Overview of open heavy-flavour and quarkonia measurements with ALICE

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Abstract.
Heavy-flavour hadrons, i.e. hadrons containing charm or beauty quarks, are effective probes to test perturbative-QCD (pQCD) calculations, to investigate the different hadronisation mechanisms, and to study the quark–gluon plasma (QGP) produced in relativistic heavy-ion collisions at the LHC. Measurements performed in pp and p–Pb collisions have recently revealed unexpected features not in line with the expectations based on previous measurements from e^+e^- and ep collisions, showing that charm fragmentation fractions are not universal. The investigation of initial-state effects such as shadowing in the collision of a proton with a heavy nucleus is also performed. Measurements of open heavy-flavour and quarkonia production in Pb–Pb collisions allow for testing the mechanisms of heavy-quark transport, energy loss, and coalescence effects during the hadronisation in the presence of a QCD medium. In this contribution, the most recent results on open heavy-flavour and quarkonia production in pp, p–Pb, and Pb–Pb collisions obtained by the ALICE Collaboration are discussed.

1 Introduction

The study of heavy-flavour hadron production in proton–proton (pp) collisions provides an important test for quantum chromodynamics (QCD) calculations. Heavy-flavour hadron production is usually computed with pQCD calculations as the convolution of the parton distribution functions (PDFs) of the incoming protons, the partonic cross section and the fragmentation functions that describe the transition from charm quarks into charm hadrons. The latter are typically parametrised from measurements performed in e^+e^- or ep collisions, under the assumption that the hadronisation of charm quarks into charm hadrons is a universal process independent of the colliding system. In the presence of a quark–gluon plasma (QGP), the strongly-interacting colour-deconfined state of matter created in ultra-relativistic heavy-ion collisions, an additional hadronisation mechanism, alternative to the in-vacuum string fragmentation, is considered. In this mechanism, known as coalescence, light quarks from the medium coalesce with the heavy quark to form a meson or baryon. By studying heavy-flavour production in nucleus–nucleus collisions, the relevance of coalescence in the medium for heavy quarks can be probed. Models that include hadronisation via coalescence for charm quarks qualitatively describe D-meson measurements in Pb–Pb collisions at the LHC. The possible occurrence of coalescence in pp collisions is one of the topics of investigation to provide a better description of heavy-baryon production.

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2 Charm production and fragmentation in pp collisions

