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Hadronisation of heavy quarks in small systems with ALICE at the LHC

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Summary. — Production measurements of charm hadrons, particularly the ratios of different hadron species as a function of the transverse momentum, are important to investigate charm-quark hadronisation. Recent observations of enhanced baryon-to-meson production yield ratios in hadronic collisions, with respect to the same measurements performed in e^+e^- or $e^\pm p$ collisions, suggest that the charm fragmentation fractions are not universal and depend on the collision system. Moreover, measurements of charm baryons in p–Pb collisions are performed to examine possible modifications of their production due to the presence of cold nuclear matter effects. In these proceedings, the most recent results on charm hadron production in pp and p–Pb collisions obtained by the ALICE Collaboration are discussed.

1. – Introduction

Measurements of the production of heavy-flavour hadrons in high-energy hadronic collisions provide important tests for calculations based on perturbative quantum chromodynamics (pQCD). Typically, heavy-flavour hadron production can be calculated using the factorisation approach as a convolution of three factors: the Parton Distribution Functions (PDFs), the hard-scattering cross-section at the partonic level, and the fragmentation functions of the produced heavy quarks into given hadron species. Traditionally, the latter is assumed to be universal among collision systems. The measurements of the ratios of the production yields of different hadron species are used to probe hadronisation effects because the PDFs and partonic interaction cross-sections are common to all charm-hadron species. The study of charm-baryon production in p–Pb collisions allows us to study the initial-state and Cold Nuclear Matter (CNM) effects. This is important to disentangle these effects from QGP ones in Pb–Pb collisions. In addition, production measurements of charm baryons in p–Pb collisions permit to investigate if the characteristics of the hadronisation process are modified from pp to p–Pb collisions.

2. – Charm-hadron production and fragmentation fractions

Recently, the ALICE Collaboration reported precise measurements of D^0, D^+, D_s^+, D^{*+} charm mesons [1] and Λ_c^+, $\Sigma_\mathrm{c}^{0,++}$, $\Xi_\mathrm{c}^{0,+}$, Ω_c^0 charm baryons [2-6]. The meson-to-meson yield ratios, both for the prompt and non-prompt (coming from beauty-hadron decays) components of the D-meson production, are well described by pQCD calculations using fragmentation functions derived from $\mathrm{e}^+\mathrm{e}^-$ collision data. Measurements of charm-meson production cross-sections in pp and p–Pb collisions in ALICE [1, 7, 8] show that the $\mathrm{D}^+/\mathrm{D}^0$ and $\mathrm{D}_\mathrm{s}^+/\mathrm{D}^0$ ratios are, within uncertainties, independent of the transverse momentum (p_T), and are consistent with results from $\mathrm{e}^+\mathrm{e}^-$ and $\mathrm{e}^\pm\mathrm{p}$ collisions. The ratios are also well described by the PYTHIA 8 event generator using the Monash tune [9], which adopts hadronisation fractions based on $\mathrm{e}^+\mathrm{e}^-$ collisions. However, the charm baryon-to-meson ratios $\Lambda_\mathrm{c}^+/\mathrm{D}^0$ [2], $\Sigma_\mathrm{c}^{0,++}/\mathrm{D}^0$ [3], $\Xi_\mathrm{c}^{0,+}/\mathrm{D}^0$ [4, 5], and $\Omega_\mathrm{c}^0/\mathrm{D}^0$ [6] measured at midrapidity at the LHC show significant deviations from the values measured in $\mathrm{e}^+\mathrm{e}^-$ collisions. The top left panel of fig. 1 shows the $\Lambda_\mathrm{c}^+/\mathrm{D}^0$ yield ratio as a function of p_T compared with model calculations implementing different hadronisation processes. This first measurement of the prompt Λ_c^+ production down to $p_\mathrm{T} = 0$ probes a very important range to investigate hadronisation, as a substantial fraction of the total charm cross-section is contained at $p_\mathrm{T} < 1\,\mathrm{GeV}/c$. At low p_T, the ratio is much larger than the PYTHIA 8 Monash predicted by string fragmentation models tuned on $\mathrm{e}^+\mathrm{e}^-$ data. The ratio is qualitatively described by a tune of PYTHIA 8 with colour reconnection beyond leading colour approximation in which junction topologies increase baryon production [10], by Catania [11] and Quark Combination Model (QCM) [12], which implement hadronisation via coalescence, and by the SHM + RQM [13] Statistical Hadronisation Model with feed-down from an augmented set of higher-mass charm baryon states predicted by the Relativistic Quark Model (RQM). A similar enhancement with respect to $\mathrm{e}^+\mathrm{e}^-$ collisions is observed for the $\Sigma_\mathrm{c}^{0,++}/\mathrm{D}^0$ yield ratios shown in the top right panel of fig. 1, indicating that the enhancement of $\Lambda_\mathrm{c}^+/\mathrm{D}^0$ can be partially explained by the $\Sigma_\mathrm{c}^{0,++}$ feed-down. Furthermore, for the heavier charm-strange baryon states $\Xi_\mathrm{c}^{0,+}$ and Ω_c^0, the enhancement is even larger, as shown in the bottom panels of fig. 1. The Catania model, which assumes that the charm-quark hadronisation processes happen via both fragmentation and coalescence, is the one that better captures the strange-charm baryon enhancement.

