PROCEEDINGS OF SCIENCE

Charm cross section and fragmentation fractions in pp collisions with ALICE

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In this contribution, the latest Λ_c^+, Ξ_c^0 and the first Ξ_c^+, $\Sigma_c^{0,++}$ and Ω_c^0 baryon measurements performed with the ALICE detector at midrapidity in proton–proton collisions at $\sqrt{s} = 5.02$ TeV and 13 TeV at the LHC are presented. Recent measurements of baryon-to-meson cross-section ratios at midrapidity show significantly higher results than in e^+e^- and ep collisions, suggesting that the fragmentation of charm is not universal across different collision systems. Thus, measurements of charm-baryon production are crucial to study the charm-quark hadronisation in pp collisions and the possible difference with respect to e^+e^- and ep collisions. In addition, the baryon-production measurements were essential for the measurement of the $c\bar{c}$ production cross section performed by ALICE at midrapidity in pp collisions and also presented in this contribution. Furthermore, the new preliminary measurement of the Λ_c^+/D^0 ratio in $0 \leq p_T < 1$ GeV/c in p–Pb collisions will be discussed. The measurement of charm baryons in proton–nucleus collisions provides important information about Cold Nuclear Matter (CNM) effects. It also helps to understand how the possible presence of collective effects could modify the production of heavy-flavour hadrons and to interpret the similarities observed among pp, proton–nucleus and nucleus–nucleus systems.

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1. Introduction

The study of charm production is a powerful tool to investigate the quark-gluon plasma (QGP), the extremely hot medium formed in high-energy heavy-ion collisions. Due to their large mass, charm quarks are produced in the initial stages of the collisions via hard partonic scattering processes. They then interact with the medium constituents experiencing its whole evolution. In particular, the relative abundances of charm baryons and mesons ("baryon-to-meson ratios") are sensitive to the charm hadronisation mechanisms in the QGP. Recent observations [1–4] suggest that coalescence of the charm quarks with other light quarks in the hot medium is a process effective for charm hadron formation in heavy-ion collisions and concurrent with fragmentation in vacuum. This is expected to produce an enhancement of the baryon-to-meson ratio in heavy-ion collisions with respect to measurements performed in pp collisions. Smaller colliding systems such as pp or p–Pb, are not only useful as a reference for Pb–Pb measurements, but they are also interesting as a test of Quantum Chromodynamics (QCD) calculations based on a factorisation approach and for the study of Cold Nuclear Matter (CNM) effects. With the factorization approach [5], the p_{T} differential production cross section of hadrons containing charm quarks is calculated as a convolution of three terms: (i) the parton distribution functions (PDFs) of the incoming protons, (ii) the cross sections of the partonic scatterings producing the heavy quarks, and (iii) the fragmentation functions, which parametrise the non-perturbative evolution of a heavy quark into a given heavy-flavour hadron species. Theoretical calculations based on the factorisation approach rely on the assumption that fragmentation functions, which are typically measured in $\mathrm{e^+e^-}$ collisions, are universal across all collision systems and energies. However, the universality of the charm fragmentation fractions has recently been questioned by the observed enhancement of the charm baryon-to-meson ratio in pp collisions with respect to $\mathrm{e^+e^-}$ collisions.

