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Measurements of the nuclear modification factor and elliptic flow of leptons from heavy-flavour hadron decays in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV with ALICE

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Abstract

We present the ALICE results on the nuclear modification factor and elliptic flow of electrons and muons from open heavy-flavour hadron decays at mid-rapidity and forward rapidity in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV for different centrality intervals. The results are compared to model calculations that include interactions of heavy quarks with the medium.

Keywords: heavy flavour, charm, beauty, elliptic flow, nuclear modification factor, ALICE

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1. Introduction

Heavy quarks, i.e. charm and beauty, are sensitive probes to study the properties of the strongly-interacting matter created in heavy-ion collisions at ultra-relativistic energies, since they are mainly produced in initial hard scattering processes and experience the entire evolution of the system.

The heavy quarks traversing the medium lose energy via collisional and radiative processes in the interaction with the medium constituents. The in-medium energy loss of heavy quarks can be investigated with the nuclear modification factor (R_{AA}) of heavy-flavour particles, which is defined as the ratio of the transverse momentum (p_{T}) differential yield of particles in heavy-ion collisions ($\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}$) with respect to the p_{T}-differential cross section in pp collisions ($\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}$) scaled with the average nuclear overlap function in heavy-ion collisions ($\langle T_{\mathrm{AA}}\rangle$), i.e. $R_{\mathrm{AA}} = (\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}})/(\langle T_{\mathrm{AA}}\rangle\, \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}})$. In absence of nuclear effects, R_{AA} is expected to be unity. The energy loss of heavy flavours in the medium causes a shift of the momentum distribution towards lower values, resulting in a suppression of heavy-flavour particle yields, $R_{\mathrm{AA}} < 1$, at intermediate and high p_{T}.

Further properties of the medium can be investigated with the elliptic flow of heavy-flavour particles, $v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$, which is defined as the coefficient of the second-order harmonic of the Fourier expansion of the distribution of the particle azimuthal angle (φ) in momentum space with respect to the angle of the 2^{nd}-order symmetry plane (Ψ_2) [1]. The measurement of the heavy-flavour particle v_2 at low p_{T} provides insight into the collective motion of heavy quarks in the medium, while the heavy-flavour particle v_2 at high p_{T} is sensitive to the path-length dependence of the energy loss of heavy quarks in the almond-shaped overlap area in non-central collisions.

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The semi-leptonic decays of heavy-flavour hadrons are well suited for heavy-flavour studies, since the ALICE detector has an unique capability for identification of electrons and muons over a wide p_{T} range. In addition, the contributions of charm and beauty-hadron decays can be disentangled in the yield of electrons.

2. Analysis

Muons are reconstructed in ALICE with the Muon Spectrometer [2] at forward rapidity ($2.5 < y < 4$). The muons from background sources, mainly decays of π and K at low-intermediate p_{T} and decays of W at high p_{T}, are statistically subtracted from the measured muon sample. The contribution of muons from π and K decays is estimated with a data-tuned Monte-Carlo (MC) cocktail, while the contribution of muons from W decays is estimated with a MC simulation based on POWHEG [3]. The R_{AA} of muons from heavy-flavour hadron decays ($R_{\mathrm{AA}}^{\mu\leftarrow HF}$) at forward rapidity has been measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ [4] and 5.02 TeV for various centrality intervals. The data sample used for the analysis in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV in the 0–90% centrality class consist of $4.7 \cdot 10^7$ and 10^8 muon-triggered collisions for low- and high-p_{T} trigger thresholds, respectively. The pp reference for the R_{AA} analysis in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV is obtained by a $\sqrt{s}$-scaling [5] of the measured cross section of muons from heavy-flavour hadron decays in pp collisions at $\sqrt{s} = 7$ TeV [6] for $p_{\mathrm{T}} < 12$ GeV/c and by an extrapolation of the measured cross section for higher p_{T}. The v_2 of muons from heavy-flavour hadron decays ($v_2^{\mu\leftarrow HF}$) at forward rapidity has been measured with the two-particle Q cumulant method in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [7] in the 0–10%, 10–20%, and 20–40% centrality classes.

