Charm-baryon enhancement and charm fragmentation fractions in small systems measured with ALICE

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Abstract. Recent measurements of charm-baryon production at midrapidity by the ALICE collaboration show baryon-to-meson yield ratios significantly higher than those measured in e^+e^- collisions, suggesting that the charm fragmentations are not universal across different collisions systems. Thus, measurements of charm-baryon production are crucial to study the charm quark hadronisation in proton–proton (pp) collisions. In proton–lead (p–Pb) collisions, the measurements of charm baryons provide important information about cold nuclear matter effects and help to understand how the possible presence of collective effects could modify the production of heavy-flavour hadrons. In this contribution, the most recent results on open charm-hadron production in pp and p–Pb collisions measured by ALICE are discussed.

1 Introduction

The production of heavy-flavour hadrons in high-energy hadronic collisions can provide important tests of the theory of quantum chromodynamics (QCD). The production cross sections of heavy-flavour hadrons can be calculated using the factorisation approach as a convolution of three factors [1]: the parton distribution functions (PDFs) of the incoming nuclei, the hard-scattering cross section at partonic level, calculated as a perturbative series in powers of the strong coupling constant α_s, and the fragmentation functions of heavy quarks into corresponding heavy-flavour hadrons, which is an inherently non-perturbative process related to, or even driven by, the confining property of QCD. The heavy-flavour baryon-to-meson ratio is an ideal observable related to the hadronization mechanism since the contributions from parton distribution function and parton-parton scattering terms cancel in the ratio. The Λ_c^+/D^0 ratio at the LHC is enhanced with respect to predictions based on e^+e^- and ep experiments, suggesting that the charm fragmentation functions are not universal among different collision systems. Several hadronization mechanisms, such as colour reconnection (CR) beyond the leading colour approximation [2], coalescence [3, 4] and feed-down from a largely augmented set of higher mass charm-baryon states beyond the current listing of the particle data group (PDG) [5], have been proposed to explain this enhancement. The newest measurements of the charm baryons Λ_c^+, $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$ and Ω_c^0 performed with the ALICE experiment will be used to verify predictions from these hadronization mechanisms.
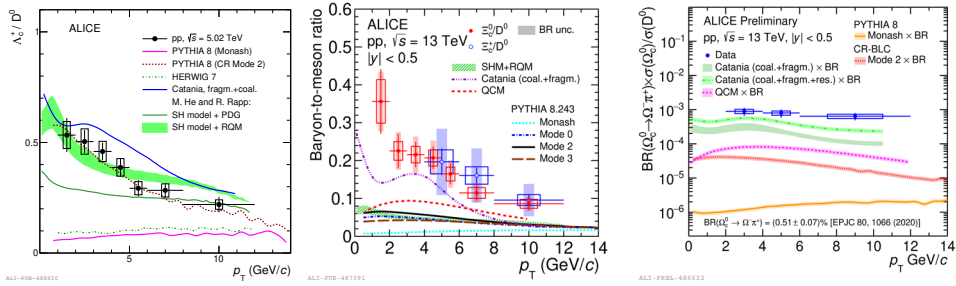
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Figure 1. Left: The Λ_c^+/D^0 ratio as a function of p_T measured in pp collisions at $\sqrt{s}$ = 5.02 TeV [7]. Middle: The Ξ_c^0/D^0 and Ξ_c^+/D^0 ratios measured in pp collisions at $\sqrt{s}$ = 13 TeV [8]. Right: The BR $\times \Omega_c^0/D^0$ measured in pp collisions at $\sqrt{s}$ = 13 TeV. All the charm baryon-to-meson yield ratios are compared to theoretical calculations [2–5, 11].

