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Charm hadronisation measurements with the ALICE experiment

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Abstract. Charm quarks are produced in hard scatterings at the early stages of the hadronic collisions due to the heavy mass of the quark. The production cross section of charm can be described by pQCD calculations based on the factorisation approach. This description traditionally assumes universal fragmentation functions of charm into hadrons among different collision systems.
The ALICE experiment measured charmed-baryon production in pp collisions for different baryon species, observing a significant enhancement of the charm baryon-to-meson yield ratios, for $p_{\mathrm{T}} < 10$–12 GeV/c, with respect to measurements performed at $\mathrm{e^+e^-}$ and ep colliders. Measurements of charmed baryon production in pp collisions also provide a fundamental reference for heavy-ion collisions, in which an enhancement of the baryon-to-meson ratio could be due to an additional hadronisation mechanism via coalescence of charm quarks with lighter quarks in a deconfined medium.
This contribution discusses the latest measurements of charm production performed by the ALICE Collaboration in pp collisions at the LHC via D mesons, Λ_{c}^{+}, $\Sigma_{\mathrm{c}}^{0,+,++}$, $\Xi_{\mathrm{c}}^{0,+}$, and Ω_{c}^{0} baryons at midrapidity at $\sqrt{s} = 5.02$ and 13 TeV. The most recent measurements of the $\Lambda_{\mathrm{c}}^{+}/\mathrm{D}^0$ ratio in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV are also presented, together with the first measurement of the charm fragmentation fraction into hadrons in pp and p–Pb collisions at the same energy.

1 Introduction

Heavy flavour production in proton–proton (pp) collisions can be described via pQCD calculations which employ the factorisation approach [1]. In particular, the cross section of charm (and beauty) hadrons is calculated as a convolution of three main terms:

1. Parton distribution functions, which account for the probability to find a specific parton inside the colliding protons carrying a given fraction of the proton momentum (Bjorken-x).

2. cross section of a quark–antiquark pair creation via parton interactions (hard scattering)

3. fragmentation functions, which describe the probability of the hadronisation of a heavy quark into a given hadron, which carries a specific fraction z of the original quark momentum.

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In particular, the fragmentation functions are traditionally assumed to be universal [2] and are constrained from e^+e^- and ep collision measurements. This assumption was observed to be not valid, given the many results reported at the LHC [3, 4] showing an increased heavy-flavour baryon production relative to mesons, with respect to measurements in e^+e^- and ep collisions.
Moreover, heavy flavours are an important tool to characterise the quark–gluon plasma, the state of matter created in relativistic heavy-ion collisions. Charm and beauty quarks are produced at the early stages of the collisions and they can interact with the medium during its entire lifetime.
This contribution presents an overview of the recent charm measurements performed by the ALICE Collaboration in pp collisions at $\sqrt{s}$ = 5.02 and 13 TeV and in p–Pb and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV.
The reconstruction of different charmed particles is performed via an invariant mass analysis of fully reconstructed decay topologies, selected with criteria based on geometrical and kinematic variables related to the displaced charmed-hadron decay vertex and on the particle identification of the decay products. The heavy-flavour hadron reconstruction strategies exploit the track impact parameter resolution provided by the ITS detector: better than 50 μm for $p_{\mathrm{T}} > 1$ GeV/c.
The production of D mesons, Λ_c^+, $\Sigma_c^{0,+,++}$, $\Xi_c^{0,+}$, and Ω_c^0 baryons at midrapidity was measured down to very low p_{T} in pp collisions at $\sqrt{s}$ = 5.02 and 13 TeV.
This contribution focuses on the discussion of the baryon-to-meson ratio measurements, since they show an intriguing dependence on the collision system, which is not observed for the yield ratios of different meson species.
In Fig. 1 (left) the D^+/D^0 yield ratios for prompt and non-prompt (i.e. originating from beauty-hadron decays) mesons are shown as a function of p_{T}, presenting a flat trend. They are in agreement within uncertainties with the measurements performed in e^+e^- and ep collisions [5], and they are well described by pQCD calculations (FONLL [6] and GM-VFNS [7]). On the other hand, the Λ_c^+/D^0 ratio measured in pp collisions at the LHC show a strong decreasing trend as a function of p_{T}, as shown in Fig. 1 (right).

