Experimental overview on open-heavy flavours

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Abstract. Heavy flavours, i.e. charm and beauty quarks, are recognised as excellent probes of the colour-deconfined medium created in ultrarelativistic heavy–ion collisions, the quark–gluon plasma (QGP). In this document, the most recent measurements of heavy-flavour hadrons in heavy-ion collisions are summarised. Measurements of nuclear modification factors and angular anisotropies of open charm and beauty hadrons are reported to investigate the properties of the heavy-quark interactions in the QGP. A particular focus is given to the measurement of heavy-flavour baryons and hadrons with strange-quark content for the study of the hadronisation mechanisms in both heavy–ion and proton–proton collisions. Finally, the polarisation of the charm vector mesons D^{*+} and J/ψ in heavy–ion collisions is presented.

1 Introduction

The charm and beauty quarks are excellent probes of the colour-deconfined medium created in heavy-ion collisions, called quark–gluon plasma (QGP). Due to their large masses, they are produced in interactions with high momentum transfer, characterised by a timescale that is shorter than the production time of the QGP, and therefore they experience the full system evolution interacting with the medium constituents. At low transverse momentum (p_T), heavy quarks are expected to undergo a diffusion motion in the QGP via multiple elastic scatterings, which might lead them to reach thermal equilibrium in the QGP. High-p_T heavy quarks are instead expected to interact with the QGP constituents mainly via inelastic processes (gluon radiation) and can be therefore used to study the quark-mass and colour-charge dependence of the in-medium energy loss. These effects are typically investigated via the measurement of the nuclear modification factor R_{AA}, defined as the ratio of the p_T-differential yields measured in heavy–ion and proton–proton (pp) collisions normalised by the average number of binary nucleon–nucleon collisions, and angular anisotropies of heavy-flavour hadrons. In fact, in non-central nucleus–nucleus collisions the initial spatial anisotropy of the overlap region is converted via multiple interactions into an azimuthally anisotropic distribution in the momentum space of the produced particles. This anisotropy is characterised in terms 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 azimuthal angle of the symmetry plane for the nth-order harmonic.

2 Interactions of heavy quarks in the QGP

Figure 1 shows a compilation of R_{AA} measurements [1, 3, 5, 7] (left panel) and second-harmonic coefficient v_2 [2, 4, 6, 8] (called elliptic flow) of prompt D mesons and muons
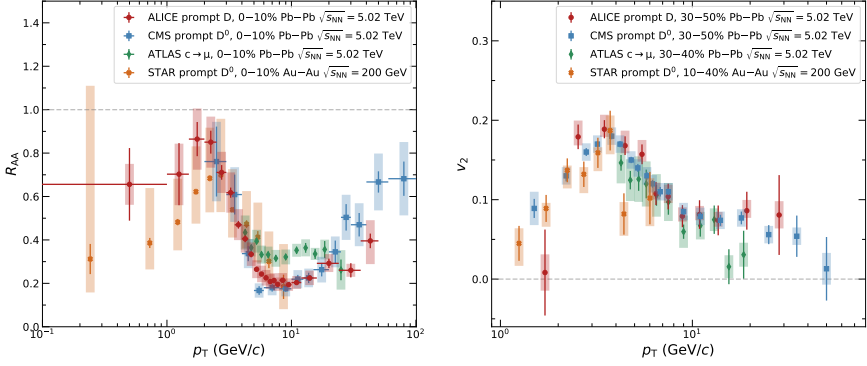
Figure 1. Collection of measured nuclear modification factors [1, 3, 5, 7] (left panel) and elliptic flow coefficients [2, 4, 6, 8] (right panel) of prompt D mesons and muons originating in charm-hadron decays in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and Au–Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

