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$\Lambda_c^+$  production in  $pp$  and in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeVS. Acharya *et al.*\*  
(ALICE Collaboration) (Received 22 December 2020; revised 4 August 2021; accepted 23 September 2021; published 9 November 2021)

The production cross section of prompt  $\Lambda_c^+$  charm baryons was measured with the ALICE detector at the LHC at midrapidity in proton-proton ( $pp$ ) and proton-lead ( $p$ -Pb) collisions at a center-of-mass energy per nucleon pair of  $\sqrt{s_{NN}} = 5.02$  TeV. The  $\Lambda_c^+$  and  $\bar{\Lambda}_c^-$  baryons were reconstructed in the hadronic decay channels  $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $\Lambda_c^+ \rightarrow pK_S^0$  and respective charge conjugates. The measured differential cross sections as a function of transverse momentum ( $p_T$ ) and the  $p_T$ -integrated  $\Lambda_c^+$  production cross section in  $pp$  and in  $p$ -Pb collisions are presented. The  $\Lambda_c^+$  nuclear modification factor ( $R_{pPb}$ ), calculated from the cross sections in  $pp$  and in  $p$ -Pb collisions, is presented and compared with the  $R_{pPb}$  of  $D$  mesons. The  $\Lambda_c^+/D^0$  ratio is also presented and compared with the light-flavor baryon-to-meson ratios  $p/\pi$  and  $\Lambda/K_S^0$ , and measurements from other LHC experiments. The results are compared to predictions from model calculations and Monte Carlo event generators.

DOI: [10.1103/PhysRevC.104.054905](https://doi.org/10.1103/PhysRevC.104.054905)**I. INTRODUCTION**

In hadronic collisions, heavy quarks (charm and beauty) are created predominantly in hard scattering processes, and therefore the measurement of charm and beauty hadron production is a powerful test of perturbative quantum chromodynamics (pQCD) calculations. Theoretical predictions based on the QCD factorization approach describe the heavy-flavor hadron production cross section as a convolution of parton distribution functions, parton hard-scattering cross sections, and fragmentation functions. The measurements of  $D$ - and  $B$ -meson production cross sections in  $pp$  collisions at center-of-mass energies between 200 GeV and 13 TeV at RHIC [1], Tevatron [2–4], and the LHC [5–9] are generally described within uncertainties by perturbative calculations at next-to-leading order with next-to-leading-log resummation, such as the general-mass variable-flavor-number scheme (GM-VFNS [10,11]) and fixed-order next-to-leading-log (FONLL [12,13]), over a wide range of transverse momentum ( $p_T$ ).

The measurement of the relative production of different heavy-flavor hadron species is also sensitive to the charm- and beauty-quark fragmentation and heavy-flavor hadron formation processes. In particular, measurements of the  $\Lambda_c^+$  production cross section relative to  $D$  mesons provide insight into the hadronization of charm quarks into baryons. A measurement of  $\Lambda_c^+$  baryon production at midrapidity in  $pp$  collisions at  $\sqrt{s} = 7$  TeV was reported by the ALICE Collaboration in Ref. [14]. The  $\Lambda_c^+/D^0$  ratio was found to be substantially higher than previous measurements at lower

energies in electron-positron ( $e^+e^-$ ) [15–18] and electron-proton ( $e^-p$ ) [19–21] collisions, challenging the assumption that the probabilities for a charm quark to hadronize into a specific charm hadron (fragmentation fractions) are universal among different collision systems [22]. In addition, the  $\Lambda_c^+/D^0$  ratio was compared with predictions from several Monte Carlo (MC) generators, which implement different fragmentation processes, such as the formation of strings (PYTHIA [23,24]), ropes (DIPSY [25,26]), or baryonic clusters (HERWIG [27]), where the fragmentation parameters for these simulations are tuned to previous  $e^+e^-$  and  $e^-p$  collision measurements. These predictions significantly underestimate the  $\Lambda_c^+/D^0$  ratio, although the prediction from PYTHIA 8 that includes additional color reconnection mechanisms [24] shows a  $p_T$  trend that is qualitatively similar to the measured trend. The CMS Collaboration has measured the  $\Lambda_c^+/D^0$  ratio in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV [28], which is consistent with predictions from PYTHIA 8 with additional color reconnection mechanisms.  $\Lambda_c^+$  production was also measured by the LHCb Collaboration in  $pp$  collisions at  $\sqrt{s} = 7$  TeV at forward rapidity [29], and the  $\Lambda_c^+/D^0$  ratio was found to be lower than that measured by ALICE at midrapidity [14]. Calculations of the charm-hadron production cross section based on the  $k_T$ -factorization approach with gluon distributions obtained on the basis of novel collinear gluon distribution functions and Peterson fragmentation functions [30] are unable to simultaneously describe the ALICE and LHCb measurements using the same set of input parameters, suggesting that the measurements are difficult to explain within the independent parton fragmentation scheme. It is also important to note here that the magnitude of the relative production of  $\Lambda_b^0$  baryons and beauty mesons in  $pp$  collisions measured by LHCb [31–33] and CMS [34] offer further hints that fragmentation fractions in the beauty sector differ between  $pp$  and  $e^+e^-/e^-p$  collisions.

Measurements in  $pp$  collisions also provide a necessary reference for studies in heavy-ion collisions, where the study

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of charm production is a powerful tool to investigate the quark–gluon plasma (QGP) [35–37], the deconfined state of matter created under extreme energy densities. In particular, the charm baryon-to-meson ratio in heavy-ion collisions is sensitive to the charm hadronization mechanisms after the QGP phase. It is expected that a significant fraction of low- and intermediate-momentum charm quarks hadronize via recombination (coalescence) with light (anti)quarks from the medium [38,39], which would manifest as an enhancement of the  $\Lambda_c^+/D^0$  ratio with respect to  $pp$  collisions. The  $\Lambda_c^+/D^0$  ratio has been measured by STAR [40] in Au–Au collisions at  $\sqrt{s_{\text{NN}}} = 200$  GeV, and by ALICE [41] and CMS [28] in Pb–Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. These measurements offer constraints to different model calculations which implement contributions to hadronization via quark recombination [42–45].

The interpretation of the results obtained in heavy-ion collisions also requires detailed studies in  $p$ –Pb collisions to assess so-called cold nuclear matter (CNM) effects in the initial and final states, which could modify the production of heavy-flavor hadrons. In the initial state, the quark and gluon distributions are modified in bound nucleons compared to free nucleons, depending on the fractional longitudinal parton momentum  $x$  and the atomic mass number [46,47]. The most relevant CNM effect at LHC energies is shadowing, i.e., a decrease of the parton densities in the small- $x$  region. This effect is due to high phase-space densities of low- $x$  partons and can be described in collinear pQCD by means of parametrizations of the modification of the nuclear parton distribution functions (nPDFs) [48,49]. In the case of saturation of the parton phase-space, the color glass condensate (CGC) effective theory [50–54] offers an appropriate theoretical framework to describe the modification of the nPDFs. Moreover, partons can lose energy in the initial stages of the collisions due to initial-state radiation [55], or experience transverse momentum broadening due to multiple soft collisions before the heavy-quark pair is created in the hard scattering [56–58]. The modification of parton distributions in the nucleus and energy loss in the initial state can affect the yields and the momentum distributions of the produced hadrons, mainly at low momenta. In addition to initial-state effects, final-state effects such as hadronic rescattering [59] or the possible formation of a small QGP droplet [60,61] can also modify the hadron yields and momentum distributions. Several measurements in high-multiplicity  $pp$  and  $p$ –Pb collisions, such as long-range correlations of charged hadrons [62–65], and the enhancement of baryon-to-meson ratios in the light-flavor sector ( $p/\pi$  and  $\Lambda/K$ ) [66–68], exhibit a similar behavior as that observed in Pb–Pb collisions, suggesting that these findings may have similar physical origins in  $pp$ ,  $p$ –A, and A–A collisions [69].  $\Lambda_c^+$  production was previously measured at midrapidity by ALICE in  $p$ –Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV [14]. The  $\Lambda_c^+/D^0$  ratio was found to be compatible within the uncertainties with that measured in  $pp$  collisions at  $\sqrt{s} = 7$  TeV. The nuclear modification factor,  $R_{p\text{Pb}}$ , was found to be compatible with unity, as well as with models that implement cold nuclear matter effects via nPDF calculations [70] or assume the production of a deconfined medium in  $p$ –Pb collisions [60]. The LHCb Collaboration has measured the  $\Lambda_c^+/D^0$  ratio at

forward rapidity in  $p$ –Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV [71] to be larger than that in  $pp$  collisions at forward rapidity [29] but smaller than the ALICE measurements in  $pp$  and  $p$ –Pb collisions at midrapidity [14].