2. Charm baryons reconstruction with ALICE

ALICE [6] is a heavy-ion dedicated experiment at CERN, aimed at studying the properties of the QGP. The ALICE apparatus is characterized by unique capabilities for Particle Identification (PID) and low-momenta tracking. It consists of a central barrel at mid rapidity, a muon spectrometer at forward rapidity and a set of detectors for triggering and event characterization. Charm hadrons are studied in ALICE at midrapidity using both hadronic and semileptonic decay channels. The Λ_{c}^{+}, Ξ_{c}^{+}, $\Sigma_{\mathrm{c}}^{0,++}$, and Ω_{c}^{0} charm baryons were reconstructed via the hadronic decay channels $\Lambda_{\mathrm{c}}^{+} \to \mathrm{pK^0_S} \to \mathrm{p}\pi^+\pi^-$, $\Lambda_{\mathrm{c}}^{+} \to \mathrm{pK^-}\pi^+$, $\Xi_{\mathrm{c}}^{+} \to \Xi^-\pi^+\pi^+$, $\Sigma_{\mathrm{c}}^{0,++} \to \Lambda_{\mathrm{c}}^{+}\pi^{-,+}$ and $\Omega_{\mathrm{c}}^{0} \to \Omega^-\pi^+$. The Ξ_{c}^{0} was reconstructed in both the hadronic $\Xi_{\mathrm{c}}^{0} \to \Xi^-\pi^+$ and semileptonic $\Xi_{\mathrm{c}}^{0} \to \Xi^-\mathrm{e}^+\nu_{\mathrm{e}}$ channels. The heavy-flavour candidates are built combining charged tracks and Ξ^- and Ω^- candidates with the proper charge-sign combination. The large combinatorial background is reduced with topological and particle identification (PID) selections. The PID exploits the energy loss measured with the Time-Projection-Chamber (TPC) and the time of flight measured with the Time-of-Flight (TOF) deterctors. The Ξ_{c}^{0} invariant-mass distribution is then obtained by subtracting the Wrong Sign (WS) invariant-mass distribution from the Right Sign (RS) one. Due to the missing momentum carried by the undetected neutrino, the invariant mass distributions for the semileptonic channel do not show a peak at the Ξ_c^0 mass. An unfolding technique is then used to convert the $e^+\Xi^-$ p_T-spectrum to the Ξ_c^0 one [3].

3. Results

The prompt Λ_c^+/D^0 yield ratios measured in pp collisions at $\sqrt{s}$ = 5.02 TeV and in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [1, 7] are reported in Fig. 1 in the top-left, and bottom panels, respectively. In the top-right panel the Λ_c^+/D^0 ratio measured as a function of p_T in two different charged-particle multiplicity classes in pp collisions at $\sqrt{s}$ = 13 TeV is shown. The results in pp collisions are also compared to several theoretical models. The baryon-to-meson ratio Λ_c^+/D^0 in pp collisions is strongly enhanced with respect to e^+e^- collisions and an evident p_T trend is