from charm-hadron decays in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and Au–Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. As a consequence of charm-quark energy loss, a strong suppression of the R_{AA} is observed at high p_T in central heavy–ion collisions, both at LHC and RHIC energies. A positive elliptic flow is also observed in midcentral heavy–ion collisions for charm hadrons, indicating that the charm quarks participate in the collective motions of the system. By comparing the measured D-meson R_{AA} and v_2 with theoretical predictions based on models that describe the heavy-quark transport in a hydrodynamically expanding QGP, the ALICE Collaboration estimated the thermalisation time (t_c) of the charm quark to be in the range $3 < t_c < 9$ fm/c, which is comparable with the QGP lifetime ($t_{QGP} \approx 10$ fm/c). Figure 2 shows the comparison of the v_2 measured for beauty hadrons (D mesons or leptons from beauty-hadron decays) [4, 9–11] with the one of charm hadrons (prompt D mesons, muons from charm-hadron decays) [2, 4, 6]. A non-zero elliptic flow is measured also for beauty hadrons, even if lower than that of charm hadrons. This observation is consistent with the fact that the beauty quark has a larger mass than the charm one, however it suggests a participation of the beauty quark in the collective motions of the system and its possible partial thermalisation in the QGP.
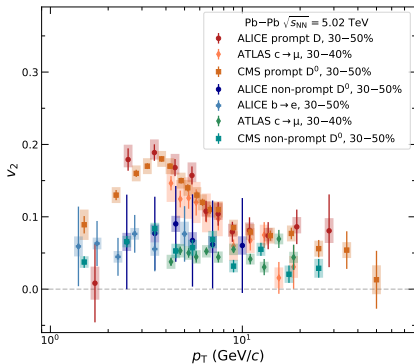

Figure 2. Collection of elliptic flow coefficients of charm and beauty hadrons measured by the ALICE [2, 9, 10], ATLAS [4], and CMS [6, 11] Collaborations in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.
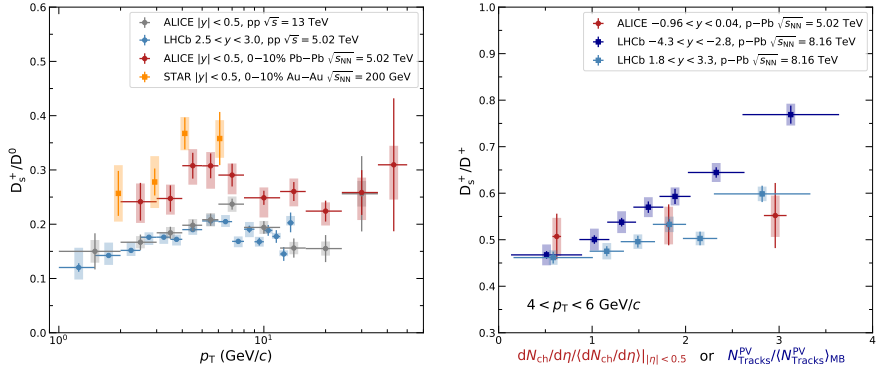
Figure 3. Left: D_s^+/D^0 ratio measured as a function of p_T in central (0–10%) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [14] and Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [15] at midrapidity, compared with the same quantity measured in pp collisions at $\sqrt{s} = 13$ TeV at mid [16] and forward [17] rapidity. Right: D_s^+/D^+ ratio in $4 < p_T < 6$ GeV/c measured as a function of the self normalised multiplicity in p–Pb collisions at midrapidity [18] and backward and forward rapidity [19].

3 Hadronisation of heavy quarks

3.1 Heavy-flavour mesons with strange-quark content

The hadronisation of heavy quarks is typically investigated via the measurement of the relative abundances of different heavy-hadron species. In particular, an enhancement of open heavy-flavour mesons with strange quark content relative to that of non-strange mesons is expected in nucleus–nucleus collisions at low and intermediate momenta as compared to pp collision, if the dominant hadronisation mechanism is the recombination of charm quarks with light quarks from the medium, due to the so-called strangeness enhancement [13]. The left panel of Fig. 3 shows the p_T-differential D_s^+/D^0 yield ratio measured at midrapidity in central Pb–Pb and Au–Au collisions at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 200$ GeV [14, 15], respectively, compared with the same quantity measured in pp collisions at $\sqrt{s} = 13$ TeV both at mid [16] and forward [17] rapidity. A larger D_s^+/D^0 ratio is observed in heavy–ion collisions for $p_T \lesssim 8$ GeV/c, as expected in case of hadronisation of charm quark via recombination. This behaviour is qualitatively described by theoretical models based on the charm-quark transport in the QGP that implement the strangeness enhancement and the hadronisation via recombination [14, 15]. The ALICE and LHCb Collaborations also investigated a possible D_s^+ enhancement in high-multiplicity p–Pb collisions, where a QGP formation is not expected. An increase of D_s^+/D^+ as a function of the self-normalised charged-particle multiplicity is observed by the LHCb collaboration at backward and forward rapidities [19], as reported in the right panel of Fig. 3. A steeper slope is measured at backward rapidity, probably due to the larger absolute average charged-particle multiplicity. The measurement of ALICE at midrapidity [18] does not show any significant increase, however it is compatible within uncertainties with the D_s^+/D^+ ratio measured at forward rapidity.