Electrons are identified at mid-rapidity with the Inner Tracking System (ITS), the Time Projection Chamber (TPC), the Time Of Flight (TOF) and the ElectroMagnetic Calorimeter (EMCal) [2]. The contribution of electrons that do not originate from heavy-flavour hadron decays, which are mainly electrons from photon conversions in detector material and from Dalitz decays of neutral mesons, is obtained exploiting the invariant mass of electron-positron pairs and/or the cocktail method, depending on the analysis. The electron background is then statistically subtracted from the measured electron sample. The R_{AA} of electrons from heavy-flavour hadron decays ($R_{\mathrm{AA}}^{e^{\pm}\leftarrow HF}$) at mid-rapidity ($|y| < 0.6$) has been measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ [8] and 5.02 TeV for several centrality classes. The data sample used for the analysis in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV consist of 10^7 semi-central (30–50%) collisions recorded with a minimum-bias trigger. The pp reference for the R_{AA} analysis in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV is obtained by interpolating the cross sections of electrons from heavy-flavour hadron decays in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV, as discussed in [9]. The v_2 of electrons from heavy-flavour hadron decays ($v_2^{e^{\pm}\leftarrow HF}$) at mid-rapidity ($|y| < 0.7$) has been measured with the event plane method [1] in three centrality classes (0–10%, 10–20%, and 20–40%) in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [10] and in 30–50% Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The V0 detector, covering the backward rapidity (V0A, $2.8 < \eta < 5.1$) and forward rapidity (V0C, $-3.7 < \eta < -1.7$) regions, is used to obtain the collision centrality and the symmetry-plane angle (Ψ_2) needed in the v_2 analysis with the event plane method.

3. Results

The $R_{\mathrm{AA}}^{\mu\leftarrow HF}$ at forward rapidity ($2.5 < y < 4$) and $R_{\mathrm{AA}}^{e^{\pm}\leftarrow HF}$ at mid-rapidity ($|y| < 0.6$) in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, as a function of p_{T} and centrality class, are shown in the left panels of Figures 1 and 2, respectively. A suppression of leptons from heavy-flavour hadron decays is observed in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, which is mainly induced by final-state effects due to heavy-quark energy loss in the medium since no significant modification of the spectra of leptons from heavy-flavour hadron decays is observed in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV relative to binary scaled pp collisions [9, 11]. The suppression decreases from central to peripheral collisions, as expected from the centrality dependence of the size and initial energy density of the medium. The same features are observed for Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [4, 8]. In fact, the R_{AA} of leptons from heavy-flavour hadron decays is compatible, within uncertainties, in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV, as shown in the right panels of Figures 1 and 2. The $R_{\mathrm{AA}}^{e^{\pm}\leftarrow HF}$ at mid-rapidity ($|y| < 0.6$) and $R_{\mathrm{AA}}^{\mu\leftarrow HF}$ at forward rapidity ($2.5 < y < 4$) in 0–10% Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV are compatible within uncertainties [8].

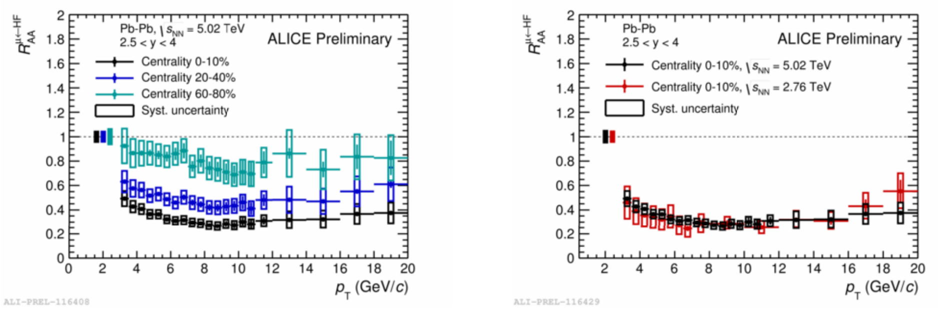

Fig. 1: Left: R_{AA} of muons from heavy-flavour hadron decays as a function of p_{T} in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV in the 0–10%, 20–40% and 60–80% centrality classes. Right: Comparison of the R_{AA} of muons from heavy-flavour hadron decays as a function of p_{T} in the 10% most central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 [4] and 5.02 TeV.

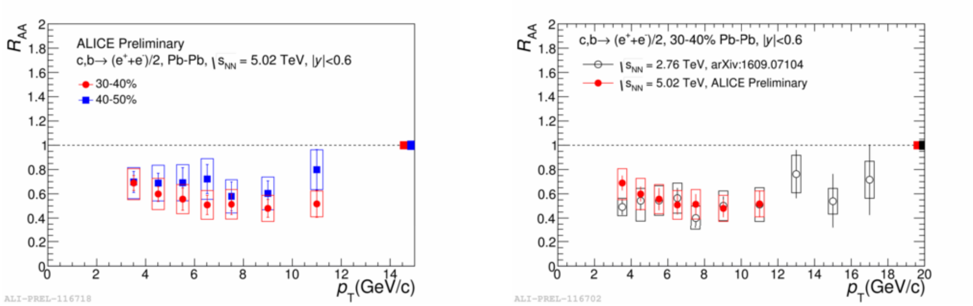

Fig. 2: Left: R_{AA} of electrons from heavy-flavour hadron decays as a function of p_{T} in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV in the 30–40% and 40–50% centrality classes. Right: Comparison of the R_{AA} of electrons from heavy-flavour hadron decays as a function of p_{T} in 30–40% Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 [8] and 5.02 TeV.