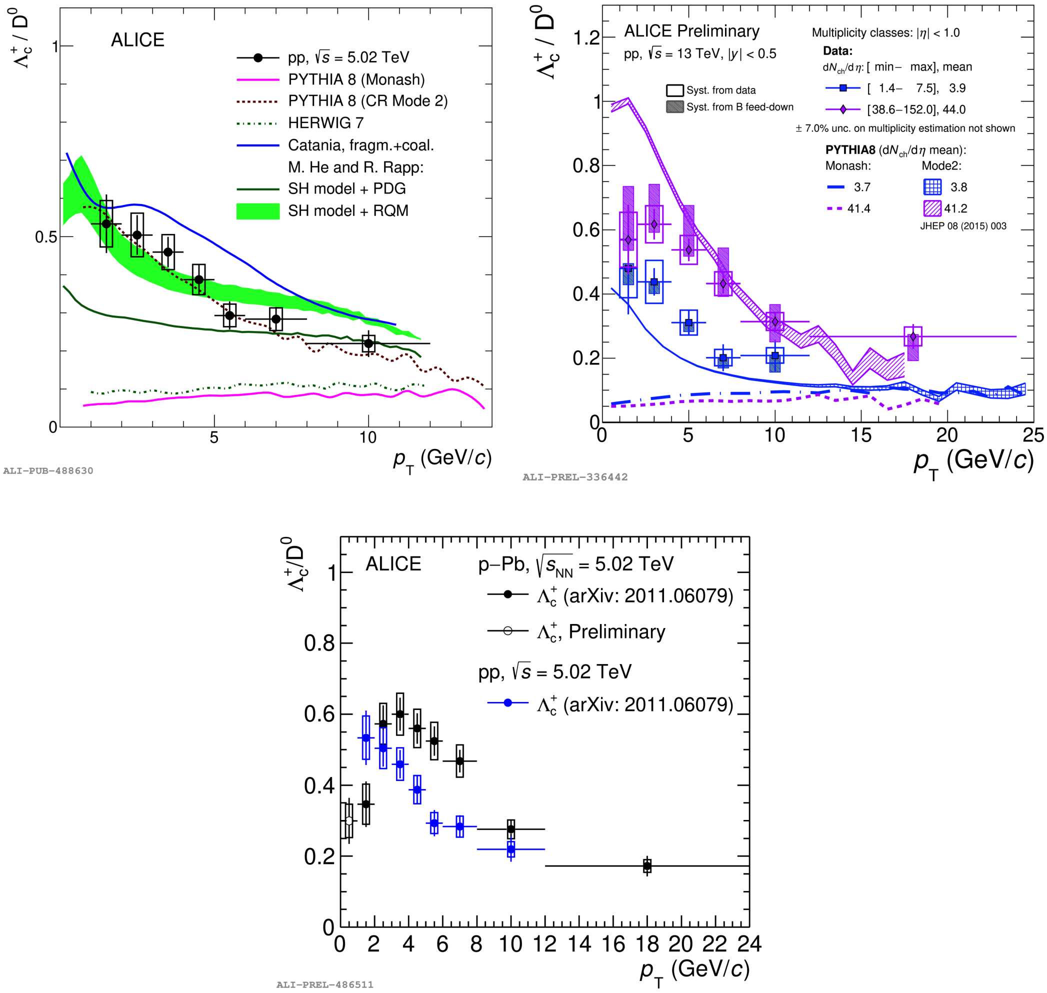

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Figure 1: Top left: prompt Λ_c^+/D^0 ratio measured in pp collisions at $\sqrt{s}$ = 5.02 TeV compared with theoretical predictions. Top right: prompt Λ_c^+/D^0 ratios measured in pp collisions at $\sqrt{s}$ = 13 TeV for the lowest (blue) and highest (purple) multiplicity classes at midrapidity. The measurements are compared to PYTHIA predictions with the Monash and the CR tunes [8, 9]. Bottom: prompt Λ_c^+/D^0 ratio measured in pp collisions at $\sqrt{s}$ = 5.02 TeV and in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.

observed. The measurement is strongly underestimated by the expectation from the default tune, Monash [8], of the PYTHIA event generator [10], in which the hadronisation processes are modelled via default string fragmentation mechanisms tuned on e^+e^- data. The PYTHIA Color-Reconnection (CR) Mode 2 tune [9], which includes string formation beyond the leading-colour approximation, provides a good description of the data collected at both $\sqrt{s}$ = 5.02 TeV and $\sqrt{s}$ = 13 TeV[2] and it also describes the p_T shape and the enhancement observed going torward higher event multiplicity. The Statistical Hadronisation Models with enhanced set of baryons (SHM+RQM) [11] describes the measurements, while the Catania model [12], in which the hadronization is implemented via both coalescence and fragmentation, tends to overestimate the data. The Λ_c^+/D^0 yield ratio measured in p–Pb collisions presents a different shape with respect to the one measured in pp collisions. There is a hint of a higher Λ_c^+/D^0 ratio at intermediate p_T that might also hint an interplay between Cold Nuclear Matter (CNM) effects and the radial-flow that pushes the spectra towards higher p_T in p–Pb.

The prompt $\Sigma_c^{0,++}$ p_T-differential production cross section was measured in pp collisions at $\sqrt{s}$ = 13 TeV [2]. Assuming the same production yield for the three isospin states $\Sigma_c^{0,+,++}$, the baryon-to-meson cross section ratio $\Sigma_c^{0,+,++}/D^0$, shown in the left panel of Fig. 2, was calculated. Values significantly larger than those measured in e^+e^- collisions are observed, indicating that baryon enhancement in hadronic collisions also extends to the other massive charm baryons.