3.2 Heavy-flavour baryons

The production of heavy-flavour baryons, such as Λ_c^+ and Λ_b^0, relative to that of mesons was found to be significantly enhanced in pp collisions compared to e^+e^- and ep collisions [20, 25, 26]. This enhancement can be explained by different models either based on
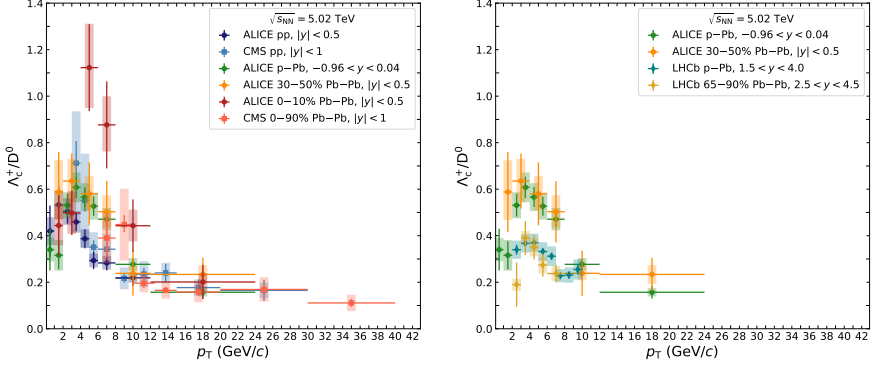
Figure 4. Left: p_T-differential Λ_c^+/D^0 ratio measured at midrapidity in pp, p–Pb, and Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [20–22]. Right: p_T-differential Λ_c^+/D^0 ratio measured at mid [20, 22] and forward [23, 24] rapidity in p–Pb and non-central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.

the Lund string fragmentation model when including colour reconnection beyond the leading colour approximation [27], statistical hadronisation with the inclusion of yet unobserved excited baryon states predicted by the relativistic quark model [28], or the hadronisation via recombination [29]. A further modification of the p_T-differential Λ_c^+/D^0 yield ratio was observed by the ALICE and CMS Collaborations in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, as reported in the right panel of Fig. 4. In particular, an increase of the Λ_c^+/D^0 at intermediate p_T was observed to be dependent on the collision centrality. This can arise both from the hadronisation via recombination, or from the collective radial expansion of the system. A similar enhancement was observed by LHCb at forward rapidity, even if quantitatively smaller (see right panel of Fig. 4). A possible modification of the baryon-to-meson production ratio was investigated also as a function of charged-particle multiplicity in pp and p–Pb collisions. The left panel of Fig. 5 shows the p_T-differential Λ_c^+/D^0 ratio in difference
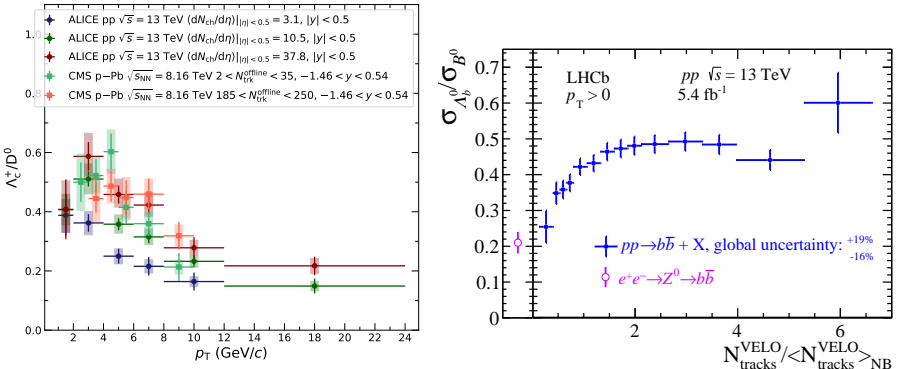

