

Prompt and non-prompt charm baryons with ALICE

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Recent measurements of prompt charm-baryon production at midrapidity in pp and p–Pb collisions show baryon-to-meson yield ratios significantly higher than those in e^+e^- collisions, suggesting that the charm fragmentation is not universal across different collision systems. Thus, more precise and broader measurements of prompt charm-baryon production are crucial to study the charm quark hadronization in a partonic-rich environment like the one produced in pp collisions at the LHC energies. Prompt charm baryon-to-meson yield ratios in proton–nucleus collisions provide important information about possible additional modification of hadronization mechanisms, on cold nuclear matter effects, and on the possible presence of collective effects that could modify the production of heavy-flavor hadrons. The non-prompt charm-hadron production can provide information about the beauty sector and can be used to study flavor dependence of heavy-quark hadronization. In this contribution, the most recent results on prompt and non-prompt charm-hadron yield ratios in pp and p–Pb collisions and on charm fragmentation fractions and charm production cross section at midrapidity per unit of rapidity measured by ALICE are discussed.

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1. Introduction

The production of heavy-flavor hadrons in high-energy hadronic collisions can provide important tests of the theory of quantum chromodynamics (QCD). The production cross sections of heavy-flavor hadrons can be calculated using the factorization approach as a convolution of three factors [1]: the parton distribution functions (PDFs) of the incoming protons, 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 to given heavy-flavor hadron species. The latter term parametrizes the result of the hadronization process, which is an inherently non-perturbative process related to, or even driven by, the confining property of QCD. The heavy-flavor baryon-to-meson yield ratio is an ideal observable to probe the hadronization mechanism since the contributions from parton distribution function and hard-scattering cross section terms almost cancel in the ratio. The Λ_c^+/D^0 ratio in pp and p-Pb collisions at the LHC is enhanced with respect to measurements at the electron colliders, and predictions of models and event generators tuned 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], quark coalescence [3, 4], and statistical hadronization model (SHM) [5] including a set of higher-mass charm-baryon states as prescribed by the relativistic quark model (RQM), have been proposed to explain this enhancement. The newest measurements of the prompt charm baryons Λ_c^+ , $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$, Ω_c^0 , and non-prompt Λ_c^+ performed with the ALICE experiment are presented in this contribution and used to verify predictions from these hadronization mechanisms.

2. Prompt and non-prompt D^+/D^0 and $D_s^+/(D^0 + D^+)$ yield ratio in pp collisions

The ratios of prompt and non-prompt D-meson yield ratios D^+/D^0 and $D_s^+/(D^0 + D^+)$ are measured at midrapidity as a function of p_T in pp collisions at $\sqrt{s} = 5.02$ TeV with the ALICE experiment. The results are independent of p_T within the current experimental precision and are compatible with the FONLL [6] predictions in the case of prompt D^0 and D^+ mesons and FONLL+PYTHIA 8, to model the B hadron decay kinematics, in the case of non-prompt D mesons. These predictions are based on the factorization approach with universal fragmentation functions.

3. Prompt and non-prompt Λ_c^+/D^0 yield ratio in pp collisions

In Fig. 1, the prompt Λ_c^+/D^0 yield ratio measured at midrapidity as a function of p_T in pp collisions at $\sqrt{s} = 5.02$ TeV (left panel) and at $\sqrt{s} = 13$ TeV (right panel) is shown. Recently, the production cross section of prompt Λ_c^+ has been extended down to $p_T = 0$ at both collision energies. The prompt Λ_c^+/D^0 is significantly underestimated by the Monte Carlo generator PYTHIA 8 (Monash tune) [7] tuned on measurements in e^+e^- collisions, but it is better described by a model with color reconnection (CR) beyond the leading color approximation [2], a statistical hadronization model with an augmented set of charm baryon states predicted by the relativistic quark model (SHM+RQM) [5], or a model relying on hadronization via coalescence and fragmentation (Catania) [3].

