Investigation of charm-quark hadronization into baryons in hadronic collisions with ALICE

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Abstract. A comprehensive investigation into charm-baryon production provides insight into understanding charm-quark hadronization process. In this contribution, the charm-quark hadronization mechanism is discussed in terms of the production yield ratio between charm hadron species measured by ALICE Collaboration. Measurements of Λ_c^+, $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$ and Ω_c^0 in pp collisions, Λ_c^+ and Ξ_c^0 in p–Pb collisions are presented, together with the Λ_c^+ measurement in larger collision systems, Pb–Pb collisions. Furthermore, the charm-quark hadronization mechanism is discussed based on the fragmentation fractions computed for pp and p–Pb collisions. A preliminary result on $\Sigma_c^{0,++}$ measurement with Run 3 data is also presented.

1 Introduction

In hadronic collisions, heavy-flavour (HF) hadrons are produced from the hadronization of heavy quarks generated through the hard-scattering process occurring in the initial collision stages. Typically, the production cross section of HF hadrons in pp collisions is computed based on the QCD factorization approach, as a convolution of three independent terms: i) the parton distribution functions, ii) the production cross section of the heavy quarks and iii) the fragmentation functions which model the heavy-quark hadronization. The fragmentation functions, which cannot be calculated with perturbative QCD (pQCD) framework, are constrained from the measurements performed for e^+e^- or ep collisions. This approach relies on the assumption that the fragmentation functions are universal across different collision systems.

From an experimental point of view, measuring HF hadrons in pp collisions provides a fundamental test for the validity of the pQCD calculations and their assumptions. In particular, the production yield ratio between hadron species can be a good tool to understand how the heavy quarks hadronize into given hadrons. The hadronization process in more complex environments can be studied in larger collisions systems, such as p–Pb or Pb–Pb collisions. In p–Pb collisions, the cold nuclear matter effects can be studied in detail, and the measurements in Pb–Pb collisions allow us to investigate the modification of the hadronization process in an extreme environment, in which strongly interacting QCD matter exists. Furthermore, a comprehensive study of the measurements from small to large collision systems provides insight into how the hadronization process evolves with the collision system size and on the possible onset of further hadronization mechanisms in addition to quark fragmentation, such as the coalescence.

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Thanks to its excellent tracking, vertexing and particle identification capabilities, ALICE was able to measure several charm baryons, Λ_c^+, $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$ and Ω_c^0, in different collision systems, using the data samples collected during the LHC Run 2 data taking.

2 Charm baryon measurement with ALICE

2.1 Non-strange charm-baryon measurements

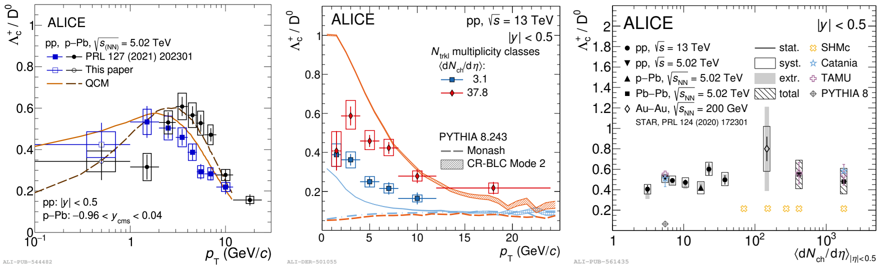

Figure 1. Left: Λ_c^+/D^0 ratios in pp and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV along with QCM predictions. Middle: Λ_c^+/D^0 ratios in pp collisions at $\sqrt{s} = 13$ TeV for two different classes of event-multiplicity. Right: p_T-integrated Λ_c^+/D^0 ratio as a function of average event multiplicity along with theory predictions.

