Λ_c^+ Production and Baryon-to-Meson Ratios in pp and p-Pb Collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV at the LHC

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The prompt production of the charm baryon Λ_c^+ and the Λ_c^+/D^0 production ratios were measured at midrapidity with the ALICE detector in pp and p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. These new measurements show a clear decrease of the Λ_c^+/D^0 ratio with increasing transverse momentum (p_T) in both collision systems in the range $2 < p_T < 12$ GeV$/c$, exhibiting similarities with the light-flavor baryon-to-meson ratios p/π and Λ/K_S^0. At low p_T, predictions that include additional color-reconnection mechanisms beyond the leading-color approximation, assume the existence of additional higher-mass charm-baryon states, or include hadronization via coalescence can describe the data, while predictions driven by charm-quark fragmentation processes measured in e^+e^- and e^-p collisions significantly underestimate the data. The results presented in this Letter provide significant evidence that the established assumption of universality (colliding-system independence) of parton-to-hadron fragmentation is not sufficient to describe charm-baryon production in hadronic collisions at LHC energies.

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Heavy-flavor hadron production in hadronic collisions occurs through the fragmentation of a charm or beauty quark, created in hard parton-parton scattering processes, into a given meson or baryon. Theoretical calculations of heavy-flavor production generally use the QCD factorization theorem [1], which describes the hadron cross section as the convolution of three terms: the parton distribution functions, the parton hard-scattering cross sections, and the fragmentation functions. It is generally assumed that the fragmentation functions are universal between collision systems and energies, and the measurement of the relative production of different heavy-flavor hadron species is sensitive to fragmentation functions used in perturbative QCD (pQCD)-based calculations. While perturbative calculations at next-to-leading order with next-to-leading-log resummation [2–5] generally describe the D- and B-meson cross-section measurements [6–10] and the ratios of strange and nonstrange D mesons [6,10] within uncertainties, heavy-flavor baryon production is less well understood.

The Λ_c^+ production cross section in pp collisions at $\sqrt{s} = 7$ TeV and p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV was reported by ALICE [11]. It was shown that in both collision systems the p_T-differential Λ_c^+ production cross section is higher than predictions from pQCD calculations with charm fragmentation tuned on previous e^+e^- and e^-p measurements [2,3]. The Λ_c^+/D^0 ratio in pp and p-Pb collisions is consistent in both collision systems and also significantly underestimated by several Monte Carlo generators implementing different charm-quark fragmentation processes [12–15], suggesting that the fragmentation fractions of charm quarks into different hadronic states are nonuniversal with respect to collision system and center-of-mass energy. The production of charm baryons has recently been calculated within the k_T-factorization approach using unintegrated gluon distribution functions and the Peterson fragmentation functions [16], and with the general-mass variable-flavor-number scheme using updated fragmentation functions from OPAL and Belle [17]. These approaches are unable to simultaneously describe ALICE and LHCb data with the same set of parameters, suggesting that the independent parton fragmentation scheme is insufficient to fully describe the results. An alternative explanation has been offered by a statistical hadronization model, taking into account an augmented list of charm-baryon states based on guidance from the relativistic quark model (RQM) [18] and lattice QCD [19], which is able to reproduce the Λ_c^+/D^0 ratio measured by ALICE. The magnitude of the relative yields of Λ_b^0 baryons and beauty mesons in pp collisions measured by LHCb [20–22] and CMS [23] offers further evidence that the fragmentation fractions in the beauty sector also vary between collision systems.