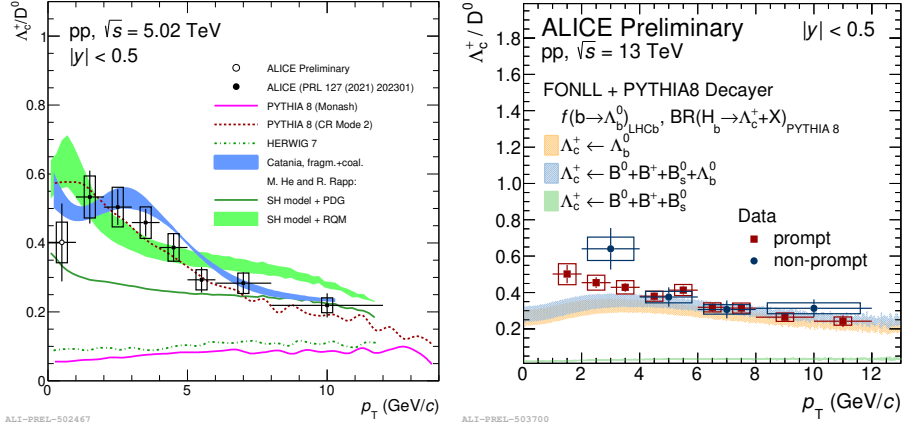


Figure 1: Left: Prompt Λ_c^+/D^0 yield ratio in pp collisions at $\sqrt{s} = 5.02$ TeV compared with model predictions. Right: Prompt and non-prompt Λ_c^+/D^0 yield ratio in pp collisions at $\sqrt{s} = 13$ TeV compared with model predictions.

The non-prompt Λ_c^+/D^0 yield ratio measured in pp collisions at $\sqrt{s} = 13$ TeV is shown in the right panel of Fig. 1. It is similar to the prompt Λ_c^+/D^0 yield ratio. The data points are compared with theoretical models based on the B-hadron cross section predicted by FONLL and the beauty-quark fragmentation fractions to Λ_b^0 baryons measured by the LHCb collaboration at forward rapidity [8], $f(b \rightarrow \Lambda_b^0)$, and to B mesons in e^+e^- collisions, $f(b \rightarrow B)$. The resulting beauty-hadron cross section was then folded with the $H_b \rightarrow H_c + X$ decay kinematics obtained with PYTHIA 8 in order to obtain the non-prompt Λ_c^+ cross section. The data and the model are compatible within 1.5σ .

4. Prompt $\Sigma_c^{0,+,++}$, $\Xi_c^{0,+}$ and inclusive Ω_c^0 over D^0 yield ratios in pp collisions

The measurement of $\Sigma_c^{0,+,++}$ production is very important to constrain the production of Λ_c^+ since $\Sigma_c^{0,+,++}$ almost completely decays to Λ_c^+ . In the left panel of Fig. 2, the $\Sigma_c^{0,+,++}/D^0$ yield ratio is shown as a function of p_T in pp collisions at $\sqrt{s} = 13$ TeV and compared with model predictions. The $\Sigma_c^{0,+,++}/D^0$ yield ratio shows a similar p_T trend as the Λ_c^+/D^0 yield ratio. The data indicate that the enhancement of Λ_c^+/D^0 ratio in pp collisions can be partially explained by $\Sigma_c^{0,+,++}$ feed-down. All models mentioned above except PYTHIA 8 with Monash tune can describe the measured $\Sigma_c^{0,+,++}/D^0$ yield ratio.

