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Studying charm-quark hadronization via charm-baryon production measurements in pp collisions at the LHC with ALICE

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Abstract. In these proceedings, the measurements of strange ($\Xi_c^{0,+}$) and non-strange (Λ_c^+, $\Sigma_c^{0,++}$) charm-baryon production are reported. Moreover, the first measurements of the $\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$ cross-section ratio and Λ_c^+–p angular correlation are discussed utilizing the large data sample of pp collisions at $\sqrt{s}$ = 13.6 TeV collected during LHC Run 3. These results are compared with various theoretical model predictions.

1 Introduction

Charm-baryon production measurements in proton–proton (pp) collisions at the LHC are fundamental to investigate the charm-quark hadronization process and test perturbative QCD-based calculations. Recent measurements in pp collisions reveal baryon-to-meson ratios significantly higher than those observed in e^+e^- collisions [1], challenging the validity of theoretical calculations based on the factorization approach and the assumption of universal fragmentation functions across collision systems [2]. Several QCD-inspired effective models (e.g., Catania [3], POWLANG [4], QCM [5]) and Monte Carlo generators (e.g., PYTHIA 8 [6, 7], EPOS 4 [8, 9]) employ different approaches to describe charm-quark hadronization and to explain the observed baryon production at the LHC. However, most models struggle to simultaneously describe the production of strange and non-strange charm hadrons. Therefore, precise measurements of both strange and non-strange charm-baryon production are crucial to constrain model calculations and to improve the understanding of the mechanisms governing charm-quark hadronization in pp collisions.

In these proceedings, the ALICE measurements of strange and non-strange charm-baryon production in pp collisions are discussed. The charm-baryon reconstruction is performed using the central-barrel detectors [10, 11], which cover the pseudorapidity range $|\eta| < 0.9$. The Inner Tracking System (ITS) provides primary and secondary-vertex reconstruction as well as charged-particle tracking, while the Time Projection Chamber (TPC) offers tracking and particle identification (PID) capabilities. Additional PID is achieved with the Time-Of-Flight (TOF) detector. Together, these detectors assure excellent tracking and PID performance down to very low momentum. The datasets used consist of a sample of pp collisions collected in 2023 during Run 3 at $\sqrt{s}$ = 13.6 TeV and of the full minimum bias sample collected during Run 2 at $\sqrt{s}$ = 13 TeV. They correspond to integrated luminosities of 5 pb^{-1} and 32 nb^{-1}, respectively. In Run 3, the impact-parameter resolution in the transverse plane is improved by a factor of about two compared to Run 2, thanks to the detector upgrade [12].

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2 Results and Discussion

A remarkable enhancement is observed in the $\Sigma_c^{0,++}/D^0$ and $\Sigma_c^{0,++}/\Lambda_c^+$ ratios compared to the results from e^+e^- collisions [13]. The $\Sigma_c^{0,++}/D^0$ ratio is underestimated by the PYTHIA 8 Monash tune [14], while it is described by the other mentioned models, and by a version of PYTHIA 8 with colour reconnection beyond leading colour (CR-BLC) [7]. In contrast, the $\Sigma_c^{0,++}/\Lambda_c^+$ ratio is overestimated by the PYTHIA 8 CR-BLC. These measurements suggest that further input from excited charm-baryon measurements may be necessary to improve the modeling of charm-baryon production.

In Fig. 1, the ratio $\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$ is shown as a function of transverse momentum (p_T) in pp collisions at $\sqrt{s}$ = 13.6 TeV in the interval $6 < p_T < 16$ GeV/c, and compared with PYTHIA 8 CR-BLC Mode 2 [7]. In PYTHIA 8 CR-BLC, the model parameter `probQQ1toQQ0join_charm` determines the suppression of spin–1 charm–light diquark production in junctions relative to spin–0 charm-light diquarks: this regulates the relative abundances of $\Sigma_c^{0,++}$ and Λ_c^+ states produced in junctions. The value of this parameter close to 0 means that spin–1 diquark production is largely suppressed while the value 1 implies no suppression. This parameter can be tuned based on these measurements [1]. In the Fig 1, it can be seen that the model describes the data better when the value of this parameter increases up to unity.

