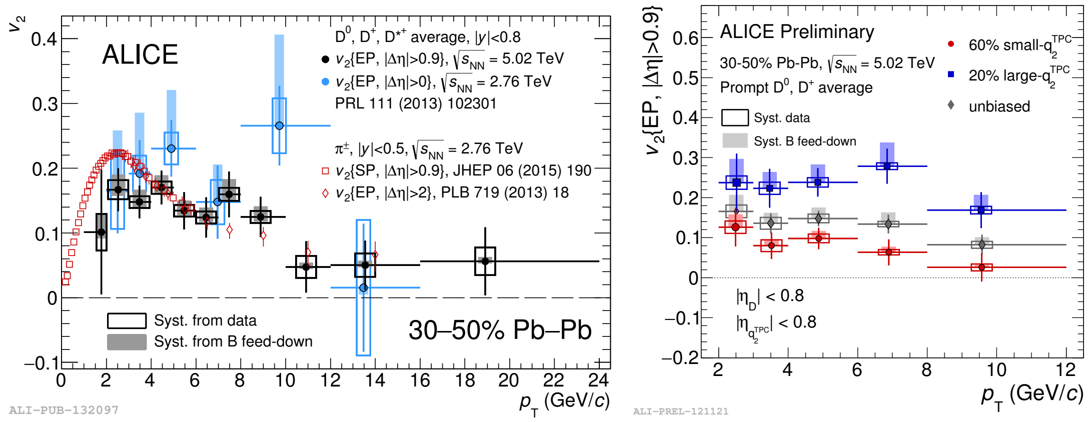

Figure 3: Left: v_2 of D mesons (average of D^0, D^+ and D^{*+}) as a function of p_T for 30–50% centrality class in Pb–Pb collisions at $\sqrt{s_\mathrm{NN}} = 5.02$ TeV [26], compared with the same measurement at $\sqrt{s_\mathrm{NN}} = 2.76$ TeV [27] and that of $\pi^\pm$ at $\sqrt{s_\mathrm{NN}} = 2.76$ TeV measured with the event plane method [28] and the scalar product method [29]. Right: v_2 of D mesons in 60% small and 20% large q_2 (see definition in the text) classes for semi-central (30–50%) Pb–Pb collisions at $\sqrt{s_\mathrm{NN}} = 5.02$ TeV, compared with the same measurement without the eccentricity selections.

heavy-flavour particles is sensitive to recombination effects in the hadronization process, as well as to the heavy-quark coupling to the QGP and hadronic matter [33].

The left panel of figure 3 shows the p_T-differential average v_2 of D^0, D^+ and D^{*+} in semi-central Pb–Pb collisions at $\sqrt{s_\mathrm{NN}} = 5.02$ TeV [26]. It is compatible with the same measurement at $\sqrt{s_\mathrm{NN}} = 2.76$ TeV [27], which has uncertainties larger by a factor of about two compared to the new result at 5.02 TeV. The observed positive D-meson v_2 at low and intermediate p_T indicates that charm quarks take part to the collective motion in the QCD medium. The D-meson v_2 is similar to that of $\pi^\pm$ [28, 29] in the common p_T interval (1–16 GeV/c).

ALICE also measured v_2 of open heavy-flavour decay electrons at mid-rapidity ($|y| < 0.7$) in Pb–Pb collisions at $\sqrt{s_\mathrm{NN}} = 5.02$ TeV [18] and 2.76 TeV [34], and open heavy-flavour hadron decay muons at forward rapidity ($2.5 < y < 4$) in Pb–Pb collisions at $\sqrt{s_\mathrm{NN}} = 2.76$ TeV [35]. Positive v_2 values of open heavy-flavour decay leptons are observed at intermediate p_T at both mid-rapidity and forward rapidity in semi-central Pb–Pb collisions. The v_2 of open heavy-flavour decay electrons is consistent with that of muons within uncertainties and the values are insensitive to the collision energy. Those results support the conclusion that heavy quarks undergone strong interactions in the QCD medium in a wide rapidity window.

The right panel of figure 3 shows the v_2 of D mesons in two selected classes of event-by-event cumulant of the second order flow harmonic ($q_2 \simeq \sqrt{1 + \langle M-1 \rangle \langle v_2^2 \rangle}$), which is related to the event eccentricity, in 30–50% semi-central Pb–Pb collisions at $\sqrt{s_\mathrm{NN}} = 5.02$ TeV, compared with the same measurement without the q_2 selections. The v_2 measurement of D mesons at different q_2 values (Event-shape engineering) provides the opportunity to study the charm-quark coupling to the light-hadron bulk [36]. The results show that D-meson v_2 in events with large and small q_2 values are clearly separated. This phenomenon suggests that charm quarks are sensitive to the light-hadron bulk collectivity of Pb–Pb collisions.

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