The large data samples collected during Run 2 of the LHC at $\sqrt{s}$ = 5.02 and 13 TeV allowed ALICE to measure the vast majority of charm quarks produced at midrapidity in the proton-proton (pp) collisions by reconstructing the decays of the ground-state charm hadrons down to very low transverse momenta (p_T), i.e. all charm-meson species (D^0, D^+, D_s^+ [1]) and charm-baryon species (Λ_c^+ [2], $\Xi_c^{0,+}$ [3, 4] and Ω_c^0). The ratios of different hadron species as function of the transverse momentum p_T help to study heavy flavour hadronisation. Both the prompt and non-prompt (coming from B-hadron decays) meson-to-meson yield ratios of D mesons are compatible with pQCD calculations [5–7] using fragmentation fractions extracted from e$^+$e$^-$ collision data. Such calculations, however, significantly underpredict all the measured baryon-to-meson yield ratios, indicating that the fragmentation fractions are not universal. The Λ_c^+/D^0 ratio in pp collisions, reported in the left panel of Fig. 1, shows a clear decrease with increasing p_T and it is better described by models with an extension of colour reconnection beyond the leading colour approximation [8], models relying on hadronisation via coalescence [9, 10], or statistical hadronisation models with an augmented set of baryon states predicted by the relativistic quark model (RQM) [11]. Measurements of the heavier charm-strange baryons $\Xi_c^{0,+}$ and Ω_c^0 pose further important constraints to charm-quark hadronisation models. For the Ω_c^0 the absolute branching ratio (BR) of the decay channel $\Omega_c^0 \to \Omega^\pm \pi^\mp$ is not measured, hence only the BR multiplied with the cross section is reported. The yield ratios of these charm baryons to the D^0-meson one are presented in the middle and right panel of Fig. 1, and compared to predictions from the same models that describe the Λ_c^+/D^0 ratio. For the $\Xi_c^{0,+}/D^0$ and BR$\times\Omega_c^0/D^0$ all calculations, except the Catania model [10], which gets closer to the data and relies on hadronisation via coalescence, are underpredicting the measured ratios, hinting to an even stronger enhancement for charm-strange baryons. The predictions tuned on measurements in e$^+$e$^-$ collisions underestimate all three baryon-to-meson yield ratios [12], providing further evidence that different processes are involved in charm hadronisation for elementary and hadronic collisions. These new charm-baryon measurements provide important constraints to models of charm-quark hadronisation in pp collisions, being, in particular, sensitive to the description of charm-strange baryon production in the colour reconnection approach, and to the possible contribution of coalescence to charm-quark hadronisation in pp collisions.
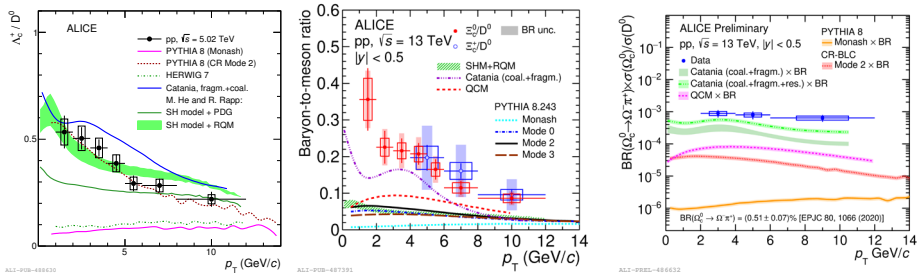

Figure 1. Left panel: The Λ_c^+/D^0 ratio measured in pp collisions at $\sqrt{s}$ = 5.02 TeV [2]. Middle panel: The Ξ_c^0/D^0 and Ξ_c^+/D^0 ratios as a function of p_T in pp collisions at $\sqrt{s}$ = 13 TeV [4]. Right panel: The BR $\times \Omega_c^0/D^0$ as a function of p_T in pp collisions at $\sqrt{s}$ = 13 TeV. All yield ratios are compared to theoretical model calculations.

The charm fragmentation fractions, $f(\text{c} \to \text{H}_c)$ (shown in the left panel of Fig. 2), which represent the probabilities of a charm quark to hadronise into a given charm hadron, were

