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Probing parton propagation in heavy-ion collisions with ALICE heavy-flavour measurements

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Abstract. Heavy quarks (charm and beauty) are valuable probes for investigating the properties of the quark–gluon plasma (QGP) formed in ultra-relativistic heavy-ion collisions, as they are mainly produced through hard-scattering processes prior to the formation of the QGP, and their number is conserved during the subsequent QGP evolution. Measurements of the nuclear modification factor R_{AA} of charm and beauty hadrons allow us to characterise the in-medium energy loss of heavy quarks while traversing the QGP. Information on their diffusion and degree of participation in the collective motion of the medium can be obtained by measuring the elliptic-flow coefficient v_2 of heavy-flavour particles. Complementary insights into heavy-quark fragmentation and energy redistribution can be obtained by measuring angular correlations involving heavy-flavour particles.

In this contribution, the recently published results on the non-prompt v_2 coefficient of D^0 mesons are presented, comparing them with those of other particle species in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. Additionally, we report the recent findings on the R_{AA} of prompt D mesons and Λ_{c}^{+} baryons in Pb–Pb collisions at the same energy. Furthermore, we discuss the new Pb–Pb results on angular correlations between heavy-flavour decay electrons and charged particles in the same collision system.

1 Introduction

The QGP, a phase of matter made of colour-deconfined quarks and gluons, is created in ultrarelativistic heavy-ion collisions [1]. This state of matter has been extensively studied at particle colliders such as the RHIC, and LHC. Measurements from experiments at those colliders suggest that the QGP behaves as a strongly-coupled, low-viscous, nearly perfect fluid. The short lifetime of the QGP makes a direct study of its properties very difficult [2]. Thus, various indirect approaches are employed to investigate the properties of this medium, by studying peculiar phenomena induced by its presence which reflect to the final-state particles, such as azimuthal anisotropy, jet quenching, and strangeness enhancement. Utilizing heavy quarks (charm and beauty) to study these phenomena provides additional benefits, as they are produced at the initial stage of the collision, mostly through hard scattering processes on timescales shorter than the QGP formation time. Consequently, they undergo the full evolution of the medium and serve as effective probes for studying the properties and dynamics of the QGP [2]. While traversing the QGP, heavy quarks interact with the medium

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constituents exchanging energy and momentum via elastic and inelastic processes, leading to a modification of their momentum distribution.

One of the key signatures that gives information on these interactions is the nuclear modification factor, R_{AA} [3]. R_{AA} is a measurement of the modification of the final-state particle spectra induced by QGP effects on the partons traversing it, and is defined as the ratio between the p_{T} differential production yields of the particle of interest produced in the nucleus–nucleus collisions with respect to the differential production yields in proton–proton (pp) collisions, normalised by the average number of binary collisions.

Another signature of QGP formation is the “jet quenching”, i.e., a suppression of the jet energy and transverse-momentum distribution induced by a modification of parton showers, due to the interactions of energetic quarks and gluons with the medium leading to parton energy loss through medium-induced gluon radiation and collisional processes. Jet quenching is typically assessed by measuring angular correlations between a high p_{T} "trigger" particle and other charged particles produced in the event, and measuring the modification of the yields of the correlation distribution from pp to Pb–Pb (I_{AA}) in different angular regions. On the near side ($\Delta\varphi \approx 0$), deviations from unity in I_{AA} can indicate changes in fragmentation functions and quark–gluon jet ratios. On the away-side ($\Delta\varphi \approx \pi$), an $I_{\mathrm{AA}} < 1$ at high p_{T} can point toward the presence of parton energy loss, while values of $I_{\mathrm{AA}} > 1$ at low p_{T} can be induced by mechanisms such as k_{T} broadening and medium excitation. Jet properties depend on the initiating parton species (quark/gluon) and mass. Gluon-initiated jets exhibit wider cones, contain more soft gluons, and are expected to lose more energy due to their larger color charge. The comparison of the angular distribution, and of the I_{AA} values, obtained considering as trigger particles heavy-flavour hadron decay electrons or lighter hadrons, can provide valuable insights into jet quenching features, highlighting differences in the interactions of quarks and gluons within the hot and dense medium created in heavy-ion collisions [5–7].