Recent attempts have been made to model charm-baryon production in  $pp$  and  $p$ –Pb collisions. A framework based on a statistical hadronization model [72], which takes into account an increased set of charm-baryon states beyond those listed by the particle data group (PDG), is able to reproduce the  $\Lambda_c^+/D^0$  ratios measured by ALICE in the  $pp$  and  $p$ –Pb collision systems, although it overestimates the LHCb measurement in  $pp$  collisions. A model implementing hadronization via recombination [73,74], where the  $p_T$  distributions of light and charm quarks and antiquarks are inputs of the model and the relative production of single-charm baryons to single-charm mesons is treated as a free parameter, is able to reproduce the  $p_T$  dependence of the  $\Lambda_c^+/D^0$  ratio measured by ALICE at central rapidity in  $pp$  and  $p$ –Pb collisions, and by LHCb at forward rapidity in  $p$ –Pb collisions. While models implementing different approaches to  $\Lambda_c^+$  production are effective in describing the measured  $\Lambda_c^+/D^0$  ratio and  $R_{p\text{Pb}}$ , the large statistical and systematic uncertainties of the current measurements do not provide the discriminating power needed to differentiate between the various models. Therefore, more precise measurements are crucial to constrain predictions.

This paper presents the measurement of the  $p_T$ -differential production cross section of charm  $\Lambda_c^+$  baryons in  $pp$  collisions in the rapidity interval  $|y| < 0.5$  and in  $p$ –Pb collisions in  $-0.96 < y < 0.04$  at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV, performed with the ALICE detector at the LHC. The rapidity  $y$  here and throughout this paper is defined in the center-of-mass system, and in  $p$ –Pb collisions the rapidity sign is positive in the  $p$ -going direction. The ratio of the production cross sections of  $\Lambda_c^+$  baryons and  $D^0$  mesons,  $\Lambda_c^+/D^0$ , and the nuclear modification factor  $R_{p\text{Pb}}$  are also presented. Finally, the  $\Lambda_c^+$  production cross section per unit of rapidity at midrapidity is computed by integrating the  $p_T$ -differential  $\Lambda_c^+$  production cross section after extrapolating down to  $p_T = 0$ , and the  $p_T$ -integrated  $\Lambda_c^+/D^0$  ratios are presented. Two hadronic decay channels of  $\Lambda_c^+$  were studied:  $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $\Lambda_c^+ \rightarrow pK_S^0$ . Different analysis strategies were implemented, taking advantage of the methods used in previous analyses for the hadronic decays of  $D$  mesons [75–80] and  $\Lambda_c^+$  baryons [14]. With respect to our previous measurement of  $\Lambda_c^+$  production [14], the  $p_T$  reach was extended, the overall uncertainties of the measurements were reduced, and the analysis was performed in finer  $p_T$  intervals. The precision of the measurement of the nuclear modification factor  $R_{p\text{Pb}}$  was improved with respect to the previously published result thanks to the larger data samples as well as a  $pp$  reference measured at the same center-of-mass energy.

The measurements are performed as the average of the particle and antiparticle cross sections, and so both  $\Lambda_c^+$  and  $\bar{\Lambda}_c^-$  baryons are referred to collectively as  $\Lambda_c^+$  in the following. In all measurements the production cross section of prompt  $\Lambda_c^+$  is reported, i.e.,  $\Lambda_c^+$  from direct hadronization of a charm quark or from decays of directly produced excited charm states. For the center-of-mass energy of  $pp$  collisions the simplified notation  $\sqrt{s}$  is used throughout this paper.

It is noted that the  $\Lambda_c^+/D^0$  baryon-to-meson ratio is the focus of a dedicated letter [81], and this document presents a more detailed description of the analysis procedure as well as supplementary results.

## II. EXPERIMENTAL SETUP AND DATA SAMPLES

The ALICE apparatus is composed of a central barrel, consisting of a set of detectors for particle reconstruction and identification covering the midrapidity region, a muon spectrometer at forward rapidity and various forward and backward detectors for triggering and event characterization. The central barrel detectors cover the full azimuth in the pseudorapidity interval  $|\eta| < 0.9$  and are embedded in a large solenoidal magnet that provides a  $B = 0.5$  T field parallel to the beam direction ( $z$  axis in the ALICE reference frame). A comprehensive description and overview of the typical performance of the detectors in  $pp$  and  $p$ -Pb collisions can be found in Refs. [82,83].

The tracking and particle identification capabilities of the ALICE central barrel detectors were exploited to reconstruct the  $\Lambda_c^+$  decay products at midrapidity. The inner tracking system (ITS), consisting of three subdetectors, the silicon pixel detector (SPD), the silicon drift detector (SDD), and the silicon strip detector (SSD), each made of two concentric layers, allows for a precise determination of the track impact parameter (the distance of closest approach between the track and the primary vertex of the collision) in the transverse plane with a resolution better than  $75 \mu\text{m}$  for tracks with  $p_T > 1 \text{ GeV}/c$  [84]. The time projection chamber (TPC) is the main tracking detector of the experiment [85]. It provides up to 159 space points to reconstruct the charged-particle trajectory, and provides charged-particle identification (PID) via the measurement of the specific energy loss  $dE/dx$ . The particle identification capabilities are extended by the time-of-flight (TOF) detector, which is used to measure the flight time of charged particles from the interaction point. The TOF detector is an array of multigap resistive plate chambers. It measures the particle arrival time at the detector with a resolution of about 80 ps. The start time of the collision is obtained for each event either using the TOF detector, the T0 detector, or a combination of the two [86]. The T0 detector consists of two arrays of Cherenkov counters, located on both sides of the interaction point, covering the pseudorapidity regions  $4.61 < \eta < 4.92$  and  $-3.28 < \eta < -2.97$ , respectively. The time resolution of the T0 detector in  $pp$  and  $p$ -Pb collisions is about 50 ps for events in which a measurement is made on both sides of the interaction point [86]. The V0 detector system, used for triggering and event selection, consists of two scintillator arrays covering the full azimuth in the pseudorapidity intervals  $2.8 < \eta < 5.1$  and  $-3.7 < \eta < -1.7$  ([82], Section 5.1). The zero degree calorimeter (ZDC), used for offline event rejection in  $p$ -Pb collisions, consists of two sets of neutron and proton calorimeters positioned along the beam axis on both sides of the ALICE apparatus, about 110 m from the interaction point ([82], Section 5.4).