2 Charm baryon-to-meson yield ratios in pp collisions

Thanks to the large data sample collected during the Run 2 period in pp collisions at $\sqrt{s}$ = 5.02 and 13 TeV, ALICE measured all the ground-state charm hadrons down to low transverse momentum (p_T), including charm mesons (D^0, D^+, D_s^+ [6]) and charm baryons (Λ_c^+ [7], $\Xi_c^{0,+}$ [8, 9], and Ω_c^0). The Λ_c^+/D^0 yield ratio is measured as a function of p_T in pp collisions at $\sqrt{s}$ = 5.02 TeV as shown in Fig. 1 (left), the Ξ_c^0/D^0 and Ξ_c^+/D^0 yield ratios are measured in pp collisions at $\sqrt{s}$ = 13 TeV as shown in Fig. 1 (middle). For Ω_c^0, the absolute decay branching ratio (BR) of $\Omega_c^0 \to \Omega^- \pi^+$ is not measured, hence the BR of $\Omega_c^0 \to \Omega^- \pi^+$ times cross section of Ω_c^0 over cross section of D^0 in pp collisions at $\sqrt{s}$ = 13 TeV is reported in Fig. 1 (right). In order to compare data with models, a theoretical calculation of BR($\Omega_c^0 \to \Omega^- \pi^+$) [10] is used to multiply different models. The Λ_c^+/D^0 and Ξ_c^0/D^0 ratios show a downward trend with increasing p_T. The Monte Carlo generator PYTHIA8 (Monash) [11] tuned on measurements in e^+e^- collisions largely underestimates all four charm baryon-to-meson yield ratios, providing evidence of different charm hadronisation mechanisms between e^+e^- and pp collisions. The Λ_c^+/D^0 ratio is better described by a model with colour reconnection beyond the leading colour approximation [2], a statistical hadronisation model with an augmented set of charm baryon states predicted by the relativistic quark model (RQM) [5], or a model relying on hadronisation via coalescence and fragmentation [3]. However, all the models underestimate the $\Xi_c^{0,+}/D^0$ and BR $\times \Omega_c^0/D^0$ ratios, except the Catania model [3] including charm quark hadronisation via both coalescence and fragmentation, which would indicate a partonic system similar to a quark–gluon plasma (QGP) in pp collisions.

3 Charm production and fragmentation in pp collisions

The charm fragmentation fraction $f(c \to H_c)$ shown in Fig. 2 (left) represents the probability of a charm quark hadronising into a given charm hadron. The fragmentation fraction for the Ξ_c^0 baryon is the first measurement in any collision system. An increase of about a factor of 3.3 for the fragmentation fraction for the Λ_c^+ baryon with respect to e^+e^- and ep collisions, and a corresponding decrease of about a factor of 1.2–1.4 for the D^0 meson are observed, showing that the assumption of the charm fragmentation universality (collision-system independence) is broken. Charm quarks hadronise into baryons almost 40% of the time, which is four times more often than what was measured at colliders with electron beams.
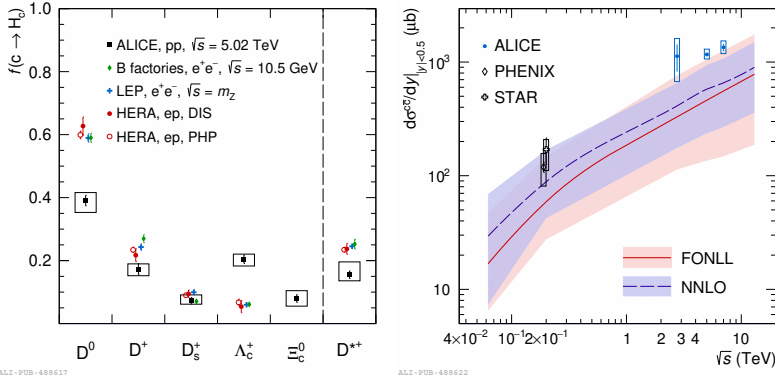
Figure 2. Left: Charm-quark fragmentation fractions into charm hadrons measured in pp collisions at $\sqrt{s}$ = 5.02 TeV in comparison with experimental measurements performed in e$^+$e$^-$ and ep collisions [18]. Right: Charm production cross section at midrapidity per unit of rapidity as a function of the collision energy at the LHC [18] and RHIC [14, 15] compared to FONLL [16] and NNLO [17] calculations.