The azimuthal anisotropy in the momentum distribution of final-state particles serves as an important observable for probing the properties of the QGP. In non-central nucleus–nucleus collisions, the initial spatial anisotropy of nucleons participating in the collision, resulting from the asymmetry of the nuclear overlap region, is transferred to the final-state particle momentum distribution through multiple collisions of partons, driven by hydrodynamics laws. This phenomenon, known as anisotropic flow, is quantified by the harmonic coefficients $v_n = \langle\cos[n(\varphi - \Psi_n)]\rangle$ of the Fourier expansion of the particle azimuthal angle (φ) relative to the collision symmetry planes Ψ_n [4]. The second harmonic coefficient, v_2 (also known as elliptic flow), is the largest coefficient in non-central heavy-ion collisions. At low p_{T} ($p_{\mathrm{T}} < 6\,\mathrm{GeV}/c$), heavy-flavour v_2 helps quantify the extent to which charm and beauty quarks participate in the collective expansion of the medium. At intermediate p_{T} v_2 also provides information on the impact of recombination mechanisms on the heavy-quark hadronisation. At high p_{T}, the v_2 of heavy-flavour hadrons constrains the path-length dependence of energy loss in the medium for heavy quarks [4].

2 Results and Conclusion

The nuclear modification factor R_{AA} of prompt Λ_c^+, D_s^+, and the average of D^0, D^+, and D^{*+} mesons is shown in Fig. 1 (left) for 0–10% central Pb–Pb collisions [8, 9]. The suppression of all charm-meson (baryon) species for $p_{\mathrm{T}} \gtrapprox 3(6)$ GeV/c is understood as being primarily due to the interaction of charm quarks with the QGP constituents, which modifies their momentum spectra. For the region $4 < p_{\mathrm{T}} < 8$ GeV/c there is a hint of a hierarchy, with $R_{\mathrm{AA}}(\mathrm{D}) < R_{\mathrm{AA}}(\mathrm{D}_s^+) < R_{\mathrm{AA}}(\Lambda_c^+)$, which could be understood as due to the effect of recombination and radial flow. At high-p_{T}, the effect on R_{AA} is attributed to the energy loss of heavy quarks in the QGP.

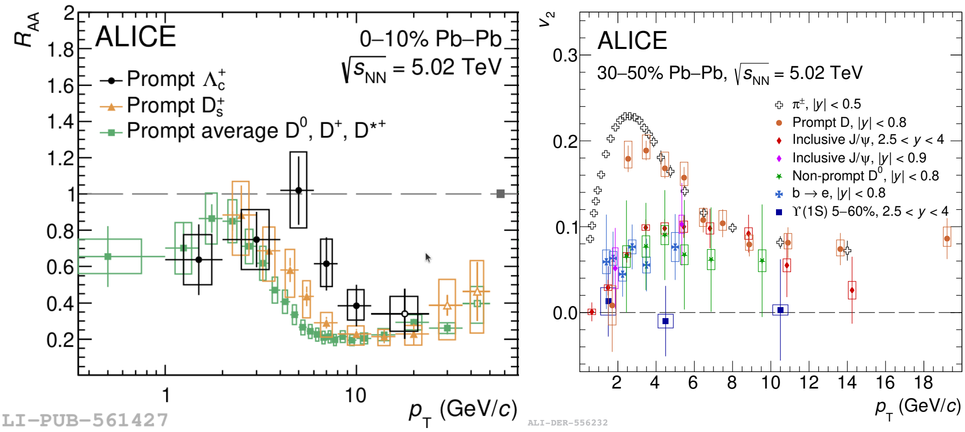

Figure 1. R_{AA} (left) for prompt Λ_c^+ baryon, D_s^+ meson, and average of D^0, D^+, D^{*+} mesons in 0–10% central Pb–Pb collisions and (right) elliptic-flow coefficient (v_2) of various particle species in 30–50% central Pb–Pb collisions [9].