The results presented in this paper were obtained from the analysis of the LHC Run 2 data samples collected from  $pp$  collisions at  $\sqrt{s} = 5.02 \text{ TeV}$  in 2017 and  $p$ -Pb collisions

at  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$  in 2016. The proton–nucleon center-of-mass system in  $p$ -Pb collisions is shifted in rapidity by  $\Delta y = 0.465$  in the Pb-going direction (negative rapidity) due to the asymmetric beam energies of 4 TeV for protons and 1.59 TeV per nucleon for Pb nuclei. The analyses used events recorded with a minimum bias (MB) trigger, which was based on coincident signals from the V0 detectors in both  $pp$  and  $p$ -Pb collisions. To remove background from beam–gas collisions and other machine-induced backgrounds, in  $pp$  collisions the events were further selected offline based on the correlation between the numbers of clusters and track segments reconstructed in the SPD, and V0 timing information. The latter was also used for the  $p$ -Pb analysis, together with the timing from the ZDC. To maintain a uniform ITS acceptance in pseudorapidity, only events with a  $z$  coordinate of the reconstructed vertex position within 10 cm from the nominal interaction point were analysed. Events with multiple interaction vertices due to pileup from several collisions were removed using an algorithm based on tracks reconstructed with the TPC and ITS detectors [83]. Using these selection criteria, approximately one billion MB-triggered  $pp$  events were analyzed, corresponding to an integrated luminosity of  $\mathcal{L}_{\text{int}} = 19.5 \text{ nb}^{-1} (\pm 2.1\% [87])$ , while approximately 600 million MB-triggered  $p$ -Pb events were selected, corresponding to  $\mathcal{L}_{\text{int}} = 287 \mu\text{b}^{-1} (\pm 3.7\% [88])$ .

## III. $\Lambda_c^+$ ANALYSIS OVERVIEW AND METHODS

The analysis was performed using similar techniques to those reported in Ref. [14].  $\Lambda_c^+$  baryons were reconstructed in two hadronic decay channels:  $\Lambda_c^+ \rightarrow pK^-\pi^+$  (branching ratio,  $\text{BR} = 6.28 \pm 0.33\%$ ) and  $\Lambda_c^+ \rightarrow pK_S^0$  ( $\text{BR} = 1.59 \pm 0.08\%$ ), followed by the subsequent decay  $K_S^0 \rightarrow \pi^+\pi^-$  ( $\text{BR} = 69.2 \pm 0.05\%$ ) [89]. For the former, the  $\Lambda_c^+$  decays to the  $pK^-\pi^+$  final state via four channels:  $\Lambda_c^+ \rightarrow p\bar{K}^{*0}(892)$ ,  $\Lambda_c^+ \rightarrow \Delta^{++}(1232)K^-$ ,  $\Lambda_c^+ \rightarrow \Lambda(1520)\pi^+$ , and the nonresonant  $\Lambda_c^+ \rightarrow pK^-\pi^+$  decay. As these channels are indistinguishable in the analysis, all four are considered together.

The selection of candidates was performed using a combination of kinematical, geometrical, and PID selections. The selection criteria were tuned on Monte Carlo simulations to maximize the statistical significance in each  $p_T$  interval.  $\Lambda_c^+$  candidates were reconstructed by combining reconstructed tracks with  $|\eta| < 0.8$  and at least 70 reconstructed space points in the TPC. For all decay products in the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  analysis and for the proton-candidate tracks in the  $\Lambda_c^+ \rightarrow pK_S^0$  analysis, at least one cluster was required in either of the two SPD layers. The PID selections for all analyses were performed utilising the Bayesian method for combining the TPC and TOF signals, as described in Ref. [90]. The Bayesian method entails the use of priors, an *a priori* probability of measuring a given particle species, which are determined using measured particle abundances. Where possible, the TPC and TOF signals were combined; however, if the TOF signal was absent for a given track, the TPC signal alone was used. For the  $\Lambda_c^+ \rightarrow pK_S^0$  analysis in  $p$ -Pb collisions, a machine learning approach with boosted decision

trees (BDTs) was applied to select  $\Lambda_c^+$  candidates, using the toolkit for multivariate data analysis (TMVA) [91].

The detector acceptance for  $\Lambda_c^+$  baryons varies as a function of rapidity, in particular falling steeply to zero for  $|y| > 0.5$  at low  $p_T$ , and  $|y| > 0.8$  for  $p_T > 5$  GeV/c. For this reason, a fiducial acceptance selection was applied on the rapidity of candidates,  $|y_{\text{lab}}| < y_{\text{fid}}(p_T)$ , where  $y_{\text{fid}}$  increases smoothly from 0.5 to 0.8 in  $0 < p_T < 5$  GeV/c and  $y_{\text{fid}} = 0.8$  for  $p_T > 5$  GeV/c [75].

For the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  analysis, candidates were formed by combining triplets of tracks with the correct configuration of charge sign. For this decay channel, the high-resolution tracking and vertexing information provided by the ITS and TPC allows the interaction point (primary vertex) and the reconstructed decay point of the  $\Lambda_c^+$  candidate (secondary vertex) to be distinguished from one another, despite the short decay length of the  $\Lambda_c^+$  ( $c\tau = 60.7 \mu\text{m}$  [89]). Once the secondary vertex was computed from the three tracks forming the  $\Lambda_c^+$  candidate, selections were applied on variables related to the kinematic properties of the decay, the quality of the reconstructed vertex, and the displaced decay-vertex topology. These variables comprise the transverse momenta of the decay products; the quadratic sum of the distance of closest approach of each track to the secondary vertex; the decay length of the  $\Lambda_c^+$  candidate (separation between the primary and secondary vertices); and the cosine of the pointing angle between the  $\Lambda_c^+$  candidate flight line (the vector that connects the primary and secondary vertices) and the reconstructed momentum vector of the candidate. Pions, kaons, and protons were identified using the *maximum-probability* Bayesian PID approach [90], where a probability is assigned to each track for every possible species based on the TPC and TOF signals and the identity of the track is taken to be the species with the highest probability value. This approach allows for a higher-purity sample to be selected, reducing the large level of combinatorial background and facilitating the signal extraction.

The  $\Lambda_c^+ \rightarrow pK_S^0$  analysis started from a  $K_S^0 \rightarrow \pi^+\pi^-$  candidate, which is reconstructed as a pair of opposite-sign charged tracks forming a neutral decay vertex displaced from the primary vertex (a  $V^0$  candidate). This  $V^0$  candidate was paired with a proton-candidate track originating from the primary vertex to form a  $\Lambda_c^+$  candidate. Two strategies were then used to select  $\Lambda_c^+$  candidates in  $pp$  and  $p$ -Pb collisions. In  $pp$  collisions, the analysis was based on rectangular selection criteria. The  $V^0$  candidate was required to have an invariant mass compatible with the  $K_S^0$  mass from the PDG [89] within  $8(20) \text{ MeV}/c^2$  at low (high)  $p_T$ , corresponding to one or two times the resolution of the  $K_S^0$  invariant mass, depending on the  $p_T$  interval and the collision system. The  $V^0$  candidates were selected based on the  $p_T$  and impact parameter of the decay pions to the  $K_S^0$  decay vertex, and the cosine of the pointing angle between the  $V^0$  flight line and its reconstructed momentum. Proton-candidate tracks were selected based on their  $p_T$ , their impact parameter to the primary vertex, the number of reconstructed TPC clusters, and a cluster being present on at least one of the two SPD layers. Particle identification was performed on the proton-candidate track, first using a loose  $|n_\sigma| < 3$  preselection on the TPC response,

where  $n_\sigma$  corresponds to the difference between the measured and expected  $dE/dx$  for a given particle species, in units of the resolution. This was followed by a strict requirement that the Bayesian posterior probability for the track to be a proton must be greater than 80%.