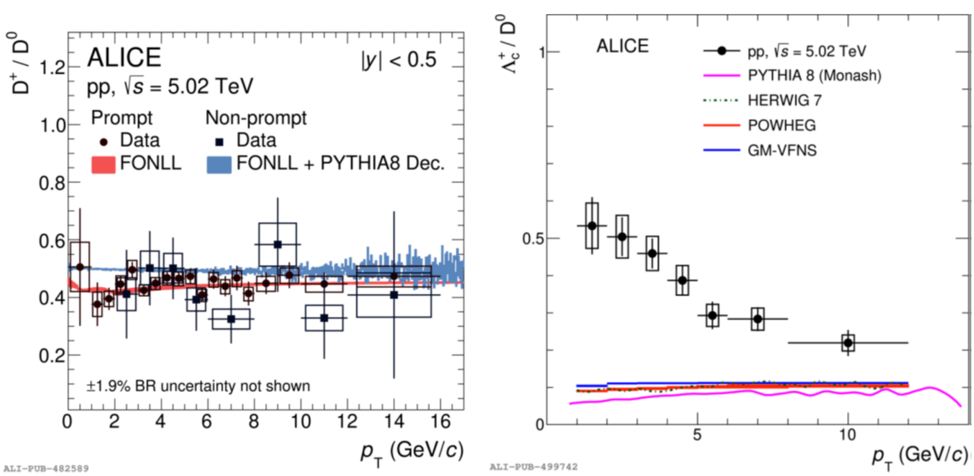

Figure 1. Comparison of measured production cross section ratios with Monte Carlo generators using D^+/D^0 meson ratios (left) [5] and Λ_c^+/D^0 baryon-to-meson ratio in pp collisions at 5.02 TeV (right) [3].

The baryon-to-meson measurements performed in pp collisions at midrapidity by the ALICE Collaboration show a different behaviour both with respect to results from e^+e^- collisions at LEP ($\Lambda_c^+/D^0 \approx 0.11$ [2]) and to pQCD calculations and event generators, in which the charm-quark fragmentation is constrained using e^+e^- and ep results [3]. The underestimation of the baryon-to-meson ratio might be due to modified hadronisation mechanisms in the parton-rich environment created in pp collisions at the LHC, which enhance the production of baryons relative to mesons, thus breaking the universality of fragmentation.

2 Recent results and discussion

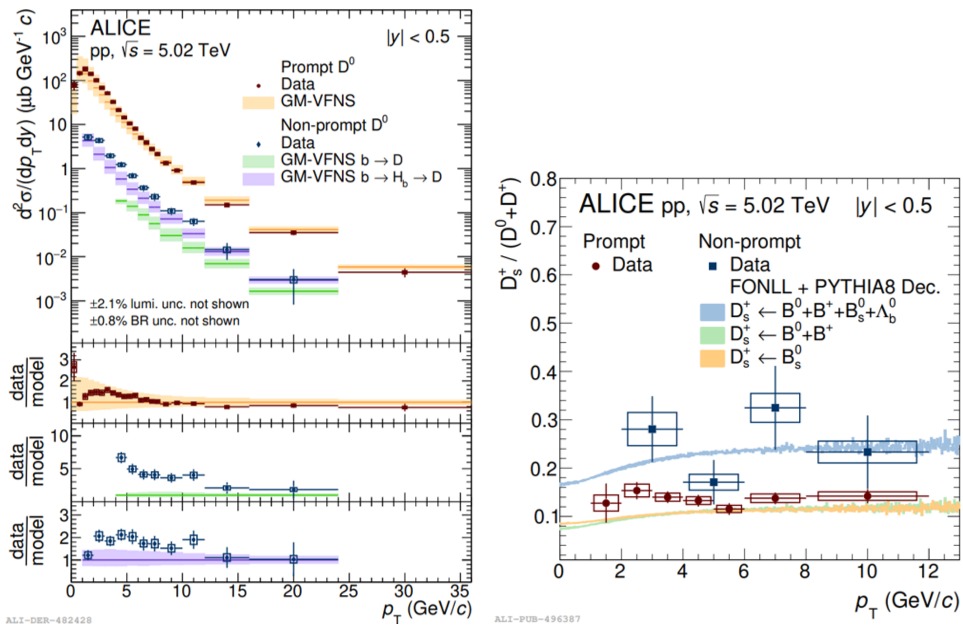

Figure 2. Prompt and non-prompt production of D^0 mesons in pp collisions at $\sqrt{s} = 5.02$ TeV compared to pQCD calculations [5] down to $p_T = 0$ (left) and ratio between D_s^+ and the sum of D^+ and D^0 meson yields (right).