The $c\bar{c}$ production cross section per unit of rapidity at midrapidity ($d\sigma^{c\bar{c}}/dy|_{|y|<0.5}$) is calculated by summing the p_T-integrated cross sections of all measured ground-state charm hadrons (D^0, D^+, D_s^+, Λ_c^+, Ξ_c^0 and their charge conjugates). The contribution of Ξ_c^0 is multiplied by a factor of 2 in order to account for the contribution of Ξ_c^+. Since the absence of a Ω_c^0 production measurement at hadron colliders, an asymmetric systematic uncertainty is assigned assuming a contribution equal to the one of Ξ_c^0 considering the prediction of the Catania model [3]. The resulting $c\bar{c}$ production cross section per unit of rapidity at midrapidity is $d\sigma^{c\bar{c}}/dy|_{|y|<0.5}^{\text{pp, 5.02 TeV}} = 1165 \pm 44(\text{stat})^{+134}_{-101}(\text{syst})\ \mu b$. The updated fragmentation fractions obtained in pp collisions at $\sqrt{s}$ = 5.02 TeV allow 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, which are about 40% higher than the previously published results [12, 13]. The measured $c\bar{c}$ production cross section per unit of rapidity at midrapidity together with measurements at RHIC [14, 15] are located at the upper edge of FONLL [16] and NNLO [17] predictions.

4 Charm hadronisation in p–Pb collisions

Charm hadronisation in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV is also investigated. The left panel of Fig. 3 shows the Λ_c^+/D^0 ratio as a function of p_T in pp and p–Pb collisions at 5.02 TeV. This ratio is measured down to p_T = 0 in p–Pb collisions for the first time at the LHC. The measurements of Λ_c^+/D^0 in pp and p–Pb collisions are qualitatively consistent with each other, although a larger 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. A clear decreasing trend with increasing p_T is obtained in both pp and p–Pb collisions for $p_T > 2$ GeV/c. The nuclear modification factor R_{pPb} of the Λ_c^+ baryon measured as a function of p_T together with R_{pPb} of non-strange D mesons are shown in the right panel of Fig. 3. There is a significant suppression for $p_T < 2$ GeV/c and enhancement for $4 < p_T < 8$ GeV/c in p–Pb collisions with respect to pp collisions, which is similar as the p_T distribution of Λ_c^+/D^0 ratio, suggesting the presence of possible radial flow effects or a further modification of the charm hadronisation mechanism in p–Pb collisions. The measurement of R_{pPb} for the Λ_c^+ baryon is compared to model calculations. The POWHEG [19] + PYTHIA6 simulations use the POWHEG event generator
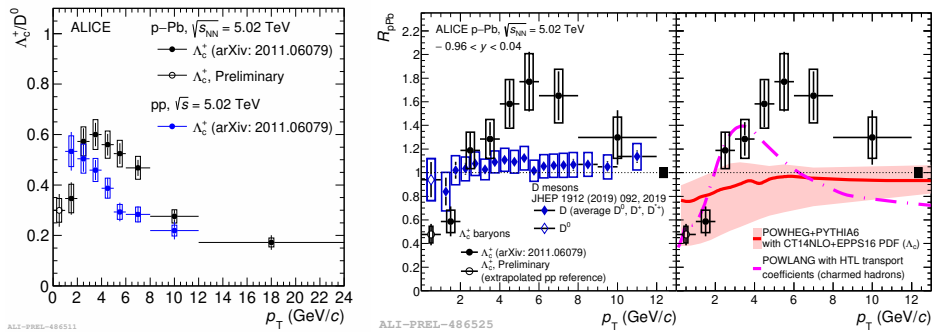
Figure 3. Left: The Λ_c^+/D^0 ratio as a function of p_T measured in pp collisions and p–Pb collisions at 5.02 TeV [7]. Right: The nuclear modification factor R_{pPb} of the Λ_c^+ baryon as a function of p_T in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, compared to R_{pPb} of D mesons, as well as to model expectations [7].

with PYTHIA6 parton shower and EPPS16 [20] parameterisation of the nuclear modification of the PDFs. The POWLANG model [21] assumes that a hot deconfined medium is formed in p–Pb collisions. The two models capture some features of the data, but neither of them can quantitatively reproduce the data in the measured p_T interval.

5 Acknowledgments

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