The measurement of baryon production has also been important in heavy-ion collisions, where the high energy density and temperature create a color-deconfined state of matter [24]. A measured enhancement of the light-flavor

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[25,26] and charm [27–29] baryon-to-meson ratio at the LHC and RHIC can be explained via an additional mechanism of hadronization known as coalescence (or recombination), where soft quarks from the medium recombine to form a meson or baryon [30], in addition to hydrodynamical radial flow. Measurements in p-Pb collisions are crucial to provide an "intermediate" collision system where the generated particle multiplicities and energy densities are between those generated in pp and A-A collisions. ALICE and CMS reported an enhancement of the baryon-to-meson ratios in the light-flavor sector (p/π and Λ/K^0_S) at intermediate p_T ($2 < p_T < 10$ GeV/c) in high-multiplicity pp and p-Pb collisions similar to that observed in heavy-ion collisions [31,32]. This adds to the evidence that small systems also exhibit collective behavior, which may have similar physical origins in pp, p-A, and A-A collisions [33]. It has been suggested that hadronization of charm quarks via coalescence may also occur in pp and p-Pb collisions [34–36].

In this Letter, the measurements of the prompt production of the charm baryon Λ_c^+ in pp collisions at $\sqrt{s} = 5.02$ TeV in $|y| < 0.5$ and in p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV in $-0.96 < y < 0.04$ are presented, with a focus on the Λ_c^+/D^0 production ratios. The measurement is performed as an average of the Λ_c^+ and its charge conjugate $\bar{\Lambda}_c^-$, collectively referred to as Λ_c^+ in the following. Two hadronic decay channels were measured: $\Lambda_c^+ \to pK^-\pi^+$ (branching ratio BR $= 6.28 \pm 0.33\%$), and $\Lambda_c^+ \to pK^0_S$ (BR $= 1.59 \pm 0.08\%$)[37], which were reconstructed exploiting the topology of the weakly decaying Λ_c^+ ($c\tau = 60.7$ μm) [37]. The results from both decay channels were averaged to obtain more precise production cross sections. With respect to the results presented in [11], this work studies a different center-of-mass energy for pp collisions, and the cross section is measured in finer p_T intervals and over a wider p_T range. The overall precision of the measurements is significantly improved by a factor of 1.5–2, depending on p_T, for both pp and p-Pb collisions. For a detailed description of the analysis techniques, corrections, systematic uncertainty determination, and supplementary measurements, the reader is referred to [38].

A description of the ALICE detector and its performance are reported in [39,40]. The pp data sample was collected in 2017, and the p-Pb data sample was collected in 2016 during the LHC Run 2. Both pp and p-Pb collisions were recorded using a minimum bias (MB) trigger, which required coincident signals in the two V0 scintillator detectors located on either side of the interaction vertex. Further offline selection was applied in order to remove background from beam-gas collisions and other machine-induced backgrounds. To reduce superposition of more than one interaction within the colliding bunches (pileup), events with multiple reconstructed primary vertices were rejected. Only events with a z coordinate of the reconstructed vertex position within 10 cm of the nominal interaction point were used. With these requirements, approximately 1×10^9 MB-triggered pp events were selected, corresponding to an integrated luminosity of $\mathcal{L}_{\rm int} = 19.5$ nb^{-1} ($\pm 2.1\%$ [41]). Approximately 600×10^6 MB-triggered p-Pb events were selected, corresponding to $\mathcal{L}_{\rm int} = 287$ μb^{-1} ($\pm 3.7\%$ [42]).

The analysis techniques used for the results presented here are described in detail in [38]. Charged-particle tracks and particle decay vertices are reconstructed in the central barrel using the Inner Tracking System (ITS) and the Time Projection Chamber (TPC), which are located inside a solenoid magnet of field strength 0.5 T. In order to reduce the large combinatorial background, selections on the Λ_c^+ candidates were made based on the particle identification (PID) signals and the displacement of the decay tracks from the collision point. The PID was performed using information on the specific energy loss of charged particles as they pass through the gas of the TPC and, where available, with flight-time measurements given by the Time-Of-Flight detector (TOF).

For the $\Lambda_c^+ \to pK^-\pi^+$ analysis, candidates were built by reconstructing triplets of tracks with the correct configuration of charges. For this analysis, the high-resolution tracking provided by the detectors meant that the decay vertex of the Λ_c^+ candidates could be resolved from the interaction point. To identify each of the p, K, and π daughter tracks, information from the TPC and TOF was combined using the "maximum-probability" Bayesian approach described in [43]. Kinematic selections were made on the p_T of the decay products of the Λ_c^+, and geometrical selections were made on topological properties related to the displaced vertex of the Λ_c^+ decay.