The production of D mesons in pp collisions at $\sqrt{s} = 5.02$ TeV has been measured down to $p_T = 0$ for D^+ and D^0 mesons. In Fig. 2 (left) the measured production cross sections of prompt and non-prompt D^0 mesons is compared with pQCD calculations based on the factorisation approach, namely GM-VFNS. Results for prompt D mesons are described well by GM-VFNS calculations, while the measurements of non-prompt D^0 production are underestimated: this is especially true for the case in which the fragmentation and decay are done in one step ($b \rightarrow D$ curve), while the two-steps approach ($b \rightarrow H_b \rightarrow D$) describes better the data. On the other hand, the ratio between the yields of non-prompt charmed strange D_s^+ mesons and the sum of non-prompt D^0 and D^+, reported in Fig. 2 (right), shows a good agreement within the uncertainties with predictions based on FONLL calculations for beauty-hadron production and PYTHIA 8 for the $B \rightarrow D$ decays. As for the D^+/D^0 ratio shown in Fig. 1 (right), no trend with p_T is observed within current uncertainties.
The Λ_c^+/D^0 ratio, now measured down to $p_T = 0$ in pp collisions at $\sqrt{s} = 13$ and 5.02 TeV, is found to be compatible at the two considered centre-of-mass energies (Fig. 3 left).

As seen in the previously published results, we notice that PYTHIA8 with Monash tune [8] and HERWIG7 [10] results are underestimating the measured ratio (because the parton fragmentation in these event generators is tuned on e^+e^- measurements at LEP), while the

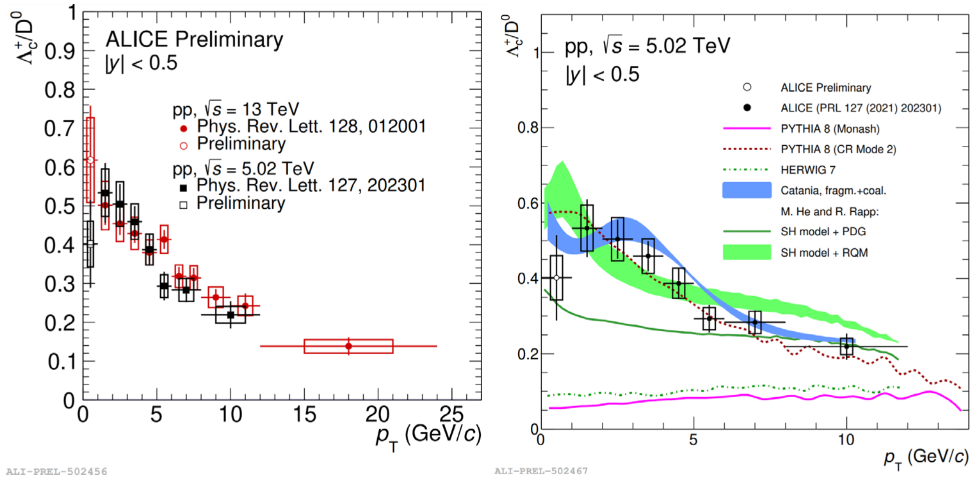

Figure 3. Prompt Λ_c^+/D^0 production ratio in pp collisions at $\sqrt{s}$ = 13 and 5.02 TeV (left) and comparison of the ratio with various event generators and model calculations including the ones with enhanced baryon production mechanisms (right).

PYTHIA8 event generator with enhanced colour reconnection mechanisms [9], the Catania model [12], and the Statistical Hadronisation Model (SHM) [11] provide a better description of the data. The presence of junction topologies in PYTHIA8 with enhanced colour reconnection mechanisms increases the production of baryons; the Catania model assumes the presence of a medium of thermalised quarks and gluons, in which hadron formation occurs both with fragmentation and quark coalescence (recombination); in the SHM, instead, it is assumed that hadron abundances follow the equilibrium populations of a hadron–resonance gas including also not yet measured baryon resonances foreseen by the RQM models [11].

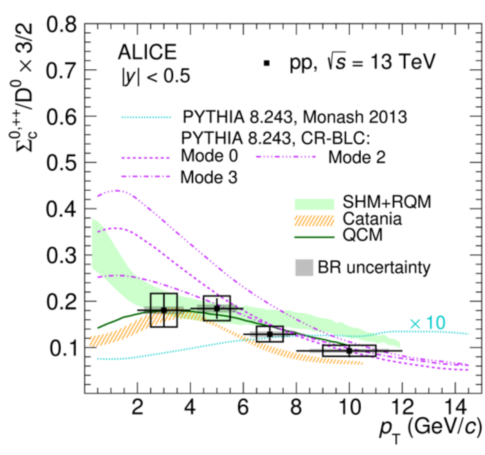

Figure 4. Prompt $\Sigma_c^{0,+,++}/D^0$ production ratio in pp collisions at $\sqrt{s}$ = 13 compared to different models [14].

