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CONSTRAINING HADRONIZATION PROCESSES WITH CHARM BARYONS IN *pp* AND *p*–Pb COLLISIONS WITH ALICE*

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In this contribution, we present the latest measurements of D^0, D^+, and D_s^+ mesons together with the final measurements of Λ_c^+, $\Xi_c^{0,+}$, $\Sigma_c^{0,++}$, and the first measurement of Ω_c^0 baryons performed with the ALICE detector at midrapidity in *pp* collisions at $\sqrt{s} = 5.02$ and $\sqrt{s} = 13$ TeV. Recent measurements of charm-baryon production at midrapidity in small systems show a baryon-to-meson ratio significantly higher than that in e^+e^- and e^-p 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 hadronization in a parton-rich environment like the one produced in *pp* collisions at the LHC energies. Furthermore, the recent Λ_c^+/D^0 yield ratio, measured down to $p_{\mathrm{T}} = 0$ in *p*–Pb collisions will be discussed. The measurement of charm baryons in *p*-nucleus collisions provides important information about a 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-flavour hadrons. Finally, the first measurements of charm fragmentation fractions and charm production cross section at midrapidity per unit of rapidity will be shown for *pp* and *p*–Pb collisions using all measured single-charm ground-state hadrons.

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1. Heavy-flavour (HF) production in *pp* collisions

The measurements of heavy-flavour hadron production at the LHC are fundamental tests of perturbative QCD calculations in proton–proton (*pp*) collisions. The standard description of heavy-flavour hadron production is based on a factorization approach [1], according to which it can be expressed

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as the convolution of: (a) the parton distribution functions (PDFs), describing how partons are distributed within the colliding protons; (b) the cross section of the partonic scattering, in which heavy quarks are produced; (c) the fragmentation functions, which quantify the probability for a quark to produce a hadron of a certain species with a given momentum fraction. The latter ingredients, encoding information about charm hadronization, are usually considered universal among collision systems and constrained from e^+e^- and e^-p collision measurements [2]. The charm-quark hadronization can be investigated experimentally by measuring the relative charm-hadron abundances, corresponding to ratios of charm fragmentation functions.

2. Relative charm-meson abundances measurements

The theoretical calculations based on the factorization approach successfully describe the measurements of prompt and non-prompt D^+/D^0 and $D_s^+/(D^0 + D^+)$ ratios at midrapidity in pp collisions at $\sqrt{s} = 5.02$ TeV by ALICE [3]. These meson-to-meson ratios are almost independent of the transverse momentum (p_{T}) and are in agreement with e^+e^- measurements and calculations adopting the factorization approach with universal fragmentation functions. Recent measurements of baryon-to-meson ratios show a significant p_{T} dependence and an enhancement compared to e^+e^- measurements. The Λ_c^+/D^0 ratio at low p_{T} at midrapidity in pp collision at $\sqrt{s} = 5.02$ and 13 TeV [4–6] is larger by about a factor of five with respect to the Λ_c^+/D^0 value ≈ 0.11 measured in e^+e^- collisions at LEP [2] and to the predictions of the Monash tune of PYTHIA 8 event generator [7], where fragmentation functions tuned on e^+e^- results are adopted. A similar enhancement at low p_{T} for the baryon-to-meson ratio was also observed in the beauty sector [8]. Many hypotheses were proposed to explain it. The main questions raised by these results are whether the charm hadronization at the LHC is influenced, also in pp collisions, by mechanisms different from fragmentation and whether fragmentation functions are not universal.

3. The ALICE experiment

One of the main contributors to the study of the charm-quark hadronization in hadronic collisions at the LHC is the ALICE experiment. ALICE was designed specifically to study the properties of strongly-interacting matter in hadronic collisions and its phase transition to the quark–gluon plasma (QGP) state in heavy-ion collisions. The reconstruction of charm-baryon decays in the ALICE central barrel is possible thanks to the high pointing resolution provided by the Inner Tracking System (ITS), fundamental to reconstruct the charm-baryon decay point and resolve it from the beam interaction point. The purity of the decay reconstruction is enhanced by the excellent particle identification (PID) capabilities provided by the Time Projection Chamber (TPC), the main tracker of the experiment, and the Time Of Flight (TOF) detector. The charm-baryon results discussed here are obtained from the analysis of *pp* collisions at $\sqrt{s} = 5.02$ TeV ($\mathcal{L}_{\mathrm{int}} \approx 19\ \mathrm{nb}^{-1}$) and $\sqrt{s} = 13$ TeV ($\mathcal{L}_{\mathrm{int}} \approx 32\ \mathrm{nb}^{-1}$) and *p*–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV ($\mathcal{L}_{\mathrm{int}} \approx 287\ \mu\mathrm{b}^{-1}$) collected during the LHC Run 2.