In  $p$ -Pb collisions, an approach using BDTs was used for the  $\Lambda_c^+ \rightarrow pK_S^0$  decay. The BDT algorithm provides a classification tree that maps simulated  $\Lambda_c^+$  candidates to a single BDT response variable aiming to maximize the separation between signal and background candidates. The mapping function is then applied on a real data sample in which the true identities of particles are unknown, followed by the application of selections on the BDT response. Candidates were initially filtered using an  $|n_\sigma^{\text{TPC}}| < 3$  PID selection on the proton candidate. Independent BDTs were trained for each  $p_T$  interval in the analysis. The training was performed on samples of simulated events including a detailed description of the experimental apparatus and the detector response. The training sample for signal candidates was taken from a simulation of  $pp$  events containing charm hadrons generated using PYTHIA 6.4.25 [92] with the Perugia2011 tune [93], embedded into an underlying  $p$ -Pb collision generated with HIJING 1.36 [94]. The background candidates were taken from the HIJING simulation. The variables that were used in the training were the Bayesian PID probability of the proton-candidate track to be a proton, the  $p_T$  of the proton candidate, the invariant mass and  $c\tau$  of the  $K_S^0$  candidate, and the impact parameters of the  $V^0$  and the proton-candidate track with respect to the primary vertex. The MC samples used for the efficiency calculation were different from those used in the training. The selection on the BDT response was tuned in each  $p_T$  interval to maximize the expected statistical significance, which is estimated using (i) the signal obtained from the generated  $\Lambda_c^+$  yield multiplied by the selection efficiency of the trained model and (ii) the background estimated from preselected data multiplied by the background rejection factor from the BDT. The BDT analysis was cross checked with an independent analysis using rectangular selection criteria, and the two results were found to be fully consistent within the experimental uncertainties.

Signal extraction for all analyses was performed by means of a fit to the invariant mass distributions of candidates in each  $p_T$  interval under study. A Gaussian function was used to model the signal peak and an exponential or polynomial function was used to model the background. Due to the small signal-to-background ratio, the standard deviation of the Gaussian signal function was fixed to the value obtained from simulations to improve the fit stability. In  $pp$  collisions, a  $\Lambda_c^+$  signal could be extracted for the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $\Lambda_c^+ \rightarrow pK_S^0$  analyses in the range  $1 < p_T < 12$  GeV. In  $p$ -Pb collisions a  $\Lambda_c^+$  signal was extracted for the  $\Lambda_c^+ \rightarrow pK_S^0$  analysis in the range  $1 < p_T < 24$  GeV/c, and for the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  analysis in the range  $2 < p_T < 24$  GeV/c, as the larger combinatorial background in the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  channel limits the low- $p_T$  reach. A selection of the invariant mass distributions with their corresponding fit functions is displayed in Fig. 1 for different  $p_T$  intervals, decay channels, and collision systems.

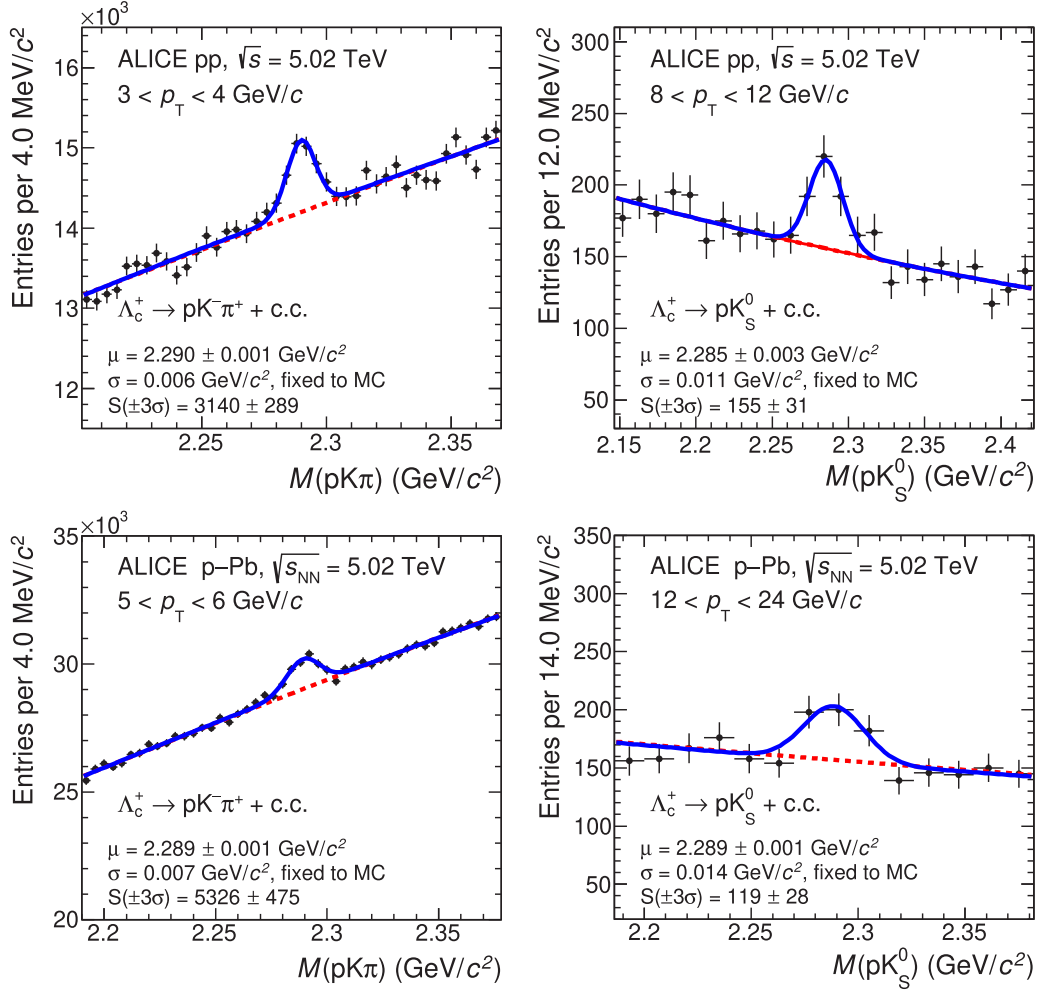


FIG. 1. Invariant mass distributions of  $\Lambda_c^+$  candidates in different  $p_T$  intervals, collision systems, and decay channels, with the corresponding fit functions. Top-left:  $\Lambda_c^+ \rightarrow pK^-\pi^+$  for  $3 < p_T < 4$  GeV/c in  $pp$  collisions; top-right:  $\Lambda_c^+ \rightarrow pK_S^0$  for  $8 < p_T < 12$  GeV/c in  $pp$  collisions; bottom-left:  $\Lambda_c^+ \rightarrow pK^-\pi^+$  for  $5 < p_T < 6$  GeV/c in  $p$ -Pb collisions; bottom-right:  $\Lambda_c^+ \rightarrow pK_S^0$  with BDT analysis in  $12 < p_T < 24$  GeV/c in  $p$ -Pb collisions. The dashed lines represent the fit to the background and the solid lines represent the total fit function.

#### IV. CORRECTIONS

The  $p_T$ -differential cross section of prompt  $\Lambda_c^+$ -baryon production was obtained for each decay channel as

$$\frac{d^2\sigma^{\Lambda_c^+}}{dp_T dy} = \frac{1}{2c_{\Delta y} \times \Delta p_T} \times \frac{1}{\text{BR}} \times \frac{f_{\text{prompt}} \times N_{|y| < y_{\text{fid}}}^{\Lambda_c^+}}{(A \times \epsilon)_{\text{prompt}}} \times \frac{1}{\mathcal{L}_{\text{int}}}, \quad (1)$$

where  $N^{\Lambda_c^+}$  is the raw yield (sum of particles and antiparticles) in a given  $p_T$  interval with width  $\Delta p_T$ ,  $f_{\text{prompt}}$  is the fraction of the raw yield from prompt  $\Lambda_c^+$ , BR is the branching ratio for the considered decay mode, and  $\mathcal{L}_{\text{int}}$  is the integrated luminosity.  $(A \times \epsilon)$  is the product of detector acceptance and efficiency for prompt  $\Lambda_c^+$  baryons, where  $\epsilon$  accounts for the reconstruction of the collision vertex, the reconstruction and selection of the tracks of the  $\Lambda_c^+$  decay products, and the  $\Lambda_c^+$ -candidate selection. The correction factor for the rapidity coverage,  $c_{\Delta y}$ , was computed as the ratio between the generated  $\Lambda_c^+$ -baryon yield in  $|y_{\text{lab}}| < y_{\text{fid}}(p_T)$  and that in  $|y_{\text{lab}}| < 0.5$ , where the  $\Lambda_c^+$ -baryon rapidity shape was taken from FONLL pQCD calculations. The factor 2 in the denominator

of Eq. (1) takes into account that the raw yield includes both particles and antiparticles, while the cross section is given for particles only and is computed as the average of  $\Lambda_c^+$  and  $\bar{\Lambda}_c^-$ .