The reconstruction of $\Lambda_c^+ \to pK^0_S$ candidates relied on reconstructing the V-shaped decay of the K^0_S meson into two pions, which was then combined with a proton track (bachelor). In pp collisions, candidates were further selected using criteria related to PID and properties of the $\Lambda_c^+ \to pK^0_S$ decay. The Bayesian probability of the combined TPC and TOF response for the bachelor track to be a proton was required to be above 80%. The selection criteria on kinematical and geometrical variables included the distance of closest approach between the decay daughters, the invariant mass, and the cosine of the pointing angle of the neutral decay vertex (K^0_S) to the primary vertex.

For the $\Lambda_c^+ \to pK^0_S$ decay channel in p-Pb collisions, the analysis was performed using a multivariate technique based on the boosted decision tree (BDT) algorithm provided by the Toolkit for Multivariate Data Analysis [44]. The BDT algorithm was trained using signal and background $\Lambda_c^+ \to pK^0_S$ decay candidates simulated using PYTHIA 6.4.25 [45] with the Perugia 2011 tune [46], and the underlying p-Pb event simulated with HIJING 1.36 [47]. Candidates obtained with the same reconstruction strategy previously described were preselected using loose geometrical selections and PID selection on the bachelor proton track. The model was trained independently for each p_T

interval analyzed, with input variables comprising the p_T and Bayesian PID probability of the proton track, the $c\tau$ and invariant mass of the K_S^0, and the impact parameters of the Λ_c^+ decay tracks to the primary vertex. This model was then applied on data, and a selection on the output response was chosen based on the expected maximum significance determined from simulations.

For both decay channels, the yield of Λ_c^+ baryons was extracted in each p_T interval via fits to the candidate invariant-mass distributions. The fitting function consisted of a Gaussian to estimate the signal and an exponential or polynomial function to estimate the background. The width of the Gaussian was fixed in each p_T interval to values obtained from Monte Carlo simulations, and the mean was treated as a free parameter. A statistical significance higher than 4 standard deviations was achieved in all p_T intervals.

Several corrections were applied to the measurement of the Λ_c^+ cross section. The geometrical acceptance of the detector as well as the selection and reconstruction efficiencies for prompt Λ_c^+ were taken into account. These correction factors were determined from pp collisions generated with PYTHIA 6 and PYTHIA 8.243 [48], with each event including either a $c\bar{c}$ or a $b\bar{b}$ pair. For p-Pb collisions, this was supplemented with an underlying event from the HIJING event generator. In p-Pb collisions, the efficiency was calculated after reweighting the events based on their charged particle multiplicity. This accounts for the fact that the event multiplicity in simulation does not reproduce the one in data, and the efficiency depends on the multiplicity of the event as a consequence of the improvement of the resolution of the primary vertex and thus of the performance of the topological selections at higher multiplicities. The fraction of the Λ_c^+ yield originating from beauty decays (feed-down) was obtained using the beauty-quark production cross section from FONLL [4,5], the fraction of beauty quarks that fragment into beauty hadrons H_b from LHCb measurements [22], and $H_b \to \Lambda_c^+ + \mathrm{X}$ decay kinematics from PYTHIA 8, as well as the selection and reconstruction efficiency of Λ_c^+ from beauty-hadron decays. The fraction of the Λ_c^+ yield from beauty decays was found to be 2% at low p_T and up to 16% at high p_T, and was subtracted from the measured yield. As done in the D-meson analysis [49], the possible modification of beauty-hadron production in p-Pb collisions was included in the feed-down calculation by scaling the beauty-quark production by a nuclear modification factor $R_{p\mathrm{Pb}}^{\text{feed-down}}$, where it was assumed that $R_{p\mathrm{Pb}}^{\text{feed-down}} = R_{p\mathrm{Pb}}^{\text{prompt}}$ with their ratio varied in the range $0.9 < R_{p\mathrm{Pb}}^{\text{feed-down}}/R_{p\mathrm{Pb}}^{\text{prompt}} < 1.3$ to evaluate the systematic uncertainties.