4. Theoretical models for charm hadronization at the LHC

In Fig. 1, the prompt Λ_c^+/D^0 ratios at midrapidity measured in *pp* collisions at $\sqrt{s} = 5.02$ and 13 TeV with the ALICE experiment are shown. The previously published measurements for $p_{\mathrm{T}} > 1$ GeV/c [4–6] are extended to lower p_{T}, providing the first production measurement of prompt Λ_c^+ baryon down to $p_{\mathrm{T}} = 0$ at the LHC. The Λ_c^+/D^0 at low p_{T} in *pp* collisions at the LHC is significantly underestimated by the Monash tune of PYTHIA. Such a behaviour is being investigated by the theory community and several model predictions with different charm hadronization mechanisms have been provided. In the PYTHIA 8 event generator with improved colour reconnection mechanisms [9], baryon production is enhanced by the junctions. This is a new string topology enabled by a colour reconnection mechanism beyond the leading colour approximation influencing partons from all the multi-parton interactions in the colliding protons and those from the beam remnants. In the Quark (re-)Combination Mechanism (QCM [10]) model, the production

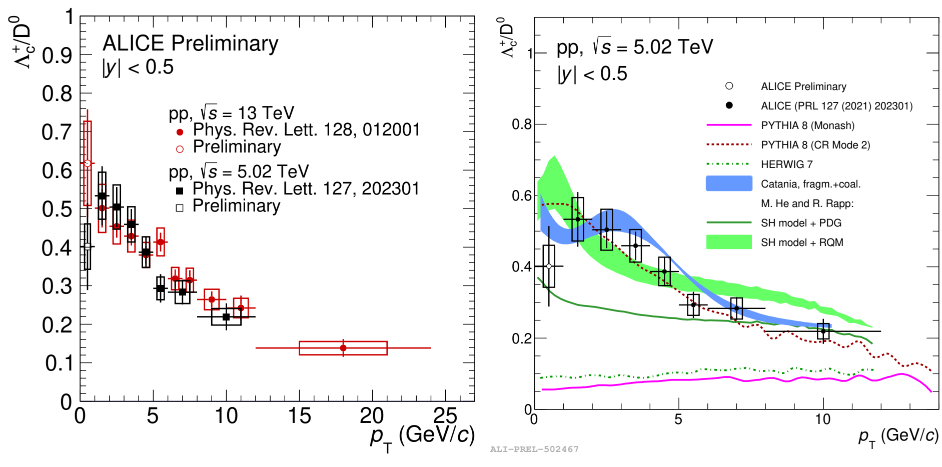

Fig. 1. Prompt Λ_c^+/D^0 ratio measured in *pp* collisions with the ALICE experiment. Left: measurements in *pp* collisions at $\sqrt{s} = 5.02$ and 13 TeV. Right: Λ_c^+/D^0 ratio in *pp* collisions at $\sqrt{s} = 5.02$ TeV compared with model predictions.

of charm hadrons at low p_{T} is explained by the coalescence of charm quarks produced in hard scatterings with equal-velocity light quarks from the fragmentation. The coalescence mechanism is responsible for the charm-hadron production at low p_{T} also in the Catania model [11], where the hadronization is conceived as an interplay between fragmentation and coalescence with light quarks present in a thermalised system of u, d, s quarks and gluons. Another approach is based on the Statistical Hadronization Model (SHM), where the hadronization is determined by thermo-statistical weights governed by the hadron masses, in the presence of an augmented set of excited charm baryons predicted by the Relativistic Quark Model (RQM), whose strong decays increment the amount of ground-state charm baryons [12].