The correction factor  $(A \times \epsilon)$  was obtained following the same approach as discussed in Ref. [78]. The correction factors were obtained from simulations in which the detector and data taking conditions of the corresponding data samples were reproduced. PYTHIA 6.4.25 and PYTHIA 8.243 [95] were used to simulate  $pp$  collisions. For  $p$ -Pb collisions, a  $pp$  event containing heavy-flavor signals was generated with PYTHIA 6 and HIJING was used to simulate the underlying background event.

The  $(A \times \epsilon)$  was computed separately for prompt and non-prompt  $\Lambda_c^+$ . The  $\Lambda_c^+ \rightarrow pK^-\pi^+$  decay channel includes not only the direct (nonresonant) decay mode but also three resonant channels, as explained in Sec. III. Due to the kinematical properties of these decays, the acceptance and efficiency of each decay mode is different and the final correction was determined as a weighted average of the  $(A \times \epsilon)$  values of the four decay channels with the relative branching ratios as weights.

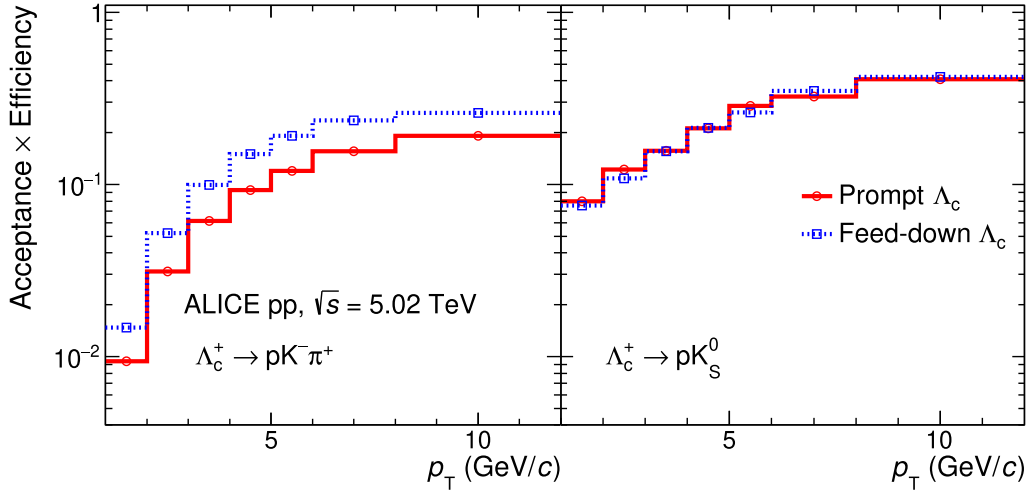


FIG. 2. Product of detector acceptance and efficiency for  $\Lambda_c^+$  baryons in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV, as a function of  $p_T$ . From left to right:  $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $\Lambda_c^+ \rightarrow pK_S^0$ . The solid lines correspond to the  $(A \times \epsilon)$  for prompt  $\Lambda_c^+$ , while the dotted lines represent  $(A \times \epsilon)$  for  $\Lambda_c^+$  baryons originating from beauty-hadron decays. The statistical uncertainties are smaller than the marker size.

Figures 2 and 3 show the product of  $(A \times \epsilon)$  for  $\Lambda_c^+$  baryons with  $|y| < y_{\text{fid}}$  in  $pp$  and  $p$ -Pb collisions as a function of  $p_T$  for the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  (left panel) and  $\Lambda_c^+ \rightarrow pK_S^0$  (right panel) decay channels. The higher  $(A \times \epsilon)$  for  $\Lambda_c^+$  from beauty-hadron decays in the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  decay channel is due to the geometrical selections on the displaced decay-vertex topology, which enhance the nonprompt component because of the relatively longer lifetime of the beauty hadrons compared to prompt  $\Lambda_c^+$ . For the  $\Lambda_c^+ \rightarrow pK_S^0$  analyses, the  $(A \times \epsilon)$  of prompt and nonprompt  $\Lambda_c^+$  are compatible, as selections based on the displaced decay-vertex topology are not applied.

Contrary to  $pp$  collisions, where the charged-particle multiplicity in data is well described by the simulation, in  $p$ -Pb collisions a weighting procedure based on the event multiplicity was used in the calculation of the reconstruction efficiency from the simulated events. This approach accounts for the

dependence of the reconstruction efficiency on the event multiplicity, which is due to the fact that the resolutions of the primary-vertex position and of the variables used in the geometrical selections of displaced decay vertices improve with increasing multiplicity. The event multiplicity was defined here using the number of tracklets, where a tracklet is defined as a track segment joining the reconstructed primary vertex with a space point on each SPD layer within the pseudorapidity range  $|\eta| < 1.0$ .

The factor  $f_{\text{prompt}}$  was calculated as in Ref. [14]:

$$\begin{aligned}
 f_{\text{prompt}} &= 1 - \frac{N^{\Lambda_c, \text{feed-down}}}{N^{\Lambda_c}} \\
 &= 1 - \frac{(A \times \epsilon)_{\text{feed-down}} c_{\Delta y} \Delta p_T \text{BR} \mathcal{L}_{\text{int}}}{N^{\Lambda_c}/2} \\
 &\quad \times \left( \frac{d^2\sigma}{dp_T dy} \right)_{\text{feed-down}}^{\text{FONLL}}, \quad (2)
 \end{aligned}$$

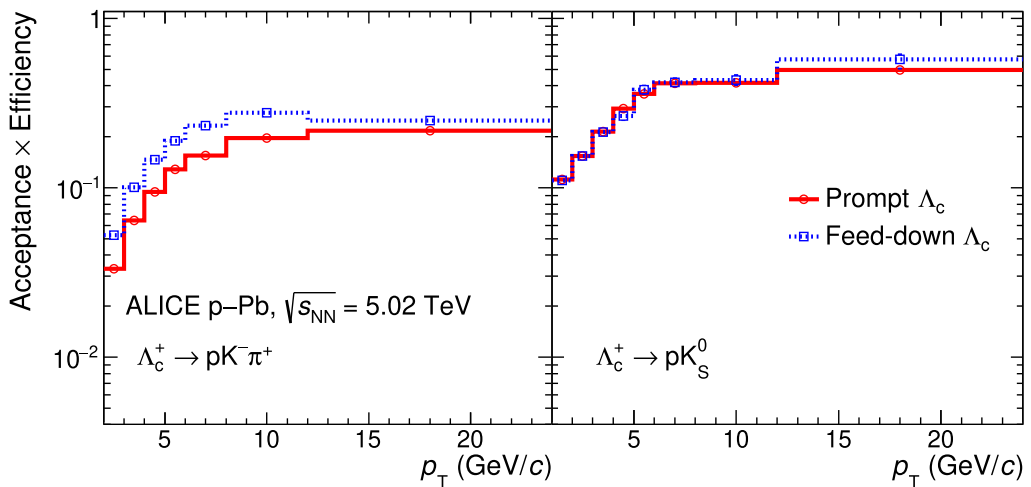


FIG. 3. Product of detector acceptance and efficiency for  $\Lambda_c^+$  baryons in  $p$ -Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV, as a function of  $p_T$ . From left to right:  $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $\Lambda_c^+ \rightarrow pK_S^0$ . The solid lines correspond to the  $(A \times \epsilon)$  for prompt  $\Lambda_c^+$ , while the dotted lines represent  $(A \times \epsilon)$  for  $\Lambda_c^+$  baryons originating from beauty-hadron decays. The statistical uncertainties are smaller than the marker size.