The strange-charm Ξ_c^0 and Ξ_c^+ baryons are also investigated, and the Ξ_c^0/D^0 and Ξ_c^+/D^0 yield ratios measured in pp collisions at $\sqrt{s} = 13$ TeV are shown in the middle panel of Fig. 2. In the right panel of Fig. 2, the measurement of the Ω_c^0/D^0 cross-section ratio times branching ratio (BR) of the $\Omega_c^0 \rightarrow \Omega^- \pi^+$ decay is reported for pp collisions at $\sqrt{s} = 13$ TeV. The absolute BR of $\Omega_c^0 \rightarrow \Omega^- \pi^+$ is not measured hence, in order to compare data with models, a theoretical calculation of $\text{BR}(\Omega_c^0 \rightarrow \Omega^- \pi^+) = (0.51^{+2.19}_{-0.31})\%$ [9] is used to multiply different models. The Ξ_c^0/D^0 and Ξ_c^+/D^0 yield ratios show a decreasing trend with p_T . The PYTHIA 8 Monash [7] tuned on measurements in e^+e^- collisions largely underestimates all charm baryon-to-meson yield ratios, providing evidence of different charm hadronization mechanisms between e^+e^- and pp collisions. The Catania model [3] is the only one that provides a fair description of the $\Xi_c^{0,+}/D^0$ and $\text{BR} \times \Omega_c^0/D^0$ yield ratios. It

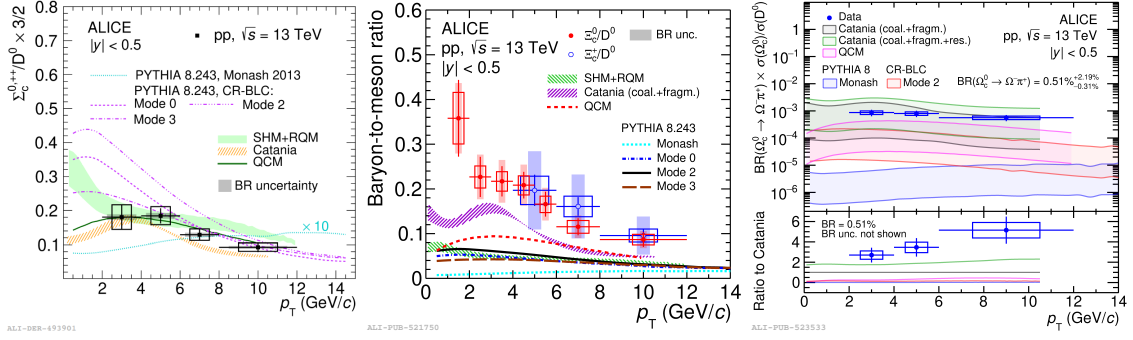


Figure 2: Left: Prompt $\Sigma_c^{0,+,++}/D^0$ yield ratio in pp collisions at $\sqrt{s} = 13$ TeV [10]. Middle: Prompt Ξ_c^0/D^0 and Ξ_c^+/D^0 yield ratios in pp collisions at $\sqrt{s} = 13$ TeV [11]. Right: Prompt $BR \times \Omega_c^0/D^0$ yield ratio in pp collisions at $\sqrt{s} = 13$ TeV [9]. All the charm baryon-to-meson yield ratios are compared to theoretical calculations [2–5, 7].

is interesting to note that in this model the formation of a small-size quark–gluon plasma (QGP) in pp collisions is assumed and hadronization occurs via coalescence in addition to fragmentation.

5. Prompt Λ_c^+/D^0 yield ratio in p–Pb collisions

The prompt Λ_c^+/D^0 yield ratio measured down to $p_T = 0$ in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is shown in the left panel of Fig. 3 and is compared with the measurement in pp collisions at $\sqrt{s} = 5.02$ TeV. The p–Pb result for $p_T > 4$ GeV/c suggests a larger ratio than that measured in pp collisions, while there is a hint of suppression in $p_T < 2$ GeV/c. This suggests a possible modification of D^0 and Λ_c^+ formation probabilities as a function of p_T in p–Pb collisions with respect to pp collisions, which could be attributed to a contribution of collective effects, i.e. radial flow, in p–Pb collisions. The p_T -integrated prompt Λ_c^+/D^0 yield ratio as a function of charged-particle multiplicity is shown in the right panel of Fig. 3. There is no significant variation as a function of multiplicity, collision system, or collision energy, which indicates that the modification observed in the study of p_T differential yields could be due to a momentum redistribution without a modification of the overall Λ_c^+ yield relative to the D^0 one.