Another result is shown in Fig. 4, in which the $\Sigma_c^{0,+,++}/D^0$ baryon-to-meson ratios are compared with the already discussed models, as well as with the Quark Recombination Model (QCM) [13], in which charm quarks are recombined with lighter quarks sharing their same

velocity. Even for this heavier charmed baryon species, the measured baryon-to-meson ratio is larger than the expected values from models using fragmentation fractions as measured at LEP or a fragmentation process tuned on e^+e^- collisions, while the models with enhanced baryon production are in better agreement with the measurements. Compared to e^+e^- measurements an enhancement up to a factor 10 is found.
Additional insight can be obtained from the results of the ratio between the charmed strange baryon $\Xi_c^{0,+}$ and the D^0 meson yields shown in Fig. 5, for which the measured values are underestimated also by the models with enhanced baryon production. When considering the $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ ratio, the PYTHIA8 generator with Monash 2013 tune is able to describe the data, thanks to the fact that a similar enhancement in pp with respect to e^+e^- collisions might be happening for the two baryon species. However, all the ratios involving the $\Xi_c^{0,+}$ baryon are in better agreement with the Catania model compared to the other calculations.

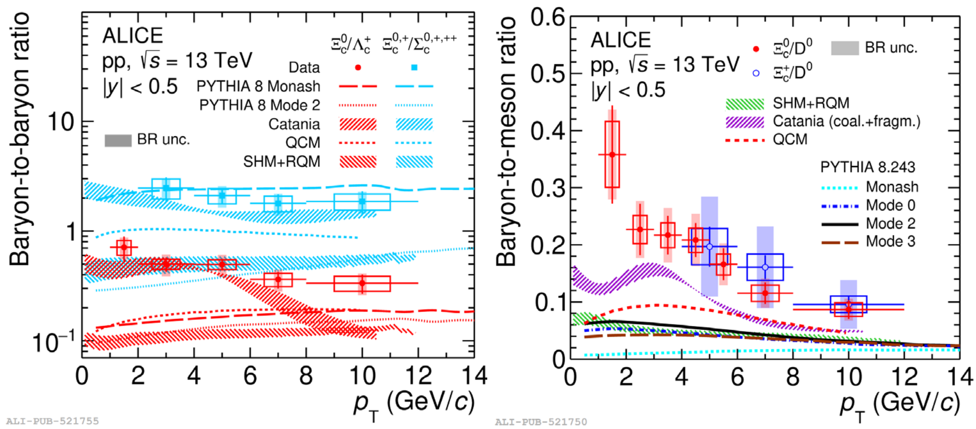

Figure 5. Prompt $\Xi_c^{0,+}$ baryon-to-baryon (left) and baryon-to-meson (right) ratio in pp collisions at $\sqrt{s}$ = 13 TeV compared to different models [15].

The last measurement performed in pp collisions and discussed in this contribution is the production cross section of the doubly strange charmed baryon Ω_c^0, whose first measurement at the LHC was performed by the ALICE Collaboration [16]. Figure 6 (left) shows the Ω_c^0/D^0 ratio as a function of p_T. The ratio is scaled by the branching ratio of the decay $\Omega_c^0 \rightarrow \Omega^-\pi^+$, which is not yet measured, but it can be estimated with theoretical calculations [17]. The measured Ω_c^0/D^0 ratio is larger than the theoretical predictions, with the Catania model being the one closer to the experimental results when adding higher mass resonance decays.