As shown in left panel of Figure 1, ALICE measured the Λ_c^+/D^0 ratio in pp and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV down to $p_T = 0$ [1]. The overall magnitude of the Λ_c^+/D^0 ratio is similar in the two collision systems, but in the intermediate p_T region a hint of a shift toward higher p_T is observed in p–Pb collisions with respect to pp collisions. Compared to the baryon-to-meson ratio measured in e^+e^- collisions, whose LEP average was found to be 0.113 ± 0.013 (stat.) ± 0.006 (syst.), the Λ_c^+/D^0 ratio in both hadronic collision systems shows a significant enhancement with strong p_T dependence. The QCM model [2] which includes a recombination scenario even for pp collisions, describes the measurements for both pp and p–Pb collisions.

Performing the measurement in different event-multiplicity classes provides further information on how hadronization process is influenced by the event-multiplicity. Figure 1 middle panel shows the Λ_c^+/D^0 ratio measured in low and high event-multiplicity classes in pp collisions at $\sqrt{s} = 13$ TeV [3]. The Λ_c^+/D^0 ratio in the high event-multiplicity class is found to be 5.3σ higher than that in the low event-multiplicity class. The PYTHIA 8 event generator with Monash tune [4], using fragmentation functions tuned to the measurements from e^+e^- collisions, failed to describe both p_T and event-multiplicity dependent Λ_c^+/D^0 ratios obtained in data, as had already been observed in the comparison to the multiplicity-integrated Λ_c^+/D^0 ratio measurement. The PYTHIA 8 CR-BLC Mode 2 tune [5], which allows further combinations of partons from different Multiple Parton Interaction (MPI) introducing *junction* topologies, reproduces the data. ALICE also measured Λ_c^+/D^0 ratio in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [6]. In that measurement, the Λ_c^+/D^0 ratio in central and mid-central Pb–Pb collisions was higher than that in pp collisions by 3.7σ and 2.0σ, respectively.

Based on these measurements, the p_T-integrated Λ_c^+/D^0 ratio as a function of average event-multiplicity was calculated to study the possible trend with increasing event-multiplicity, as shown in the right panel of Figure 1 [6]. No significant multiplicity dependence is observed, differently from what observed for the p_T-differential Λ_c^+/D^0 ratio for $1 < p_T < 12$ GeV/c. This feature could be explained by assuming a different redistribution of p_T for baryons and mesons across different multiplicities, rather than an overall baryon production enhancement. The SHMc[7], Catania[8] and TAMU[9] describe well the data, whereas PYTHIA 8 significantly underestimates the measurements.

The $\Sigma_c^{0,++}(2455)$ baryon, which is the isospin $I = 1$ partner of the isospin singlet Λ_c^+ baryon, contributes to Λ_c^+ production via its strong decay. ALICE has measured the $\Sigma_c^{0,++}(2455)$ production using the Run 2 data sample [10], and recently performed a measurement of the production of $\Sigma_c^{0,++}(2520)$ state with the larger data samples of the LHC Run 3. Figure 2 left panel shows preliminary results for the $\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$ ratio measured in pp collisions at $\sqrt{s} = 13.6$ TeV with Run 3 data, along with PYTHIA 8 CR-BLC Mode 2 predictions. Such predictions underestimate the $\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$ ratio. However, as the parameter (probQQ1toQQ0join_charm), which regulates the suppression of the heavy-diquark spin $S = 1$ state with respect to $S = 0$ state is increased with respect to its default value, the predictions get closer to the measurement. This preliminary results suggest that the $S = 1$ diquarks may play a significant role in $\Sigma_c^{0,++}$ production [11]. This measurement is expected to provide valuable constraints for the theory development.