TABLE I. Summary of the systematic uncertainties for the two  $\Lambda_c^+$  decay modes in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV. The uncertainty sources found to be  $<1\%$  were considered negligible (“negl.” in the table).

	$\Lambda_c^+ \rightarrow pK^-\pi^+$		$\Lambda_c^+ \rightarrow pK_S^0$	
	Lowest $p_T$	Highest $p_T$	Lowest $p_T$	Highest $p_T$
Yield extraction (%)	10	8	8	7
Tracking efficiency (%)	6	7	3	5
Selection efficiency (%)	6	6	3	3
PID efficiency (%)	5	5	2	4
MC $p_T$ shape (%)	negl.	negl.	negl.	negl.
$(A \times \varepsilon)$ stat. unc. (%)	1.7	1.8	1.7	3.5
Beauty feed-down (%)	+1.1 -1.8	+5.3 -8.0	+0.8 -1.3	+2.6 -4.0
Branching ratio (%)	5.1		5.0	
Luminosity (%)	2.1			

where  $N^{\Lambda_c}/2$  is the raw yield divided by a factor of two to account for particles and antiparticles. The production cross section of  $\Lambda_c^+$  from beauty-hadron decays,  $(\frac{d^2\sigma}{dp_T dy})_{\text{feed-down}}^{\text{FONLL}}$ , was calculated using the b-quark  $p_T$ -differential cross section from FONLL calculations [12,13], the fraction of beauty quarks that fragment into beauty hadrons  $H_b$  estimated from LHCb measurements [33], and the  $H_b \rightarrow \Lambda_c^+ + X$  decay kinematics and branching ratios of  $f(H_b \rightarrow \Lambda_c^+ + X)$  modelled using PYTHIA 8 simulations [95].

The beauty-hadron fragmentation was derived from the LHCb measurements of the  $\bar{B}_s^0$ - and  $\Lambda_b^0$ -production fraction relative to  $\bar{B}^0$  and  $B^-$  mesons in  $pp$  collisions at  $\sqrt{s} = 13$  TeV [33], which indicates that the fraction of  $b$  quarks hadronizing into a  $\Lambda_b^0$  baryon is strongly  $p_T$ -dependent in the measured range of  $4 < p_T < 25$  GeV/ $c$ . The fits to the production fractions of  $\bar{B}_s^0$  and  $\Lambda_b^0$  hadrons normalized to the sum of  $B^-$  and  $\bar{B}^0$  hadrons are presented in Ref. [33] as a function of the beauty-hadron  $p_T$  as

$$\frac{f_s}{f_u + f_d}(p_T) = A[p_1 + p_2 \times (p_T - \langle p_T \rangle)] = X, \quad (3)$$

$$\frac{f_{\Lambda_b^0}}{f_u + f_d}(p_T) = C[q_1 + \exp(q_2 + q_3 \times p_T)] = Y, \quad (4)$$

where  $f_u$ ,  $f_d$ ,  $f_s$ , and  $f_{\Lambda_b^0}$  are the fractions of  $b$  quarks that hadronize into  $\bar{B}^0$ ,  $B^-$ ,  $\bar{B}_s^0$ , and  $\Lambda_b^0$ , respectively, and  $A$ ,  $p_1$ ,  $p_2$ ,  $\langle p_T \rangle$ ,  $C$ ,  $q_1$ ,  $q_2$ , and  $q_3$  are free parameters of the fits to the measured ratios. The beauty hadron fragmentation fractions are defined assuming  $f_u = f_d$  and  $f_u + f_d + f_s + f_{\Lambda_b^0} = 1$ . Around 90% of the feed-down  $\Lambda_c^+$  comes from  $\Lambda_b^0 \rightarrow \Lambda_c^+ + X$  decays, and the  $\Lambda_b^0$  fragmentation fraction can be defined as

$$f_{\Lambda_b^0}(p_T) = \frac{Y}{(X + Y + 1)}. \quad (5)$$

For  $p_T = 5$  GeV/ $c$ ,  $f_{\Lambda_b^0}$  is around 0.2, and it decreases to a value of around 0.09 for  $p_T > 20$  GeV/ $c$ . For  $p_T < 5$  GeV/ $c$  it was assumed that  $f_{\Lambda_b^0} = 0.2$ , since measurements of the ratio  $\Lambda_b^0/\bar{B}^0$  in  $pp$  collisions at  $\sqrt{s} = 7$  TeV and 8 TeV [32] are flat as a function of  $p_T$  in this interval within the experimental uncertainties. It was assumed that there is no rapidity dependence of  $f_{\Lambda_b^0}$  since the LHCb measurements of

beauty-production ratios are flat as a function of rapidity in  $2 < y < 5$  within the experimental uncertainties [32,33].

For  $p$ -Pb collisions, a hypothesis on the nuclear modification factor  $R_{p\text{Pb}}^{\text{feed-down}}$  of  $\Lambda_c^+$  from beauty-hadron decays was included as an additional factor in the last term of Eq. (2). As in the  $D$ -meson analyses [76], it was assumed that the  $R_{p\text{Pb}}$  of prompt and feed-down  $\Lambda_c^+$  are equal. The values of  $f_{\text{prompt}}$  in both collision systems range between 87% and 98% for the  $\Lambda_c^+ \rightarrow pK_S^0$  decay channel and between 84% and 98% for the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  decay channel.

## V. EVALUATION OF SYSTEMATIC UNCERTAINTIES

This section describes the various sources of systematic uncertainties of the measured cross section in each analysis and the methods used to estimate them. A summary of the systematic uncertainties is shown in Tables I and II for the  $pp$  and  $p$ -Pb analyses, respectively. The different sources of systematic uncertainty are assumed to be uncorrelated, and their contributions are added in quadrature to calculate the overall systematic uncertainty in each  $p_T$  interval.

The systematic uncertainty on the yield extraction was estimated by repeating the fits to the invariant mass distributions several times, varying (i) the lower and upper limits of the fit interval and (ii) the functional form of the background (linear, exponential, and second-order polynomial functions were used). For each of the above trials, the fit was repeated with different hypotheses on the signal peak width and mean, with variations including (a) treating both the Gaussian width and mean as free parameters, (b) fixing the peak width to the MC expectation and leaving the mean free, (c) fixing the mean to the MC expectation and leaving the peak width free, and (d) fixing both the peak width and mean to the MC expectation. The systematic uncertainty was defined as the RMS of the distribution of the raw yield values extracted from these trials.

The systematic uncertainty on the tracking efficiency was estimated by (i) comparing the probability of prolonging a track from the TPC to the ITS (“matching efficiency”) in data and simulation and (ii) varying track selection criteria in the analyses. The matching efficiency in simulation was determined after reweighting the relative abundance of primary and secondary particles to match that in data. The uncertainty on



TABLE II. Summary of the systematic uncertainties for the two  $\Lambda_c^+$  decay modes in  $p$ -Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. The uncertainty sources found to be  $<1\%$  were considered negligible (“negl.” in the table).

	$\Lambda_c^+ \rightarrow pK^-\pi^+$		$\Lambda_c^+ \rightarrow pK_S^0$	
	Lowest $p_T$	Highest $p_T$	Lowest $p_T$	Highest $p_T$
Yield extraction (%)	8	10	10	8
Tracking efficiency (%)	6	6	6	5
Selection efficiency (%)	10	6	15	8
PID efficiency (%)	5	5	negl.	negl.
MC $p_T$ shape (%)	1	1	1	1
$(A \times \varepsilon)$ stat. unc. (%)	1.1	4.0	0.5	3.0
Beauty feed-down (%)	+1.8 -3.0	+4.2 -6.7	+0.9 -1.5	+4.6 -7.0
Branching ratio (%)	5.1		5.0	
Luminosity (%)	3.7			

the matching efficiency was defined as the relative difference in the matching efficiency between simulation and data. It is species-dependent and therefore it was determined individually for protons, kaons, and pions. In the  $\Lambda_c^+ \rightarrow pK_S^0$  analysis only the proton matching efficiency uncertainty was included since no ITS condition was required for the pion tracks from the  $K_S^0$  decay. The per-track uncertainty on the matching efficiency is  $p_T$  dependent and it was propagated to the  $\Lambda_c^+$  taking into account the decay kinematics and treating the uncertainty as correlated among the tracks. The second contribution to the track reconstruction uncertainty was estimated by repeating the analysis varying the TPC track selection criteria. The uncertainty was defined as the RMS of the  $\Lambda_c^+$  cross section values obtained with the different track selections. The total uncertainty on the tracking efficiency was defined as the quadratic sum of these two contributions.