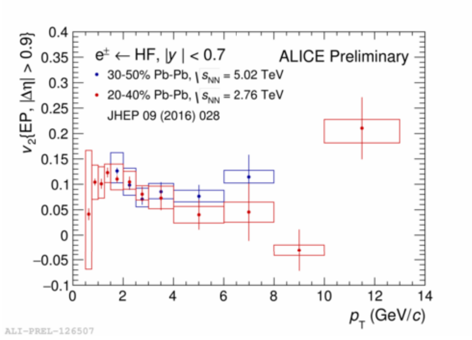

Fig. 3: v_2 of electrons from heavy-flavour hadron decays as a function of p_{T} in 20–40% Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV [10] and in 30–50% Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV.

The p_{T} dependence of the $v_2^{e^{\pm}\leftarrow HF}$exhibits the same trend in 20–40% Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV [10] and in 30–50% Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, as shown in Fig. 3. A positive v_2 at low-intermediate p_{T} is observed in both collision energies: at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV the significance has a maximum of 5.9σ in the 2–2.5 GeV/c interval and at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV the maximum significance is 5.3σ in the 1.5–2 GeV/c interval. The data suggest that heavy quarks are affected by the collective motion of the system. The $v_2^{e^{\pm}\leftarrow HF}$at mid-rapidity ($|y| < 0.7$) and the $v_2^{\mu\leftarrow HF}$at forward rapidity ($2.5 < y < 4$) in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV are compatible within uncertainties [10].

Figure 4 shows the p_T dependence of the $R_{AA}^{e^{\pm}\leftarrow HF}$(left panel) and $v_2^{e^{\pm}\leftarrow HF}$(right panel) measured in 30–50% Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compared with model calculations [12–17]. The models can describe qualitatively the measurements, although the simultaneous description of the $R_{AA}^{e^{\pm}\leftarrow HF}$and $v_2^{e^{\pm}\leftarrow HF}$measurements remains a challenge for some of the models.

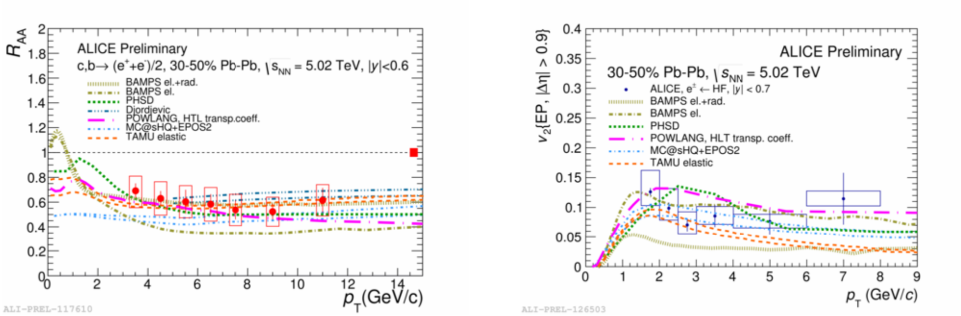

Fig. 4: Left: R_{AA} of electrons from heavy-flavour hadron decays as a function of p_T in 30–50% Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. Right: v_2 of electrons from heavy-flavour hadron decays as a function of p_T in 30–50% Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. Results are compared with model calculations [12–17].

4. Conclusions

The R_{AA} and v_2 of electrons and muons from heavy-flavour hadron decays have been measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV. The R_{AA} results show a strong suppression of leptons from heavy-flavour hadron decays in central Pb–Pb collisions, which is mainly induced by final-state effects due to heavy-quark energy loss in the medium. A positive v_2 of leptons from heavy-flavour hadron decays is observed in semi-central Pb–Pb collisions, suggesting that heavy quarks participate in the collective motion of the system. The R_{AA} and v_2 measurements of leptons from heavy-flavour hadron decays show no dependence on rapidity and collision energies within the uncertainties. The presented models can describe qualitatively the suppression and elliptic flow of electrons from heavy-flavour hadron decays, however the simultaneous description of the R_{AA} and v_2 measurements is a challenge for some of them.

5. Acknowledgements

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