The charm fragmentation fractions, $f(\mathrm{c} \rightarrow \mathrm{H_c})$ shown in the left panel of fig. 2, represent the likelihood for a charm quark to hadronise into a given charm-hadron species. The charm fragmentation fractions measured in pp and p–Pb collisions are compatible, suggesting that the hadronisation mechanisms are not modified from pp to p–Pb collisions. In the right panel of fig. 2, the total $\mathrm{c\bar{c}}$ production cross-section per unit of rapidity at midrapidity ($\mathrm{d}\sigma^{\mathrm{c\bar{c}}}/\mathrm{d}y|_{|y|<0.5}$) is calculated by summing the p_T-integrated cross-sections of the measured charm hadrons (D^0, D^+, D_s^+, Λ_c^+, $\Xi_\mathrm{c}^{0,+}$ and their charge conjugates). The resulting $\mathrm{c\bar{c}}$ production cross-section per unit of rapidity at midrapidity in p–Pb collisions after scaling by the Pb ion mass number is shown as well. It is compatible with the one in pp collisions. The $\mathrm{c\bar{c}}$ cross-sections measured at midrapidity in pp and p–Pb collisions at the LHC lie at the upper edge of the theoretical pQCD calculations.

3. – Cold Nuclear Matter (CNM) effects

The CNM effects are studied via the measurements of the nuclear modification factor $R_\mathrm{pPb} = \frac{\mathrm{d}\sigma_\mathrm{pPb}/\mathrm{d}p_\mathrm{T}}{A\cdot\mathrm{d}\sigma_\mathrm{pp}/\mathrm{d}p_\mathrm{T}}$, where $\mathrm{d}\sigma_{\mathrm{pPb(pp)}}/\mathrm{d}p_\mathrm{T}$ are the p_T-differential cross-section in p–Pb