The uncertainty on the  $\Lambda_c^+$  selection efficiency due to imperfections in the simulated kinematical and geometrical variables used to select  $\Lambda_c^+$  candidates was estimated by varying the selection criteria. For the BDT analysis in the  $\Lambda_c^+ \rightarrow pK_S^0$  channel, variations were made on the selection of the BDT response. The systematic uncertainty was estimated in each  $p_T$  interval as the RMS of the distribution of the corrected cross section values resulting from these variations.

Systematic uncertainties can arise from discrepancies in the PID efficiency between simulation and data. In the case of the  $\Lambda_c^+ \rightarrow pK_S^0$  analysis in  $pp$  collisions, the systematic uncertainty associated with the PID efficiency was estimated by varying the minimum probability threshold required to identify a track as a proton. For the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  analysis, the systematic uncertainty was estimated by applying a minimum threshold selection on the Bayesian probability to assign the track identity, with the threshold varying between 30% and 80%. The systematic uncertainty in both cases was defined based on the variation of the corrected cross section. For the  $\Lambda_c^+ \rightarrow pK_S^0$  analysis in  $p$ -Pb collisions, the PID variables were included as part of the BDT, and therefore the PID uncertainty is already accounted for by varying the selection on the BDT response. The contribution due to the  $3\sigma$  PID preselection was found to be negligible.

An additional source of systematic uncertainty was assigned due to the dependence of the efficiencies on the generated  $p_T$  distribution of  $\Lambda_c^+$  in the simulation (“MC  $p_T$  shape” in Tables I and II). To estimate this effect the efficiencies were evaluated after reweighting the  $p_T$  shape of the PYTHIA 6 simulations to match the  $p_T$  spectrum of  $D$  mesons from FONLL pQCD calculations. An uncertainty was assigned in each  $p_T$  interval based on the difference between the central and reweighted efficiencies.

The relative statistical uncertainty on  $(A \times \varepsilon)$  was considered as an additional systematic uncertainty source, originating from the finite statistics in the simulation used to calculate the efficiency.

The systematic uncertainty on the prompt fraction (“Beauty feed-down” in Tables I and II) was estimated by varying independently (i) the production cross section of beauty quarks within the theoretical uncertainties in FONLL [13] and (ii) the function describing the fragmentation fraction  $f_{\Lambda_b^0}$ . For the variation of (ii), the free parameters defined in Ref. [33] were varied independently within their uncertainties. For  $p_T(\Lambda_b^0) < 5$  GeV/c, the lower uncertainty bound of  $f_{\Lambda_b^0}$  was taken to be equal to the lower bound of the fit at  $p_T(\Lambda_b^0) = 5$  GeV/c, independent of  $p_T$ , while the upper uncertainty bound was taken to be equal to the  $p_T$ -dependent upper bound of the fit. To account for a possible  $\sqrt{s}$  dependence of the fragmentation fractions, an additional reduction of the lower bound of  $f_{\Lambda_b^0}$  was considered based on the spread of the LHCb measurements at different values of  $\sqrt{s}$ . In the  $p$ -Pb analyses the uncertainty on the hypothesis of the nuclear modification factor of  $\Lambda_c^+$  from beauty-hadron decays was estimated by varying the ratio  $R_{pPb}^{\text{feed-down}}/R_{pPb}^{\text{prompt}}$  in the range  $0.9 < R_{pPb}^{\text{feed-down}}/R_{pPb}^{\text{prompt}} < 1.3$ . This range was chosen based on theoretical calculations of charm and beauty hadron production in  $p$ -Pb collisions as explained in Ref. [76]. The overall uncertainty on the prompt fraction was defined as the envelope of these variations, which leads to an asymmetric uncertainty.

The uncertainty on the luminosity measurement is 2.1% for  $pp$  collisions [87] and 3.7% for  $p$ -Pb collisions [88]. The uncertainty on the branching fractions are 5.1% for the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  channel, and 5.0% for the  $\Lambda_c^+ \rightarrow pK_S^0$  channel [89].

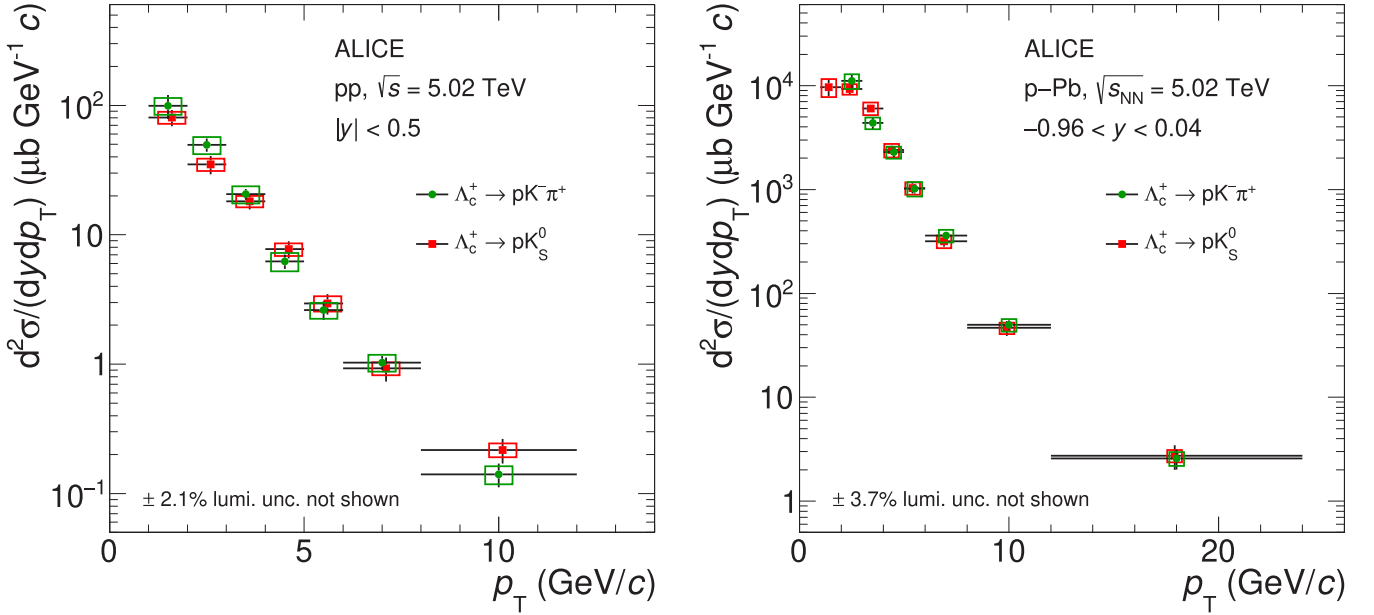


FIG. 4. Left:  $p_T$ -differential prompt  $\Lambda_c^+$ -baryon cross section in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV in the interval  $1 < p_T < 12$  GeV/c. Right:  $p_T$ -differential prompt  $\Lambda_c^+$ -baryon cross section in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV in the interval  $1 < p_T < 24$  GeV/c. The statistical uncertainties are shown as vertical bars and the systematic uncertainties are shown as boxes. Horizontal position of points are shifted to provide better visibility.