As reported on the right panel of Fig. 2, the feed-down contribution to Λ_c^+ production from $\Sigma_c^{0,+,++}$ ($\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}/\Lambda_c^+$) can explain part of the Λ_c^+ enhancement in pp collisions: at low p_T up approximately 40% of the Λ_c^+ yield comes from $\Sigma_c^{0,+,++}$ decay. The PYTHIA prediction with CR tunes reproduces the $\Sigma_c^{0,+,++}/D^0$ but overestimates the $\Lambda_c^+(\longleftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$ ratio. Both measurements are described within uncertainties by the SHM+RQM, by the Catania models and by the quark coalescence model (QCM) [13].

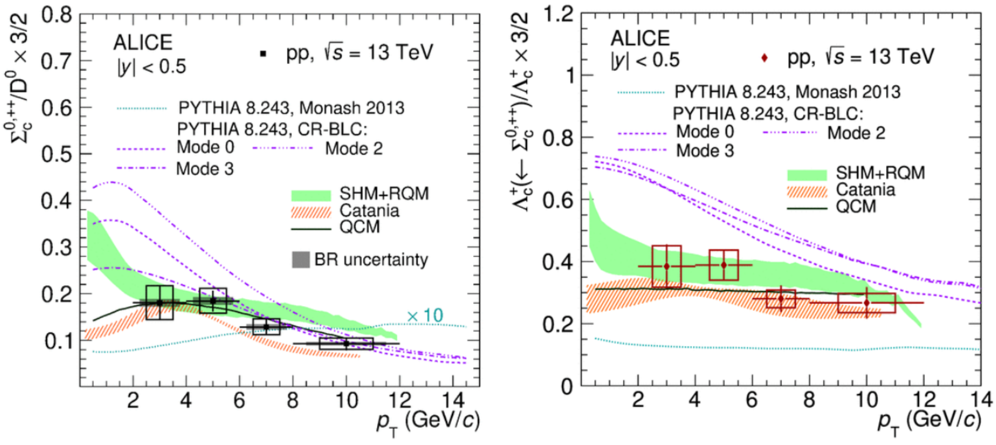

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Figure 2: Prompt $\Sigma_c^{0,+,++}/D^0$(left) and $\Lambda_c^+(\longleftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$ (right) ratios measured in pp collisions at $\sqrt{s}$ = 13 TeV, compared with model expectations.

The enhancement of the baryon-to-meson ratio is observed for the Ξ_c^0 and Ξ_c^+ as well [3, 4]. In Fig. 3, the Ξ_c^0/D^0 and the $\Xi_c^{0,+}/D^0$ ratios are reported in pp collisions at $\sqrt{s}$ = 5.02 TeV and $\sqrt{s}$ = 13 TeV, respectively. Differently to what has been observed for the Λ_c^+/D^0, the CR Mode 2 version of PYTHIA and the SHM+RQM models underestimate the observed $\Xi_c^{0,+}/D^0$ ratio, while the Catania model lies on the lower edge of the data uncertainty band.