5. Recent charm baryon-to-meson measurements by ALICE

To understand the underlying mechanisms governing the charm hadronization at the LHC, the model predictions need to be compared with production measurements of more charm baryons. The ALICE experiment measured for the first time the $\Sigma_c^{0,++}$ (2455) production in pp collisions at $\sqrt{s} = 13$ TeV at midrapidity [6]. The ratio to D^0 production yield is significantly larger than those in e^+e^- and e^-p results and shows a larger relative enhancement compared to that of the Λ_c^+/D^0 ratio. The $\Sigma_c^{0,++}/D^0$ enhancement partially accounts for that of Λ_c^+/D^0 and it is described by the model predictions described above. The fraction of Λ_c^+ baryons from strong decays of $\Sigma_c^{0,++}$ (2455) states amounts to about 38% in the range of $2 < p_{\mathrm{T}} < 12$ GeV/c, more than a factor 2 higher than e^+e^- and e^-p collisions. This result is overestimated by the PYTHIA 8 colour reconnection modes, suggesting that some ingredients are missing for the description of the direct Λ_c^+ production. A significant enhancement with respect to the e^+e^- results is observed also for the $\Xi_c^{0,+}(dsc, usc)/D^0$ ratio in pp collisions [13, 14], but in this case all the model predictions significantly underestimate the measurement. Given that the prompt strange-to-non-strange D-meson ratio at the same energy does not show any significant difference with e^+e^- results, it is unlikely to ascribe the reason for the $\Xi_c^{0,+}/D^0$ enhancement only to the valence strange quark of the $\Xi_c^{0,+}$. The $\Xi_c^{0,+}/\Sigma_c^{0,++}$ is compatible with the Monash predictions and show a similar enhancement with respect to e^+e^- results. A possible explanation for this behaviour may be the similar masses of the valence light diquarks in the two baryons ($m(uu, ud, dd)_1 \approx m(us)_0$). The ALICE experiment measured for the first time the $\Omega_c^0(ssc)$ production in pp collisions at $\sqrt{s} = 13$ TeV at midrapidity [15]. Also in this case, the ratio to the D^0 is significantly underestimated by the models, while the ratio to the Ξ_c^0 is described by the Catania model including higher-mass resonance decays.

In the left panel of Fig. 2, the p_{T}-differential Λ_c^+/D^0 ratio in *pp* and *p*–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured for the first time down to $p_{\mathrm{T}} = 0$ with the ALICE experiment is shown. The result in *p*–Pb collisions is larger than the *pp* one for $p_{\mathrm{T}} > 3$ GeV/c given the harder p_{T} spectrum of Λ_c^+ baryon, but the p_{T}-integrated ratio does not show any significant difference between the two collision systems. This holds also for the charm fragmentation fractions, shown in the right panel of Fig. 2, and the $c\bar{c}$ production cross section at midrapidity. As done in [16], the $c\bar{c}$ cross section is measured for the first time in *p*–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at the LHC as the sum of all ground-state charm-hadron cross sections. It is compatible with that in *pp* collisions at the same energy, after scaling for the Pb ion mass number, as well as with the FONLL prediction. ALICE studied the charm-quark hadronization also by measuring the Λ_c^+/D^0 ratio in *pp*, *p*–Pb , and Pb–Pb collisions as a function of event multiplicity. The p_{T}-integrated ratio does not show a significant multiplicity dependence and it is compatible among the different systems. More details are in [17].

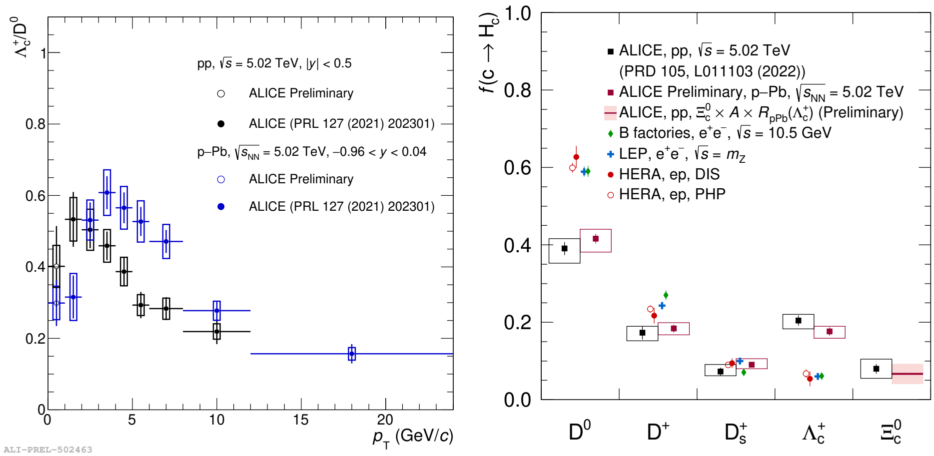

Fig. 2. Left: prompt Λ_c^+/D^0 ratio measured in *pp* and *p*–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV down to $p_{\mathrm{T}} = 0$ with the ALICE experiment. Right: p_{T}-integrated charm fragmentation fractions in *pp* and *p*–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV by ALICE.

6. Conclusions

The most recent measurements of charm-baryon production in *pp* and *p*–Pb collisions with by ALICE show significant differences with respect to results in e^+e^- and e^-p collisions, suggesting that the charm-quark hadronization is not universal among collision systems. To completely understand the mechanisms underlying these phenomena, a systematic comparison between model predictions and measurements is mandatory. The results from the ALICE experiment will improve thanks to the Run 3 data-taking campaign, given the larger data sample that will be collected and the improved spatial resolution provided by the upgraded ITS detector. These ingredients will also open the door to the full reconstruction of beauty hadrons in ALICE.

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