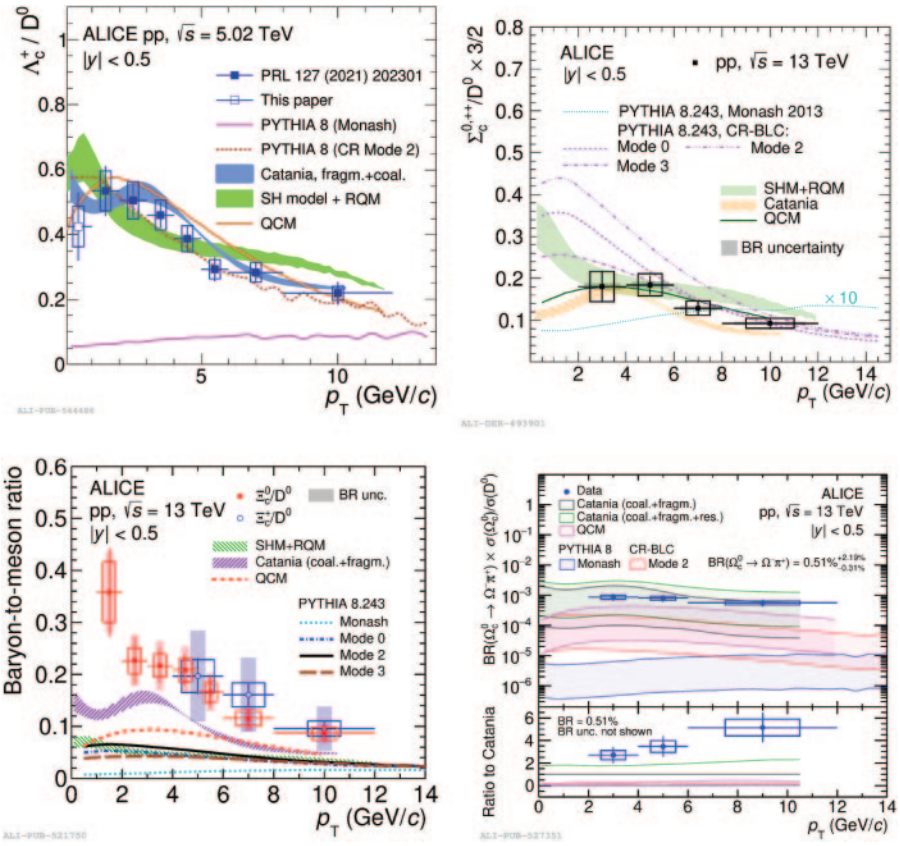

Fig. 1. – Baryon-to-meson yield ratios as a function of p_{T} for various charm baryons compared with theoretical models. Top left: prompt $\Lambda_{\mathrm{c}}^{+}/\mathrm{D}^{0}$ yield ratio in pp collisions at $\sqrt{s} = 5.02$ TeV [2]. Top right: prompt $\Sigma_{\mathrm{c}}^{0,++}/\mathrm{D}^{0}$ yield ratio in pp collisions at $\sqrt{s} = 13$ TeV [3]. Bottom left: prompt $\Xi_{\mathrm{c}}^{0,+}/\mathrm{D}^{0}$ yield ratio in pp collisions at $\sqrt{s} = 13$ TeV [4]. Bottom right: $\Omega_{\mathrm{c}}^{0}/\mathrm{D}^{0}$ yield ratio times branching fraction of the $\Omega_{\mathrm{c}}^{0} \to \Omega^{-}\pi^{+}$ decay channel [14] in pp collisions at $\sqrt{s} = 13$ TeV [6].

(pp) collisions at a given center-of-mass energy and A is the nuclear mass number. If there are no nuclear effects affecting particle production, the nuclear modification factor is expected to be unity. The following new results provide great insights into it.

The left panel of fig. 3 shows the p_{T}-integrated non-prompt D^{0} R_{pPb}, which is observed to be close to unity, indicating that the net result of CNM effects possibly influencing beauty-quark production at midrapidity is moderate. The non-prompt D^{0} R_{pPb} agrees within uncertainties with the R_{pPb} of non-prompt J/ψ measured by ALICE. Within uncertainties, the ALICE data at midrapidity agree with the B^{+} and non-prompt J/ψ R_{pPb} measured at backward and forward rapidity by LHCb. The experimental measurements are compatible with nuclear PDF (nPDF) model calculations. In the right panel, measurements of the R_{pPb} of Ξ_{c}^{0} and Λ_{c}^{+} show p_{T}-dependent nuclear modifications. The R_{pPb} of Λ_{c}^{+} is lower than unity for p_{T} below 2 GeV/c, and higher than unity at $p_{\mathrm{T}} > 2$ GeV/c. The Ξ_{c}^{0} and Λ_{c}^{+} R_{pPb} are similar.