Systematic uncertainties on the Λ_c^+ cross sections were estimated considering the same sources as described in [11]. The contributions from the raw-yield extraction were evaluated by repeating the fits varying the fit interval and the functional form of the background fit function. For each of these variations the four combinations of free and fixed Gaussian mean and width parameters of the fit were considered. Overall, the relative uncertainty ranged from 4% to 11% depending on the p_T and analysis. The uncertainties on the track reconstruction efficiency were estimated by adding in quadrature the uncertainty due to track quality selection and the uncertainty due to the TPC-ITS matching efficiency (from 3% to 7%). The former is estimated by varying the track-quality selection criteria, and the latter is estimated by comparing the probability to match the tracks from the TPC to the ITS hits in data and simulation. The uncertainty on the Λ_c^+ selection efficiency was estimated by varying the selection on the kinematical and topological properties of the Λ_c^+ decays or the selection on the BDT response (from 3% to 15%). The uncertainty on the PID efficiency was estimated by varying the selection on the Bayesian probability variables (from 2% to 5%). The systematic effect on the efficiencies due to the shape of the simulated Λ_c^+ p_T distribution was evaluated by reweighting the generated Λ_c^+ from PYTHIA 6 to match the p_T distribution obtained from FONLL calculations for D mesons (maximum 1% uncertainty). The relative statistical uncertainty on the acceptance and efficiency correction was considered as an additional systematic uncertainty source (from 1%–2% at low p_T to 3%–5% at high p_T). The uncertainties on f_{prompt} were estimated by varying the hypothesis on the production of Λ_c^+ from B-hadron decays to account for the theoretical uncertainties of b-quark production within FONLL and experimental uncertainties on B-hadron fragmentation (around 2% at low p_T and from 4% to 7% at high p_T, depending on the analysis). Global uncertainties of the measurement include those from the luminosity and Λ_c^+ branching ratios. The raw-yield extraction uncertainty source are considered to be uncorrelated across p_T bins, while all other sources are considered to be correlated.

The results in each collision system from the two Λ_c^+ decay channels were averaged to obtain the final results. A weighted average of the results was calculated, with weights defined as the inverse of the quadratic sum of the relative statistical and uncorrelated systematic uncertainties. The sources of systematic uncertainty assumed to be uncorrelated between different decay channels were those due to the raw-yield extraction, the statistical uncertainties on the efficiency and acceptance, and those related to the Λ_c^+ selection. The remaining uncertainties were assumed to be correlated, except the branching ratio uncertainties, which were treated as partially correlated among the hadronic-decay modes as defined in [37].

Figure 1 (left) shows a comparison of the Λ_c^+ p_T-differential cross sections in pp and in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The D^0 p_T-differential cross sections measured in the same collision systems and at the same center-of-mass energy during the same data taking periods