The cross section of the Ω_c^0 multiplied by the branching ratio is about 5 times larger than results obtained at BELLE in e^+e^- collisions, which might hint to the possibility of a larger than expected fraction of charm quarks fragmenting into Ω_c^0 baryons at LHC energies.
The measurements of all the ground states of charm hadrons down to very low p_T allowed ALICE to compute the fragmentation fractions in pp, and in p–Pb collisions, as shown in Fig. 6 (right), where they are compared with LEP, HERA and B factory measurements. The measured larger fraction of Λ_c^+ is compensated by a relative decrease of D^0 (and less evidently of $D^\pm$) fraction. The charm fragmentation fractions in p–Pb are compatible with those computed in pp collisions for all the particle species.
The Λ_c^+/D^0 yield ratios in different centrality intervals for Pb–Pb collisions and in pp collisions at $\sqrt{s}$ = 5.02 TeV are shown in Fig. 7. The measurements are compared to the same models used for pp collisions (Catania and SHM), and to the TAMU transport model predictions [20], in which heavy quarks are transported through the QGP phase, where they interact

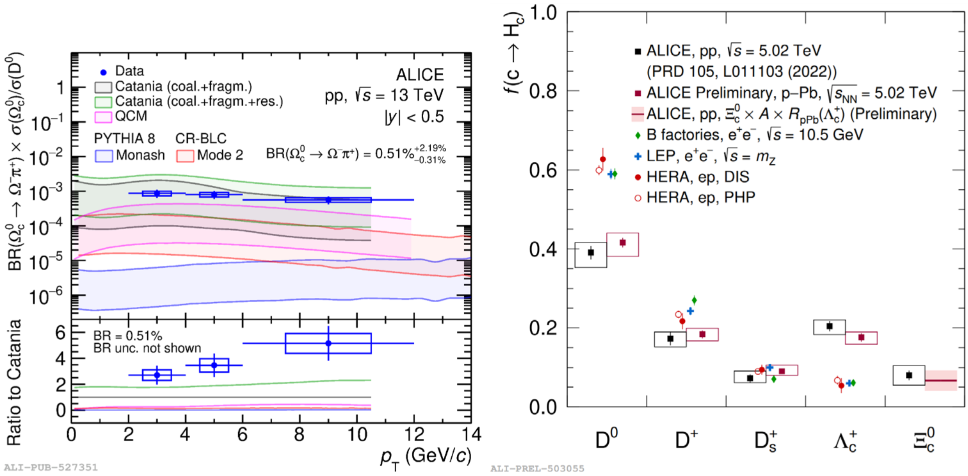

Figure 6. Ω_c^0/D^0 ratio in pp collisions at $\sqrt{s}$ = 13 TeV (left) [16] and charm fragmentation fraction results by ALICE compared to other experiments in different collision systems (right).

with the medium constituents and they can hadronise via quark recombination. The ratio presents different trends as a function of p_T for pp and Pb–Pb collisions, with the centrality interval 30-50% being closer to pp results. This might depend on the presence of radial flow, which modifies in a different way the Λ_c^+ and D^0 p_T shapes in Pb–Pb collisions at different centralities [19]. In this case, TAMU is the model that best describes the results.

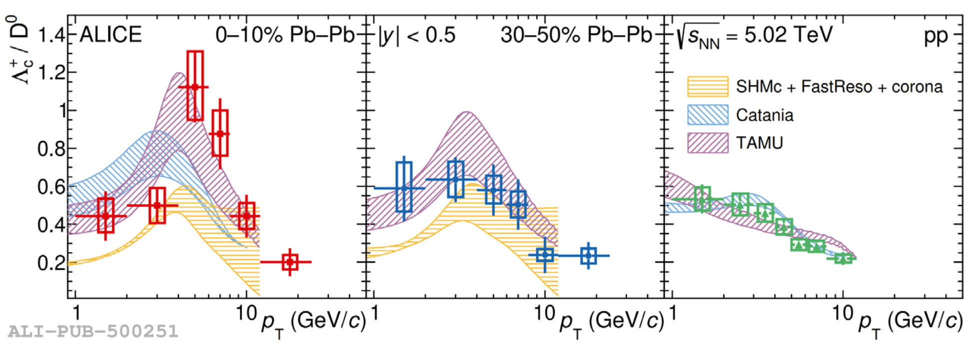

Figure 7. Λ_c^+/D^0 ratio in pp collisions and in Pb–Pb collisions in different centrality intervals compared to models [19].

3 Conclusions

The results presented in this contribution provide novel insights into the mechanisms of charm hadronisation in hadronic collisions. The comparison of the measurements of charm baryon-to-meson ratios with different models suggests that additional mechanisms for the hadronisation of charm into baryons could take place in pp collisions with respect to e^+e^- and ep collisions. More studies are needed to discriminate among different theoretical descriptions. Higher-accuracy measurements will be performed by the ALICE Collaboration exploiting the larger data samples that will be collected in Run 3 and the improved tracking resolution provided by the upgraded experiment after the Long Shutdown 2.

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