Figure 5. Left: p_T-differential Λ_c^+/D^0 ratio measured for different classes of charged-particle multiplicity in pp collisions at $\sqrt{s}$ = 13 TeV [30] and p–Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV [31] at midrapidity. Right: p_T-integrated Λ_b^0/B^0 ratio as a function of the self-normalised charged-particle multiplicity at forward rapidity in pp collisions at $\sqrt{s}$ = 13 TeV [32].
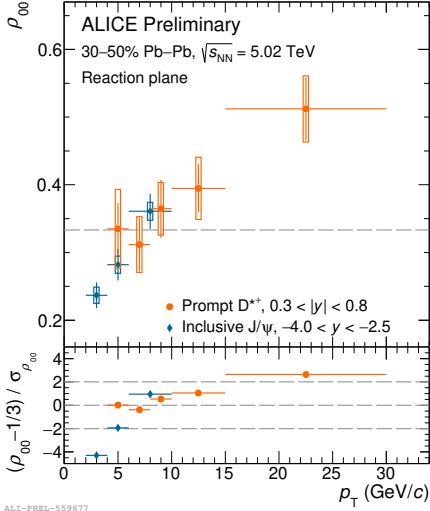
Figure 6. p_{T}-dependent ρ_{00} of prompt D^{*+} with $0.3 < y < 0.4$ and inclusive J/ψ mesons with $-4.0 < y < -2.5$ measured with respect to the axis orthogonal to the reaction plane in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The bottom panel represents the deviation from the hypothesis of no spin alignment ($\rho_{00} = 1/3$) in terms of number of standard deviations.

classes of charged-particle multiplicity in pp collisions and p–Pb collisions [30, 31]. No dependency on the multiplicity was observed in p–Pb collisions, while a modification of the p_{T}-differential distribution is found in pp collisions, especially in very low-multiplicity pp events. However, when considering the p_{T}-integrated $\Lambda_{\mathrm{c}}^{+}/\mathrm{D}^{0}$ ratios, no significant dependence was observed [30]. A dependence on the charged-particle multiplicity was instead observed for the $\Lambda_{\mathrm{b}}^{0}/\mathrm{B}^{0}$ ratio measured at forward rapidity by the LHCb Collaboration [32], as shown in the right panel of Fig. 5. In this case, the measurement at very low charged-particle multiplicity is compatible within uncertainties with the measurement performed in $\mathrm{e}^{+}\mathrm{e}^{-}$ collisions.

4 Polarisation of heavy quarks in heavy–ion collisions

The initial stages of heavy–ion collisions, with non-zero impact parameter, are expected to be characterised by a large orbital angular momentum [33] and a strong magnetic field [34]. The direction of the angular momentum and the magnetic field in such collisions are perpendicular to the reaction plane (defined by the beam axis and impact parameter of the colliding nuclei). The magnetic field is expected to reach a maximum of about 10^{16} T and decrease steeply in time. In this scenario, heavy quarks, which are produced in the very early times of the collision are expected to be sensitive to the large initial magnetic field in addition to the angular momentum. In these conditions, charm quarks can be polarised and the polarisation is expected to be further transferred to the final-state hadrons during hadronisation. It is predicted to be different in the case of hadronisation in vacuum, or recombination with light quarks from the deconfined medium.

The possible polarisation of spin-1 charm vector mesons can be studied via the measurement of the diagonal spin density matrix element ρ_{00} of the vector meson, which provides information about the spin alignment of the vector meson along the quantisation direction (in this case, the direction orthogonal to the reaction plane). In absence of polarisation, the spin of particles is homogeneously distributed and therefore all spin states are expected to be equally probable, implying $\rho_{00} = 1/3$. Figure 6 shows the p_{T}-differential ρ_{00} parameter of prompt D^{*+} mesons measured in $0.3 < |y| < 0.8$ compared to the one of inclusive J/ψ mesons with $-4.0 < y < -2.5$ [35]. On the one hand, the ρ_{00} of J/ψ is lower than $1/3$ with a

significance of about 4σ, being σ the standard deviation. This is compatible with the effect of polarisation due to the orbital angular momentum and the hadronisation via recombination. On the other hand, the D^{*+}-meson ρ_{00} is larger than 1/3 for $p_T > 15$ GeV/c with a significance of about 2.7σ, suggesting a polarisation of the charm quark transferred to the hadron through hadronisation via vacuum-like fragmentation.

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