These results are compared with predictions using POWHEG+PYTHIA 6 [23] and

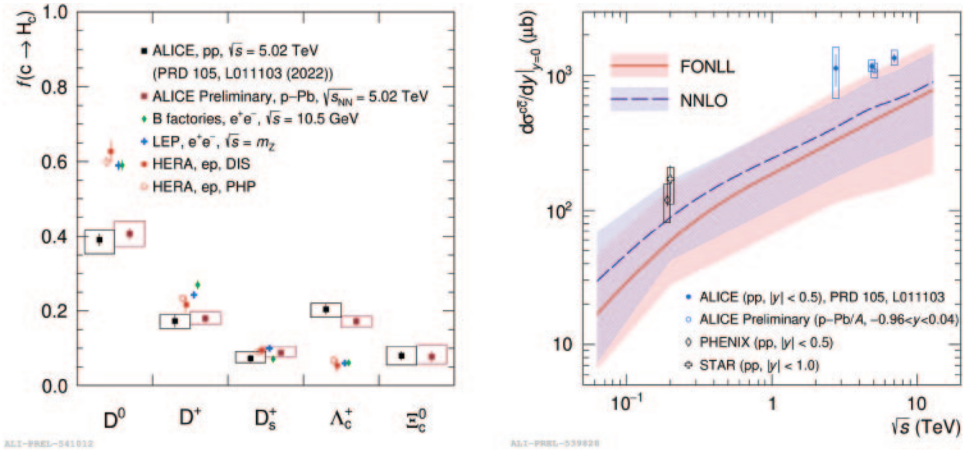

Fig. 2. – Left: charm-quark fragmentation fractions measured in pp and p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV compared with experimental measurements performed in e^+e^- collisions at LEP and B factories, and in $e^{\pm}p$ at HERA. Right: total charm production cross-section at midrapidity per unit of rapidity as a function of the collision energy at the LHC [15, 16] and RHIC [17] compared with FONLL [18] and NNLO calculations [19].

EPPS16 nPDF [24]. The calculation predicts a $R_{\rm pPb}$ consistent with unity within uncertainty, with a central value below unity at all $p_{\rm T}$. The measurements are also compared with the QCM model [25] which agrees with the $R_{\rm pPb}$ of $\Xi_{\rm c}^0$ but deviates from the $\Lambda_{\rm c}^+$ data for $p_{\rm T} > 4\,{\rm GeV}/c$.

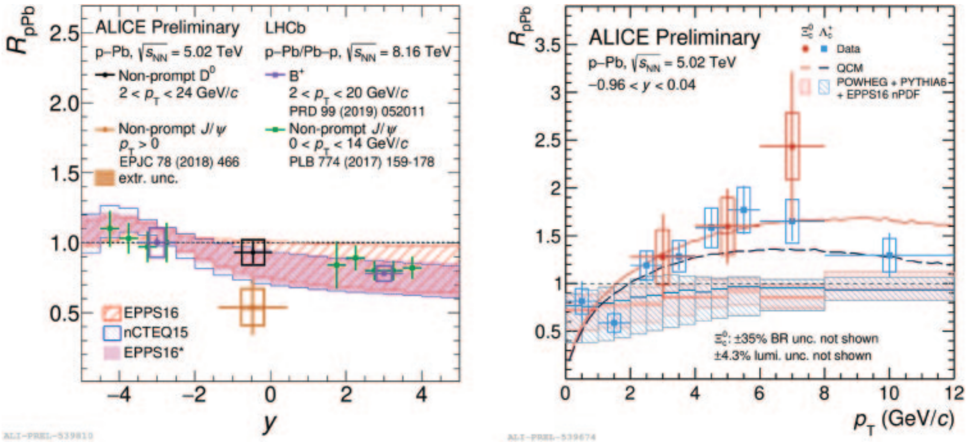

Fig. 3. – Left: nuclear modification factor $R_{\rm pPb}$ of non-prompt D^0 as a function of rapidity measured by ALICE, compared with J/ψ and B^+ measurements by LHCb and non-prompt J/ψ measurement by ALICE [20-22]. Right: nuclear modification factor $R_{\rm pPb}$ of prompt $\Xi_{\rm c}^0$ and $\Lambda_{\rm c}^+$ baryons in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV as a function of $p_{\rm T}$, compared with model calculations [23-25]. The error bars and empty boxes represent the statistical and systematic uncertainties, respectively.

4. – Conclusion

Recent measurements of charm-baryon production in pp and p–Pb collisions give stringent constraints to theoretical calculations. They indicate that the production of baryon states relative to that of meson states is enhanced in hadronic collisions with respect to electron-positron collisions, suggesting that the hadronisation mechanisms depend on the collision system. In particular, "in-vacuum" string fragmentation cannot alone describe the heavy-flavour baryon measurements in hadronic collisions. Additionally, the studies of R_{pPb} provide important inputs to constrain CNM effects. More precise measurements are expected to be performed during Runs 3 and 4 of the LHC.

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