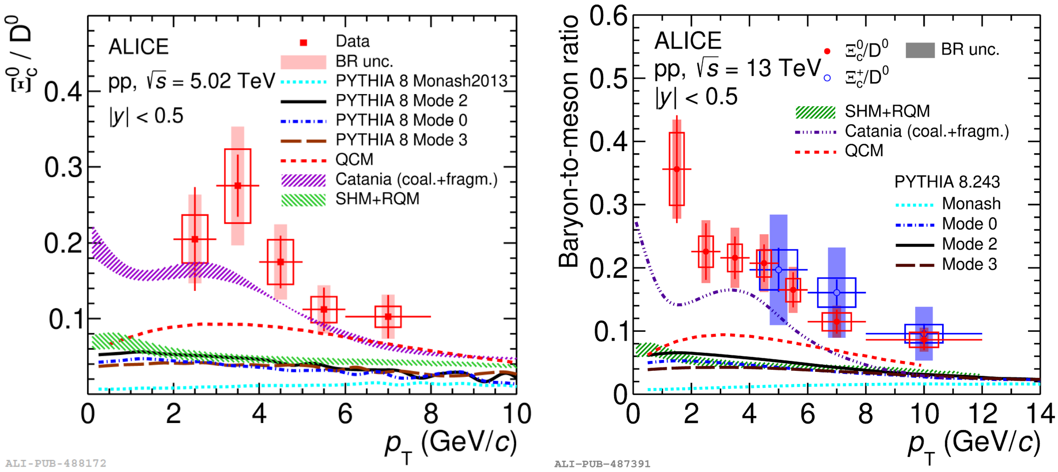

Figure 3: Left: prompt Ξ_c^0/D^0 ratio in pp collisions at $\sqrt{s}$ = 5.02 TeV compared with theoretical models. Right: prompt Ξ_c^0/D^0 and $\Xi_c^{0,+}/D^0$ ratios in pp collisions at $\sqrt{s}$ = 13 TeV compared with theoretical predictions.

The first measurement of the Ω_c^0 p_T-differential production cross section times the branching ratio BR($\Omega_c^0 \rightarrow \Omega^-\pi^+$) and the BR($\Omega_c^0 \rightarrow \Omega^-\pi^+$)×$\Omega_c^0/D^0$ ratio in pp collisions at $\sqrt{s}$ = 13 TeV are shown in Fig. 4. The BR($\Omega_c^0 \rightarrow \Omega^-\pi^+$)×$\Omega_c^0/D^0$ ratio does not show a significant p_T dependence within the uncertainties. The PYTHIA Monash tune as well as the CR modes, and the QCM model underestimate the experimental results, while the Catania model is the one that gets closer to the data.

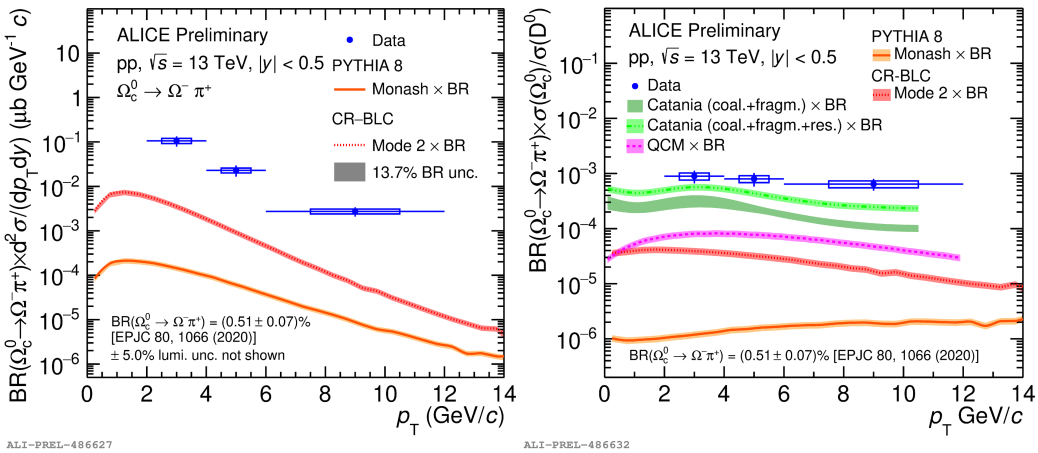

Figure 4: Left: Ω_c^0 p_T-differential production cross section times the BR($\Omega_c^0 \rightarrow \Omega^-\pi^+$) measurement compared with theoretical predictions. Right: BR($\Omega_c^0 \rightarrow \Omega^-\pi^+$)×$\Omega_c^0/D^0$ ratio in pp collisions at $\sqrt{s}$ = 13 TeV compared with model expectations.