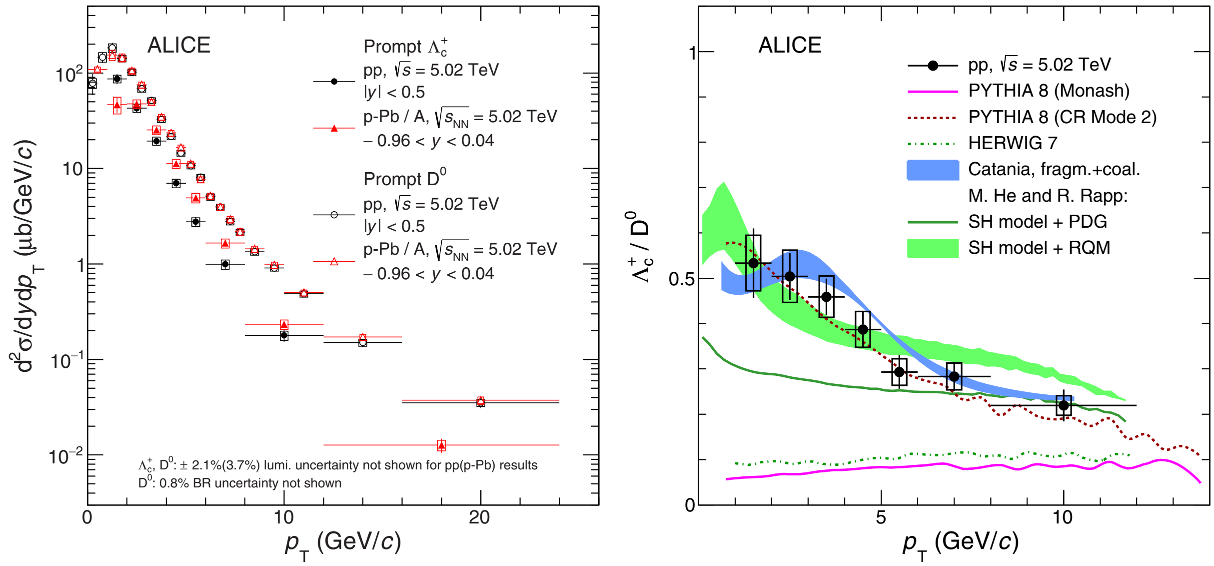

FIG. 1. Left: Prompt Λ_c^+ and D^0 p_T-differential cross section in pp collisions and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results in p-Pb collisions are scaled with the atomic mass number A of the Pb nucleus. Right: The Λ_c^+/D^0 ratio as a function of p_T measured in pp collisions at $\sqrt{s} = 5.02$ TeV compared with theoretical predictions (see text for details). Statistical uncertainties are shown as vertical bars, while systematic uncertainties are shown as boxes, and the bin widths are shown as horizontal bars.

[10,50] are also shown. In order to compare the spectral shapes in the two different collision systems at the same energy, the results in p-Pb collisions are scaled by the atomic mass number of the lead nucleus. For Λ_c^+ baryons the spectral shape in p-Pb collisions is slightly harder than in pp collisions, while for D^0 mesons the spectral shapes are fully consistent within uncertainties.

Figure 1 (right) shows the baryon-to-meson ratio Λ_c^+/D^0 measured in pp collisions at $\sqrt{s} = 5.02$ TeV as a function of p_T compared to theoretical predictions. The uncertainty on the luminosity cancels in the ratio. The Λ_c^+/D^0 ratio is measured to be 0.4–0.5 at low p_T and decreases to around 0.2 at high p_T. The previous results at $\sqrt{s} = 7$ TeV hinted at a decrease of the Λ_c^+/D^0 ratio with p_T, although the precision was not enough to confirm this [11]. The results in pp collisions at $\sqrt{s} = 5.02$ TeV, with much higher precision than $\sqrt{s} = 7$ TeV results, show a clear decrease with increasing p_T. The strong p_T dependence of the Λ_c^+/D^0 ratio is in contrast to the ratios of strange and nonstrange D mesons in pp collisions at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 7$ TeV [10,51] and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [50], which do not show a significant p_T dependence within uncertainties and thus indicate that there are no large differences between fragmentation functions of charm quarks to charm mesons. The result presented here instead provides strong indications that the fragmentation functions of baryons and mesons differ significantly.