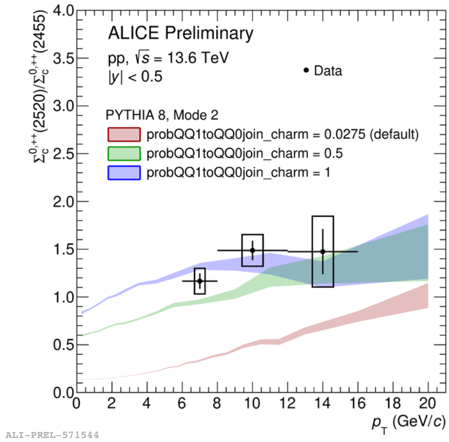

Figure 1. $\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$ ratio as a function of p_T in pp collisions at $\sqrt{s}$ = 13.6 TeV.

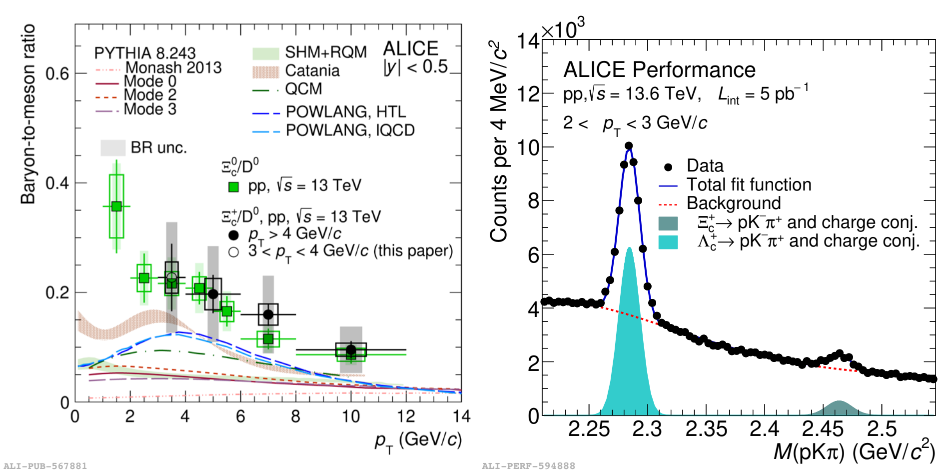

Figure 2. Left: $\Xi_c^{0,+}/D^0$ production cross-section ratio as a function of p_T in pp collisions at $\sqrt{s}$ = 13 TeV [2]; Right: (p, K, π) invariant-mass distribution showing the Ξ_c^+ and Λ_c^+ decay signals in pp collisions at $\sqrt{s}$ = 13.6 TeV.

In the left panel of Fig. 2, the production cross section ratio, $\Xi_c^{0,+}/D^0$ is shown as a function of p_T in pp collisions at $\sqrt{s}$ = 13 TeV [2]. The comparison of the measured $\Xi_c^{0,+}/D^0$ ratio

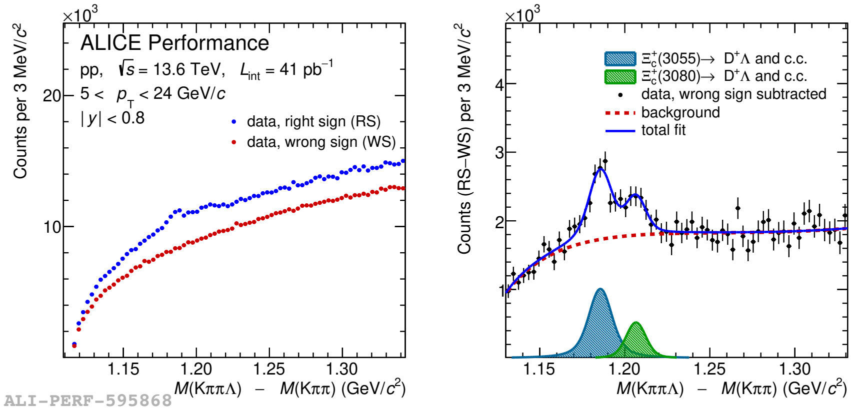

Figure 3. Left: ($D^+\Lambda$) invariant mass distribution with right charge sign and wrong charge sign; Right: subtraction of wrong charge contribution from right charge showing Ξ_c^+(3055 and 3080) decay signal in $5 < p_T < 24$ GeV/c in pp collisions at $\sqrt{s}$ = 13.6 TeV.