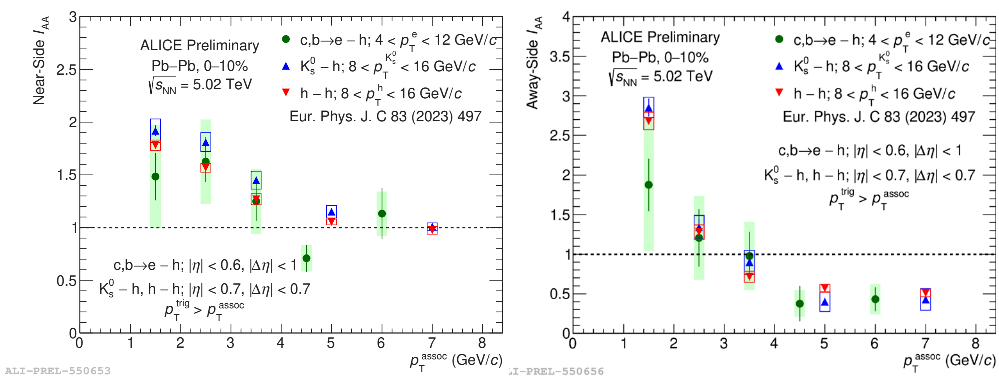

Figure 2. I_{AA} values for near- and away-side regions of two-particle azimuthal correlation distribution between heavy-flavour decay electrons and charged particles, for 0–10% central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, compared to I_{AA} values obtained considering K_s^0 and charged hadrons as trigger particles.

Figure 1 (right) shows the elliptic flow of various particle species. The observed positive elliptic flow (v_2) for open/hidden charm and beauty hadron decay electrons indicates the participation in the collective motion of charm quarks and, to a lesser extent, of beauty quarks. Notably, a mass hierarchy is observed up to 6 GeV/c, with $v_2(\Upsilon) \lesssim v_2(b \to e) \approx v_2(J/\psi) < v_2(D) \lesssim v_2(\pi)$. In the intermediate range $3 < p_T < 6$ GeV/c, hadronisation via coalescence with light quarks might contribute to v_2, as $v_2(D)$ is similar to $v_2(\pi)$ and larger than $v_2(J/\psi)$ in this p_T range. At higher p_T ($p_T > 8$ GeV/c), the path-length dependence of in-medium energy loss becomes relevant. In this regime, $v_2(J/\psi) \approx v_2(D) \approx v_2(\pi)$. The beauty quarks exhibit a lower degree of thermalisation compared to charm quarks as $v_2(\text{non-prompt } D^0) \approx v_2(b \to e) < v_2(\text{prompt } D^0)$. For Υ mesons, the elliptic flow is found to be compatible with zero, consistently with a scenario in which the v_2 of beauty quarks is small due to their incomplete thermalisation and the contribution of recombination is negligible for bottomonium. However, due to large uncertainties, no definitive conclusions can be drawn from the measured $v_2(\Upsilon)$.

To study the initial parton kinematics, fragmentation, and hadronisation of heavy quarks, ALICE measured the two-particle azimuthal correlations between heavy-flavour decay electrons and charged particles (HFe–h) [10–12] in pp and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. For this measurement, a heavy-flavour decay electron with $4 < p_{\mathrm{T}} < 12$ GeV/c is correlated with associated charged-particles in different p_{T} ranges from 1 to 7 GeV/c. The associated charged particle yield ratio (I_{AA}) of 0–10% Pb–Pb over pp collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV is shown in Fig. 2 for the near- and away-side correlation peak, and it is compared with the equivalent I_{AA} as measured by considering as trigger particles light-flavour particles ($\mathrm{K}^0_{\mathrm{s}}$ mesons or charged hadrons). In this comparison, HFe–h correlations are obtained by triggering on particles produced by quark fragmentation, so they allow to study jets initiated by quarks, whereas light-flavour correlations are mostly sensitive to jets initiated by gluons. A caveat to be considered for the comparison is related to the different trigger-particle p_{T}, and to a different average parton-to-particle p_{T} shift between the light- and heavy-flavour measurements. It is observed from Fig. 2 that I_{AA} of HFe–h correlations is consistent with the light-flavour I_{AA} within uncertainties, and it is generally consistent with unity within uncertainties. The measured I_{AA} may contain different physics processes that may impact on the results; these processes include gluon emission from quark fragmentation, jet-induced medium response at low p_{T}, and jet-quenching at the away-side due to a surface bias at high p_{T}. Performing further measurements of HFe–h correlations during the LHC Run3 with the upgraded ALICE detector and on the much larger data sample expected to be recorded will be crucial to reduce the uncertainties and to extract more stringent conclusions from the measurement.

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