measured for the first time including baryon species at midrapidity in pp collisions at the
LHC and are observed to be different from the ones measured in e^+e^- and ep collisions,
showing evidence that the assumption of universality (collision-system independence) of
charm-to-hadron fragmentation is not valid [13]. The charm quarks hadronize into baryons
almost 40% of the time, which is four times more often than what was measured at col-
liders with electron beams. The fragmentation fraction for the Ξ_c^0 was measured for the
first time in any collision system. The $c\bar{c}$ production cross section per unit of rapidity at
midrapidity ($d\sigma^{c\bar{c}}/dy|_{|y|<0.5}$) was calculated by summing the cross sections of all measured
ground-state charm hadrons (D^0, D^+, D_s^+, Λ_c^+, and Ξ_c^0 and their charge conjugates). The
contribution of the Ξ_c^0 was multiplied by a factor of two, in order to account for the con-
tribution of the Ξ_c^+. The resulting $c\bar{c}$ cross section per unit of rapidity at midrapidity is
$d\sigma^{c\bar{c}}/dy|_{|y|<0.5} = 1165 \pm 44(\text{stat})^{+134}_{-101}(\text{syst})$ μb. This measurement was done for the first time
in hadronic collisions at the LHC including the charm baryon states [13]. The newly mea-
sured fragmentation fractions at midrapidity in pp collisions at $\sqrt{s} = 5.02$ TeV allowed the
recomputation of the charm production cross sections per unit of rapidity at midrapidity in
pp collisions at $\sqrt{s} = 2.76$ and 7 TeV. The charm cross sections were obtained by scaling
the p_T-integrated D^0-meson cross section for the relative fragmentation fraction of a charm
quark into a D^0 meson. The updated $c\bar{c}$ cross sections at $\sqrt{s} = 2.76$ and 7 TeV are about 40%
higher than the previously published results, reflecting the differences in the fragmentation
into charm baryons with respect to those measured in e^+e^- and pp collisions. In the right
panel of Fig. 2, the measured $c\bar{c}$ production cross sections per unit of rapidity at midrapidity
are compared with FONLL [5] and NNLO [14, 15] predictions as a function of the collision
energy. The $c\bar{c}$ cross sections measured at midrapidity at the LHC lies at the upper edge of
the theoretical pQCD calculations. The measurements described above not only provide con-
straints to pQCD calculations but are also important as references for the investigation of the
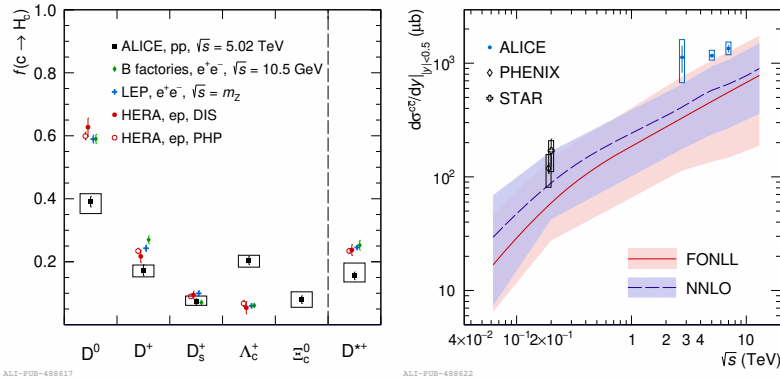charm-quark interaction with the medium created in heavy-ion collisions.

Figure 2. Left panel: Charm-quark fragmentation fractions into charm hadrons measured in pp colli-
sions at $\sqrt{s} = 5.02$ TeV in comparison with experimental measurements performed in e^+e^- and in ep
collisions [13]. Right panel: Charm production cross section at midrapidity per unit of rapidity as a
function of the collision energy. The FONLL and NNLO calculations are also shown [5, 14, 15].

3 Radial flow, hadronisation, and shadowing in p–Pb collisions

Additional investigations on the charm hadronisation measuring charm baryon production are
carried out in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [2]. The Λ_c^+/D^0 yield ratio as a function of

p_T in pp and p–Pb collisions is shown in the left panel of Fig. 3. For the first time at the LHC the Λ_c^+ has been measured down to $p_T = 0$. A clear decreasing trend with increasing p_T is seen in p–Pb collisions for $p_T > 2$ GeV/c. The ratios measured in pp and p–Pb collisions are qualitatively consistent with each other, although a larger Λ_c^+/D^0 ratio in $3 < p_T < 8$ GeV/c and a lower ratio in $1 < p_T < 2$ GeV/c are measured in p–Pb collisions with respect to pp collisions suggesting the presence of possible radial flow effect or of a further modification of the hadronisation mechanism in p–Pb collisions. In order to further investigate these effects and to study also cold nuclear matter effects (CNM), the nuclear modification factor (R_{pPb}) was measured (right panel of Fig. 3). For $p_T < 2$ GeV/c an R_{pPb} lower than unity is measured with a significance of 2.6σ, which provides a hint for a suppression of the yield in p–Pb with respect to pp collisions [2]. The suppression is described by model calculations that include modification of the parton distribution function in Pb nuclei (shadowing). For $p_T > 2$ GeV/c the R_{pPb} is systematically above unity, with a maximum deviation from $R_{pPb} = 1$ reaching 2.2σ for $5 < p_T < 6$ GeV/c. The indication that Λ_c^+ production is suppressed at low p_T and enhanced at mid p_T in p–Pb collisions with respect to pp collisions could also be seen as possible radial flow effects present in p–Pb collisions. The current precision of the measurement is not sufficient to draw conclusions on the role of different CNM effects and the possible presence of final-state effects, like the radial flow.
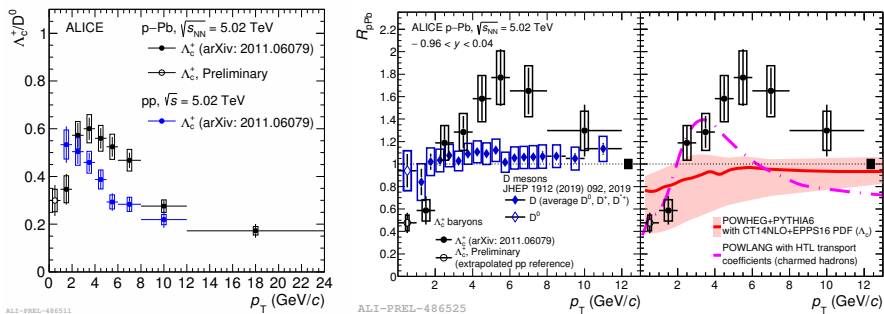