2.2 Charm-strange baryon measurements

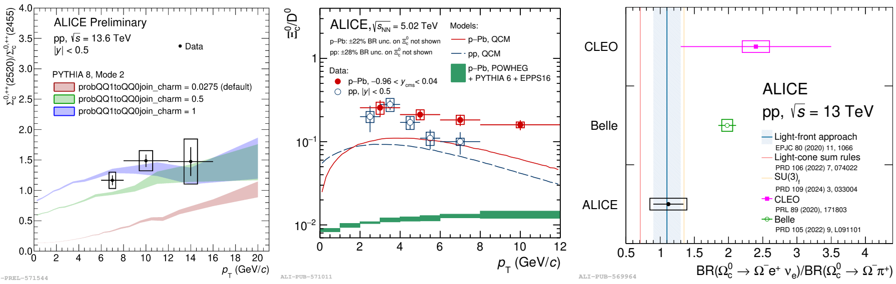

Figure 2. Left: $\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$ ratio in pp collisions at $\sqrt{s} = 13.6$ TeV along with PYTHIA 8 CR-BLC predictions. Middle: Ξ_c^0/D^0 ratio in pp and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with model predictions. Right: $BR(\Omega_c^0 \to \Omega^- e^+ \nu_e)/BR(\Omega_c^0 \to \Omega^- \pi^+)$ compared with theory calculations.

ALICE measured multiple charm baryons containing strange quarks as well. The middle panel of Figure 2 shows the Ξ_c^0/D^0 ratio measured in pp and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [12]. The QCM model, which describes correctly the Λ_c^+/D^0 ratio, underestimates the Ξ_c^0/D^0 ratio by a factor of about 2 for both pp and p–Pb collisions collisions, and POWHEG+PYTHIA6 with fragmentation functions tuned to e^+e^- measurements, underestimates the data by a factor of about 50, implying that the baryon enhancement in charm-strange baryons is even larger than for non-strange charm baryons.

The Ω_c^0 baryon was also measured in pp collisions at $\sqrt{s} = 13$ TeV [13], but a precise comparison with theory predictions is not possible, since the branching ratio (BR) of the hadronic decay channel used for the Ω_c^0 reconstruction ($\Omega_c^0 \to \Omega^- \pi^+$) has not been expermentally measured yet, and its theory estimations are affected by large uncertainties. As shown in the right panel of Figure 2, the recent ALICE measurement of the BR ratio between hadronic and semileptonic decay channels [14] is expected to provide a constraint for the Ω_c^0 branching ratio. This measurement is consistent with that measured by the CLEO [15] and Belle [16] Collaborations within 2.3σ and 1σ respectively, and also compatible with current state-of-the-art theory calculations [17–19].

2.3 Charm-quark fragmentation fraction

Measurements of the various charm baryons provide the ingredients to calculate the fragmentation fractions of charm quarks in pp and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [20], as shown in Figure 3. The fragmentation fractions measured for pp and p–Pb collisions are consistent with each other within the uncertainties. Compared to leptonic collisions, a significantly enhanced baryon production and reduced non-strange D meson production are observed. This discrepancy suggests that the hadronization process in parton-rich environment is governed by different mechanisms with respect to leptonic collisions.

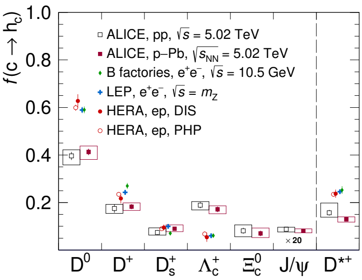

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Figure 3. Fragmentation fractions of charm-quarks in hadronic collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV [20].

3 Summary and outlook

ALICE measured charm baryons in various hadronic collision systems, and observed an enhancement of baryon-to-meson ratio with respect to that measured in leptonic collisions. The fragmentation fractions computed from these measurements clearly show that the hadron production mechanism in hadronic collisions is different from that in leptonic collisions. Models implementing baryon enhancement via modified hadronization with respect to in-vacuum fragmentation explain the charm non-strange baryon productions, while they still do not fully reproduce the phenomena obtained for charm-strange baryons. The increased size of data samples being collected at the LHC during Run 3, together with the improved detector performance after the ALICE upgrade, will allow us to reach extended p_{T} region with improved precision and shed further light on the charm-quark hadronization mechanisms.

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