The measured D^0, D^+, D_s^+, Λ_c^+ and Ξ_c^0 production cross sections in pp collisions at $\sqrt{s}$ = 5.02 TeV were employed to calculate the $c\bar{c}$ production cross section and the charm-quark fragmentation fractions at midrapidity ($|y| < 0.5$) [14]. The contribution of the Ξ_c^0 was multiplied by a factor of 2 in order to account for the contribution from the Ξ_c^+ and an asymmetric systematic uncertainty was added to consider the contribution from the Ω_c^0. The hadron fragmentation fractions were estimated as the ratio of the hadron-production cross section over the sum of cross sections of all measured ground states of charm hadrons. The D^0 fragmentation fraction was then used to update the $c\bar{c}$ cross sections calculated at $\sqrt{s}$ = 2.76 TeV and $\sqrt{s}$ = 7 TeV. The prompt charm cross section measured by ALICE, STAR [15] and PHENIX [16] is reported on the left panel of Fig. 5 as a function of the collision energy. The data sit on the upper edges of the NNLO [17] and FONLL [18] calculations, which are based on the factorization approach.

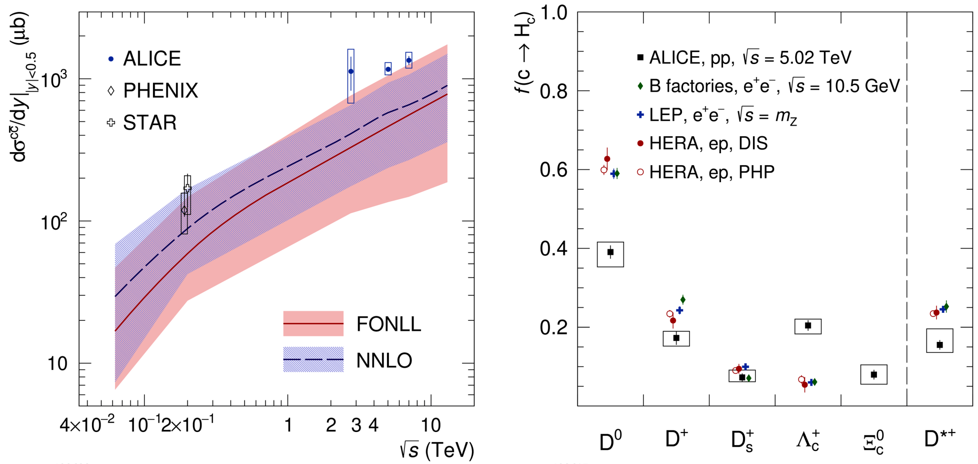

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Figure 5: Left: $c\bar{c}$ production cross section at midrapidity per unit of rapidity as a function of the collision energy. The comparison with FONLL (red band) and NNLO (violet band) pQCD calculations is shown. Right: charm-quark fragmentation fractions into charm hadrons measured in pp collisions at $\sqrt{s}$ = 5.02 TeV, compared to data from e^+e^- collisions at LEP and at B factories, and in ep collisions at HERA.

The charm fragmentation fractions measured in pp collisions at $\sqrt{s}$ = 5.02 TeV and the comparison with values derived from experimental measurements performed in e^+e^- collisions at LEP and B factories, as well as in ep collisions at HERA [19] are shown on the right panel of Fig. 5. The fragmentation fractions measured at midrapidity in pp collisions at the LHC are different from the ones measured in e^+e^- and ep collisions, providing significant evidence that the assumption of universality, i.e. indipendence from the collision system, of parton-to-hadron fragmentation is not valid already in pp collisions.

4. Conclusions

An overview of selected recent charm baryon results from ALICE in pp and p-Pb colliding systems has been presented. Baryon-to-meson ratios are significantly higher at low-intermediate p_T with respect to measurements done at the electron colliders, indicating that the charm fragmentation functions are not universal across colliding systems and that the hadronisation mechanisms in hadronic collisions are not fully understood. The ALICE upgrade program (LHC Run 3 and 4), which includes an important improvement of the Inner-Tracking-System performance (ITS), will allow for a better separation of signal and background and thus an overall enhancement of the precision of the charm-baryon measurements.

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