Figure 3. Left panel: The Λ_c^+/D^0 yield ratio as a function of p_T measured in pp and in p–Pb collisions $\sqrt{s_{NN}} = 5.02$ TeV. Right panel: R_{pPb} of prompt Λ_c^+ baryons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of p_T compared to D-meson R_{pPb} (left) and to model expectations (right) [2].

Recent measurements of inclusive, prompt, and non-prompt J/ψ production in p–Pb collisions at a nucleon–nucleon centre-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV provide additional information on the role of CNM effects [16]. The J/ψ mesons are reconstructed in the di-electron decay channel at midrapidity down to a transverse momentum $p_T = 0$. Non-prompt J/ψ mesons, which originate from the decay of beauty hadrons, are separated from promptly produced J/ψ on a statistical basis for $p_T > 1$ GeV/c. In the left panel of Fig. 4, the R_{pPb} of prompt J/ψ is reported as a function of p_T in comparison with ATLAS results [17]. Given also the relatively small fraction of J/ψ from b-hadron decays for $p_T < 14$ GeV/c, the R_{pPb} of prompt J/ψ is comparable with that of the inclusive J/ψ. As shown in the left panel of Fig. 4, both trends indicate that the suppression observed at midrapidity is a low-p_T effect, concentrated at $p_T < 3$ GeV/c. The measurements are compared with results from model predictions which embed different CNM effects into prompt J/ψ production [18]. A calculation including the effects of coherent energy loss [19], with or without the introduction of nuclear shadowing effects according to EPS09 nPDF, provides a fairly good description of the measurements. The measured value of the p_T-integrated R_{pPb} of non-prompt J/ψ (shown in the

right panel of Fig. 4) is 0.79 ± 0.11 (stat.)± 0.13 (syst.)$^{+0.01}_{-0.02}$(extr.), suggesting the presence of nuclear effects also for the non-prompt component. Within uncertainties, the measurements are compatible with those of the LHCb collaboration [20] at both forward and backward rapidity. All charmonium measurements reported here are in agreement with the mild degree of suppression predicted by models employing nPDFs.
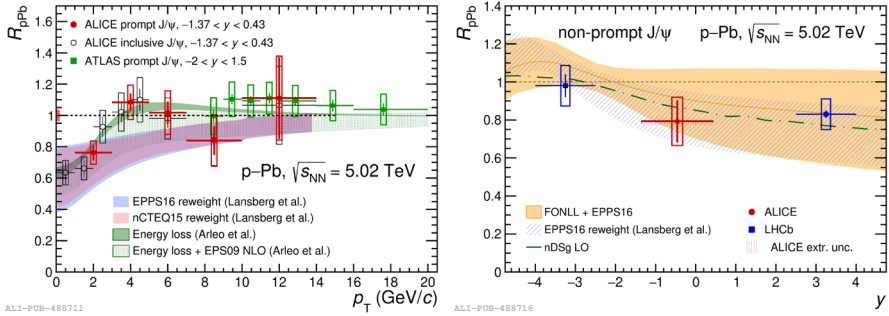

Figure 4. Left panel: R_{pPb} of prompt J/ψ as a function of p_T along with that of inclusive J/ψ at midrapidity. Right panel: Nuclear modification factor R_{pPb} of non-prompt J/ψ as a function of rapidity [16].