with model predictions shows that models successfully describing the Λ_c^+/D^0 ratio systematically underestimate the $\Xi_c^{0,+}/D^0$ results. The Catania model [3] provides values closer to the data, suggesting a possible indication of charm-quark coalescence in pp collisions. In p–Pb collisions, a possible rapidity dependence is observed in the Ξ_c^+/Λ_c^+ and Ξ_c^+/D^0 ratios, when ALICE results are compared to those by LHCb at forward and backward rapidities [15]. The large uncertainty on the branching ratios, in particular the about 50% uncertainty on BR of the $\Xi_c^+ \to pK^+\pi^-$ decay channel used by LHCb, limits the accuracy of the comparison. To overcome this limitation, a study of Ξ_c^+ production in ALICE using the $\Xi_c^+ \to pK^+\pi^-$ channel was started. The usage of this channel, which has the same final state as the $\Lambda_c^+ \to pK^+\pi^-$ one, provides the additional advantage of a partial cancellation of systematic uncertainties in the Ξ_c^+/Λ_c^+ ratio. In the right panel of Fig. 2, the invariant mass distribution obtained from the dataset collected in pp collisions at $\sqrt{s}$ = 13.6 TeV during LHC Run 3 is shown.

ALICE has recently observed the signal of excited Ξ_c^+(3055 and 3080) states in $\Xi_c^+ \to D^+\Lambda$ decay channel. The invariant mass distribution with right and wrong $D^+\Lambda$ combinations are shown in the left panel of Fig. 3 and right-sign signals after wrong-sign subtraction are visible in right panel of Fig. 3. These ongoing measurements will provide essential constraints to hadronization models, in particular for the SHM+RQM [16] model, which obtains large charm-baryon-to-meson ratios, close to measured ones, by assuming a large feed-down to ground-state baryons from a large set of higher-mass baryon states, including these excited Ξ_c^+ baryons.

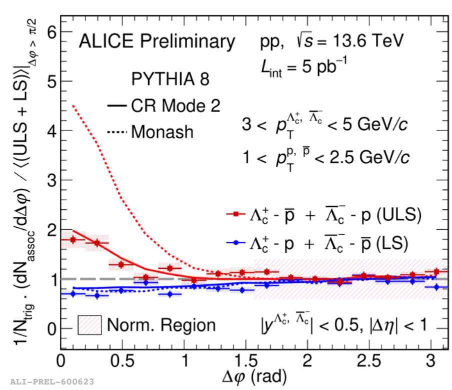

Figure 4. Λ_c^+–p angular correlation in $3 < p_T^{\Lambda_c} < 5$ GeV/c and $1 < p_T^{p} < 2.5$ GeV/c in pp collisions at $\sqrt{s}$ = 13.6 TeV.

The study of Λ_c^+–proton angular correlations in pp collisions provides a complementary perspective on charm hadronization compared to single-particle measurements. Figure 4 shows Λ_c^+–p azimuthal correlations for $3 < p_T^{\Lambda_c} < 5$ GeV/c and $1 < p_T^{p} < 2.5$ GeV/c in pp collisions at $\sqrt{s}$ = 13.6 TeV. The near-side peak observed in the unlike-sign (ULS) correlation is attributed to baryon-number compensation, which can be explained by light diquark–antidiquark production in the PYTHIA default string-breaking mechanism. In PYTHIA 8 Mode 2, the reduced near-side peak compared to the Monash tune arises from baryon production via string junctions, leading to a better agreement with the data.

3 Summary

The charm-baryon production reveals a significantly enhanced baryon-to-meson ratios compared to e^+e^- results, with varying levels of agreement across different hadronization models. While some models, such as the Catania approach, capture features of the Ξ_c production, others, including PYTHIA 8 tunes, require further tuning, particularly with inputs from excited charm-baryon states. Several measurements, affected by the large uncertainties in the branching ratios of the decay channels used in pp collisions, highlight the need for improved branching ratio measurements. Complementary Λ_c^+–proton correlation studies provide additional insight into baryon-number compensation mechanisms, offering crucial constraints for the refinement of charm-hadron production models.

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