The measured Λ_c^+/D^0 ratios in pp collisions are compared to predictions from several Monte Carlo generators and models in which different hadronization processes are implemented. The PYTHIA 8 predictions include the Monash tune [12] and a tune that implements color reconnection beyond the leading-color approximation, corresponding to CR Mode 2 as defined in [13]. Hadronization in PYTHIA is built on the Lund string fragmentation model [52,53], where quarks and gluons connected by color strings fragment into hadrons, and color reconnection allows for partons created in the collision to interact via color strings. The latter tune introduces new color reconnection topologies beyond the leading-color approximation, including "junctions" that fragment into baryons, leading to increased baryon production. As a technical point, the PYTHIA 8 simulations are generated with all soft QCD processes switched on [48]. The PYTHIA 8 Monash tune and HERWIG 7.2 [15] predictions are driven by the fragmentation fraction $f(c \to \Lambda_c^+)$ implemented in these generators, which all suggest a relatively constant Λ_c^+/D^0 ratio versus p_T of about 0.1, significantly underestimating the data at low p_T. At high p_T, the data approach the predictions from these generators, although the measurement in $8 < p_T < 12$ GeV/c is still underestimated by about a factor of 2. A significant enhancement of the Λ_c^+/D^0 ratio is seen with color reconnection beyond the leading-color approximation (PYTHIA 8 CR Mode 2). This prediction is consistent with the measured Λ_c^+/D^0 ratio in pp collisions, also reproducing the downward p_T trend. The statistical hadronization model ("SH model" in the legend) [19] uses either an underlying charm-baryon spectrum taken from the Particle Data Group, or includes additional excited charm baryons that have not yet been observed but are predicted by the RQM. These additional states decay strongly to Λ_c^+ baryons, which contribute to the prompt Λ_c^+ spectrum. The RQM predictions include a

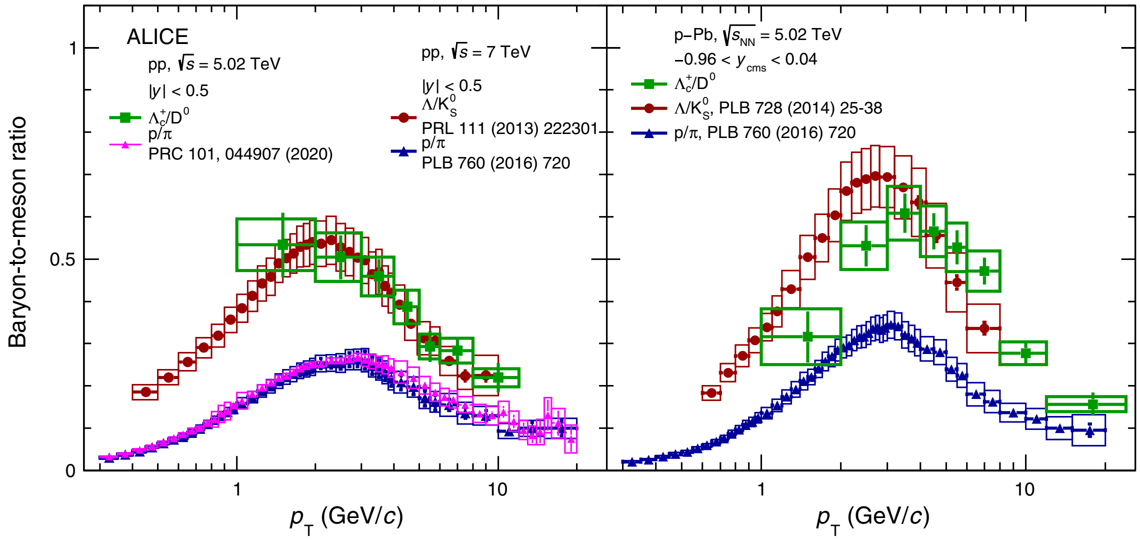

FIG. 2. The charm baryon-to-meson ratio Λ_c^+/D^0 in pp collisions (left) and p-Pb collisions (right) at $\sqrt{s_{\rm NN}} = 5.02$ TeV compared to the light-flavor baryon-to-meson ratios Λ/K_S^0 and p/π. Statistical uncertainties are shown as vertical bars, while systematic uncertainties are shown as boxes, and the bin widths are shown as horizontal bars.

source of uncertainty related to the branching ratios of the excited baryon states into Λ_c^+ final states, which is estimated by varying the branching ratios between 50% and 100%. With the Particle Data Group charm-baryon spectrum, the model underpredicts the data. With the additional baryon states, the model instead gives a good description of the pp data, both in the magnitude of the ratio and the decreasing trend with p_T. The Catania model [36] assumes that a color-deconfined state of matter is formed and hadronization can occur via coalescence in addition to fragmentation. Coalescence is implemented through the Wigner formalism, where a blast wave model is used to determine the p_T spectrum of light quarks and FONLL pQCD calculations are used for heavy quarks. Hadronization via coalescence is predicted to dominate at low p_T, while fragmentation dominates at high p_T. This model provides a good description of both the magnitude and shape of the data over the full p_T range.