4 Charm and beauty production in heavy-ion collisions

The Λ_c^+/D^0 yield ratio in central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV extends the study of the hadronisation properties of charm baryons to the extreme conditions realized in central Pb–Pb collisions. This ratio is larger than the one measured in pp collisions in the interval 4 < p_T < 8 GeV/c. Figure 5 shows the p_T-differential Λ_c^+/D^0 yield ratio measured in central collisions compared to three different theoretical predictions: Catania [21], TAMU [22], and the GSI/Hd+BW statistical hadronisation model [23]. Theoretical calculations that model the charm-quark transport in the QGP and include hadronisation via both coalescence and fragmentation processes describe the data.

The production of non-prompt D^0 and D_s^+ mesons from b-hadron decays was measured at midrapidity ($|y| < 0.5$) in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The R_{AA} of non-prompt D_s^+ is measured in the range 2 < p_T < 36 GeV/c. A significant suppression up to a factor of about three is observed for $p_T > 5$ GeV/c in the 10% most central collisions. The data are described by models that include both collisional and radiative processes in the calculation of beauty quark in-medium energy loss and quark coalescence as a hadronisation mechanism. A higher R_{AA} for non-prompt D_s^+ mesons than for prompt D_s^+ mesons is measured at $p_T > 3$ GeV/c. This is expected by models in which beauty quarks lose less energy than charm quarks in the QGP medium because of their larger mass. In the right panel of Fig. 5, the R_{AA} of non-prompt D_s^+ mesons was divided by that of non-prompt D^0 mesons and compared with the same ratio from the TAMU model [22]. The R_{AA} for non-prompt D_s^+ mesons is expected to be higher than the one of non-prompt D^0 mesons due to the enhanced production of B_s^0 mesons in heavy-ion collisions in case of beauty-quark hadronisation via coalescence. The data are in agreement with the TAMU predictions within the uncertainties.

Further studies on the evolution of heavy-flavour hadronisation across collision systems, including studies as a function of the event multiplicity for rare baryons, will be done in future LHC runs.
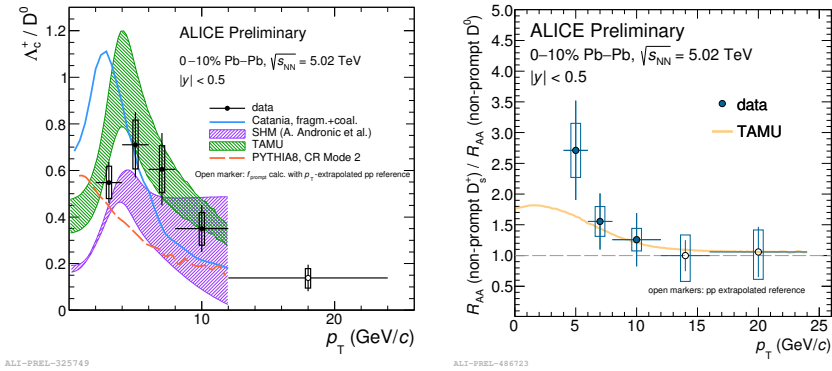
Figure 5. Left panel: The p_T-differential Λ_c^+/D^0 yield ratio in pp collisions and in the 10% most central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compared to the predictions of different theoretical calculations. Right panel: Ratio between the R_{AA} of non-prompt D_s^+ mesons and non-prompt D^0 mesons in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV for the 0–10% centrality class compared to the TAMU model [22].

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