6. Charm production and fragmentation in pp and p–Pb collisions

The charm fragmentation fraction $f(c \rightarrow H_c)$ shown in the left panel of Fig. 4 represents the probability of a charm quark hadronizing into a given charm hadron species. The fraction of charm quarks that hadronize into baryons is about 40%, which is four times larger than what was measured at colliders with electron beams, showing that the assumption of the charm fragmentation universality (collision-system independence) is not valid.

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^+ . Due to the absence of a Ω_c^0 production measurement in pp collisions at $\sqrt{s} = 5.02$ TeV, an asymmetric systematic uncertainty is assigned assuming

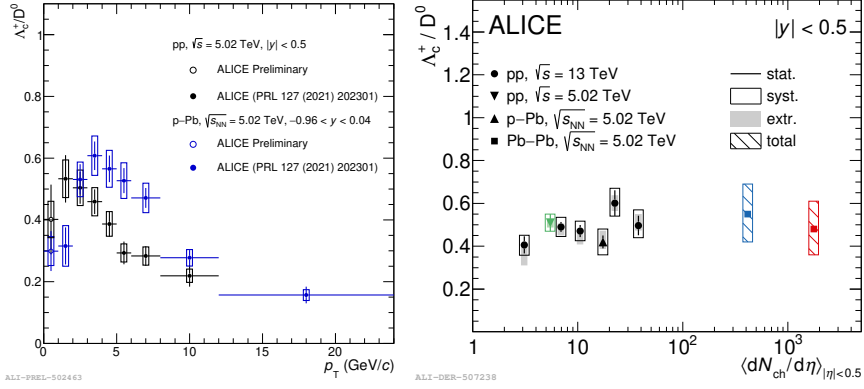


Figure 3: Left: Prompt Λ_c^+/D^0 yield ratio as function of p_T in pp and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Right: p_T -integrated prompt Λ_c^+/D^0 yield ratio as a function of charged-particle multiplicity in pp, p-Pb and Pb-Pb collisions at various collision energies.

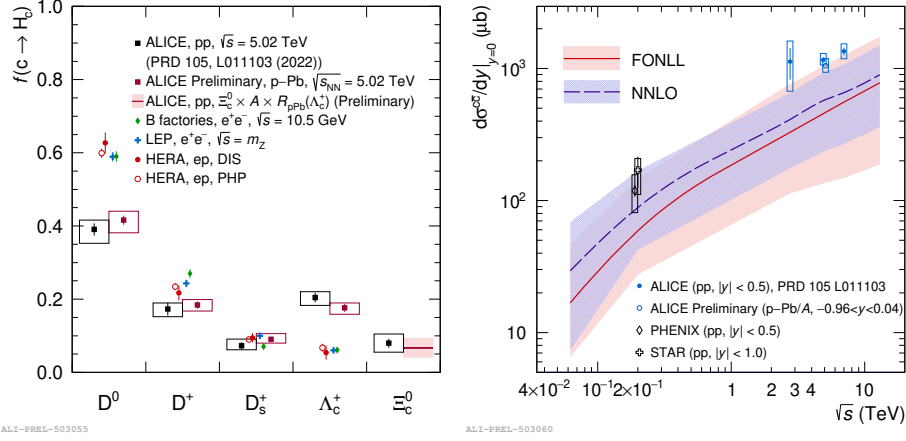


Figure 4: Left: Charm-quark fragmentation fractions into charm hadrons measured in pp and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in comparison with experimental measurements performed in e^+e^- and ep collisions [15]. Right: Charm production cross section at midrapidity per unit of rapidity as a function of the collision energy at the LHC [15] and RHIC [12, 13] compared to FONLL [6] and NNLO [14] calculations.

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 in p-Pb collisions after scaling for Pb ion mass number, shown in the right panel of Fig. 4 together with measurements at RHIC [12, 13], is compatible with that in pp collisions. The 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 which used the D-meson fragmentation fraction from e^+e^- collisions. The measured $c\bar{c}$ production cross sections per unit of rapidity at midrapidity are located at the upper edge of FONLL [6] and NNLO [14] predictions.

7. Acknowledgments

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