Figure 2 shows the Λ_c^+/D^0 baryon-to-meson ratio measured in pp collisions at $\sqrt{s} = 5.02$ TeV (left) and in p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV (right) as a function of p_T compared to baryon-to-meson ratios in the light-flavor sector, Λ/K_S^0 [25,54] and p/π [31,55] [calculated as the sum of both charged particles and antiparticles, $(p+\bar{p})/(\pi^+ + \pi^-)$]. The p/π ratio in pp collisions is shown at both $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 7$ TeV, displaying consistent results at both center-of-mass energies, while the Λ/K_S^0 ratio in pp collisions is shown only at $\sqrt{s} = 7$ TeV. Unlike heavy-flavor hadron production, which occurs primarily through the fragmentation of a charm quark produced in the initial hard scattering, light-flavor hadrons have a significant contribution from gluon fragmentation. Low-p_T light-flavor hadrons also primarily originate from soft scattering processes involving small momentum transfers. All particle yields in these ratios were corrected for feed-down from weak decays, although the pion spectrum is expected to have significant feed-down contributions also from the strong decays of other particle species, primarily ρ and ω mesons. Despite these differences, the three ratios —Λ_c^+/D^0, Λ/K_S^0, and p/π—demonstrate some remarkably similar characteristics in both collision systems. All ratios exhibit a decreasing trend after $p_T \gtrsim 2$–3 GeV/c. The Λ_c^+/D^0 and Λ/K_S^0 ratios are consistent, in terms of both shape and magnitude, within uncertainties. The light-flavor ratios both peak at ~2–3 GeV/c in both pp and p-Pb collisions, and there is an indication of a peak at $2 < p_T < 4$ GeV/c in the Λ_c^+/D^0 ratio in p-Pb collisions. These similarities between heavy-flavor and light-flavor measurements hint at a potential common mechanism for light- and charm-baryon formation in pp and p-Pb collisions at LHC energies. It is interesting to note that all baryon-to-meson ratios also indicate a shift toward higher momenta in p-Pb collisions, which for light-flavor particle production is often attributed to radial flow [54]. However, while flow effects in the charm sector (D^0 and heavy-flavor decay leptons) have been observed in high-multiplicity p-Pb collisions [56,57], these effects are expected to be smaller at lower multiplicities as well as smaller for charm than for light-flavor hadrons.

In summary, Λ_c^+-baryon production was measured in pp collisions at midrapidity ($|y| < 0.5$) and in p-Pb collisions in the rapidity interval $-0.96 < y < 0.04$ at $\sqrt{s_{\rm NN}} = 5.02$ TeV. A clear p_T dependence of the Λ_c^+/D^0 ratio is reported, with the ratio decreasing as the p_T increases. This trend is similar to that of baryon-to-meson ratios measured in the light-flavor sector in pp and p-Pb collisions, suggesting common mechanisms for light- and charm-baryon formation. While models incorporating fragmentation parameters from e^+e^- and e^-p collisions significantly underestimate the Λ_c^+/D^0 ratio, three models can reproduce the measurements. The first is a tune of PYTHIA 8 that considers that, in pp collisions at high energy, multiparton interactions produce a rich hadronic environment that requires an extension of color reconnection in hadronization processes beyond the leading-color approximation. The second method is the statistical hadronization + RQM model, which relies on the presence of a large set of yet-unobserved higher-mass charm-baryon states with relative yields following the statistical hadronization model. The third relies on hadronization via coalescence and fragmentation after the formation of a color-deconfined state of matter. All three models imply a substantially different description of the charm-baryon production in pp collisions with respect to e^+e^- and e^-p collisions, indicating that the assumption of universal parton-to-hadron fragmentation between collision systems is not sufficient to describe charm-baryon production.

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