## VI. RESULTS

### A. $p_T$ -differential cross sections

The  $p_T$ -differential cross section of prompt  $\Lambda_c^+$ -baryon production in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV, measured in the rapidity interval  $|y| < 0.5$  and  $p_T$  interval  $1 < p_T < 12$  GeV/c, is shown in Fig. 4 (left) for the two decay channels  $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $\Lambda_c^+ \rightarrow pK_S^0$ . Figure 4 (right) shows the  $p_T$ -differential cross section of prompt  $\Lambda_c^+$ -baryon production in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, measured in the rapidity interval  $-0.96 < y < 0.04$  and  $p_T$  interval  $1 < p_T < 24$  GeV/c for the two decay channels  $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $\Lambda_c^+ \rightarrow pK_S^0$ . The measurements in the different decay channels agree within statistical and uncorrelated systematic uncertainties, with the largest discrepancies among the measured values being smaller than  $1.4\sigma$ .

To obtain a more precise measurement of the  $p_T$ -differential  $\Lambda_c^+$ -baryon production cross section, the results from the two decay channels were combined, taking into account the correlation between the statistical and systematic uncertainties. The systematic uncertainties treated as uncorrelated between the different decay channels ( $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $\Lambda_c^+ \rightarrow pK_S^0$ ) include those due to the raw-yield extraction, the  $\Lambda_c^+$ -selection efficiency, and the  $(A \times \epsilon)$  statistical uncertainties. The systematic uncertainties due to the tracking efficiency, the PID efficiency, the generated  $\Lambda_c^+$   $p_T$  spectrum, the beauty feed-down, and the luminosity were treated as correlated between the two decay channels. The branching ratio uncertainties were considered to be partially correlated, as described in Ref. [89]. A weighted average of the cross section values obtained from the different analyses was calculated, using the inverse of the quadratic sum of the relative statistical and uncorrelated systematic uncertainties as weights.

Figure 5 shows the measured production cross section (average of the two decay channels) in  $pp$  collisions compared to predictions from MC generators and pQCD calculations. The left panel shows the comparison with predictions from different tunes of the PYTHIA 8 generator, including the Monash tune [23], and tunes that implement color reconnection (CR) beyond the leading-color approximation [24]. These additional color reconnection topologies include “junctions” which fragment into baryons, leading to increased baryon production. For the CR tunes, three modes are considered (Modes 0, 2, and 3), as described in Ref. [24], which apply different constraints on the allowed reconnection, taking into account causal connection of dipoles involved in a reconnection and time-dilation effects caused by relative boosts between string pieces. It is noted that Mode 2 is recommended in Ref. [24] as the standard tune, and contains the strictest constraints on the allowed reconnection. In the simulations with the three CR modes, all soft QCD processes are switched on. All PYTHIA 8 tunes underestimate the measured  $p_T$ -differential prompt  $\Lambda_c^+$  cross section. The Monash tune significantly underestimates the cross section by a factor  $\sim 12$  for  $1 < p_T < 2$  GeV/c, and around a factor 2–3 for  $p_T > 5$  GeV/c. All three CR modes yield a similar magnitude and shape of the  $\Lambda_c^+$  cross section, and predict a significantly larger  $\Lambda_c^+$  production cross section with respect to the Monash tune. However, for all three CR modes, the measured  $\Lambda_c^+$  production cross section is underestimated by a factor of about two for  $1 < p_T < 2$  GeV/c. For  $p_T > 5$  GeV/c, Mode 2 and Mode 3 provide a good description of the data, while Mode 0 underestimates the data by 15–20%. All tunes exhibit a harder  $p_T$  distribution than observed in data.

The right panel of Fig. 5 shows a comparison with a NLO pQCD calculation obtained with the POWHEG frame-

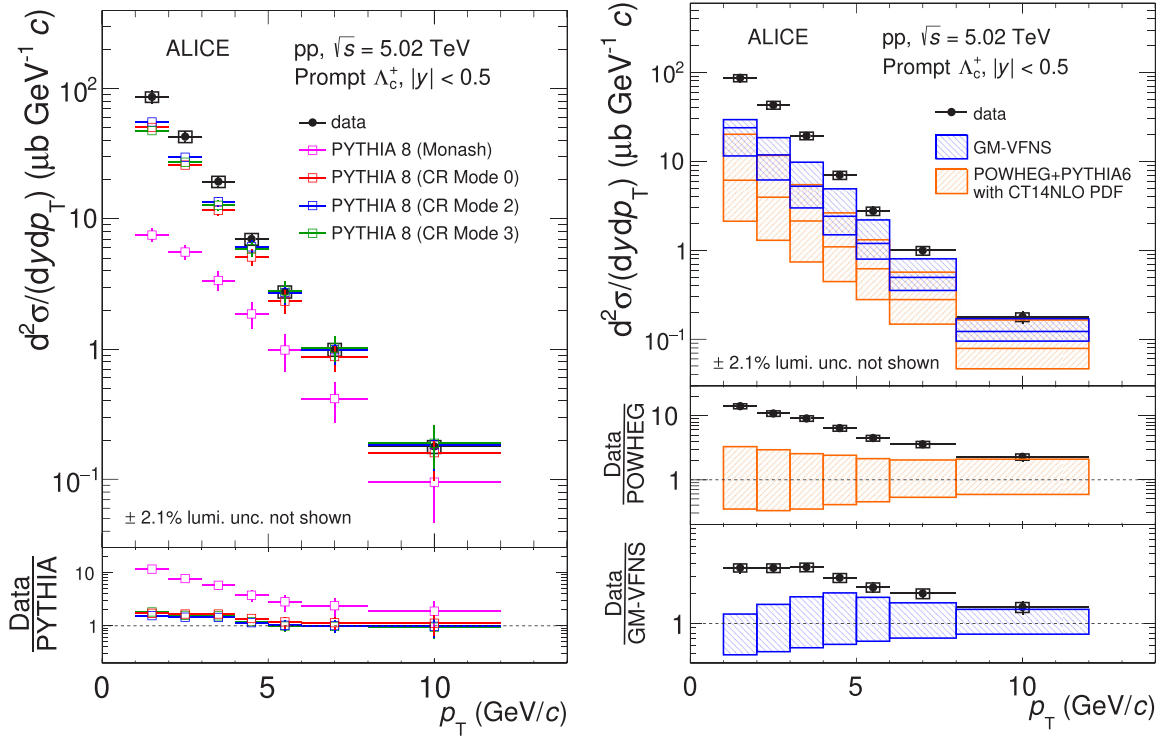


FIG. 5. Prompt  $\Lambda_c^+$ -baryon  $p_T$ -differential production cross section in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV in the interval  $1 < p_T < 12$  GeV/ $c$ . The statistical uncertainties are shown as vertical bars and the systematic uncertainties are shown as boxes. Left: Comparison to predictions from different tunes of the PYTHIA 8 event generator [23,24]. The vertical bars on the PYTHIA 8 predictions represent the statistical uncertainty from the simulation, and the vertical bars on the ratios in the bottom panel also include the statistical uncertainties from the data. Right: Comparison to predictions from the POWHEG event generator [96] and GM-VFNS calculations [98]. The orange(blue) boxes represent the uncertainties of POWHEG(GM-VFNS) due to the choice of pQCD scales. See text for details on the PYTHIA 8 and POWHEG event generator settings.

work [96], matched with PYTHIA 6 to generate the parton shower, and the CT14NLO parton distribution functions [97]. The nominal factorization and renormalization scales,  $\mu_F$  and  $\mu_R$ , were taken to be equal to the transverse mass of the quark,  $\mu_0 = \sqrt{m^2 + p_T^2}$ , and the charm-quark mass was set to  $m_c = 1.5$  GeV/ $c^2$ . The theoretical uncertainties were estimated by varying these scales in the range  $0.5\mu_0 < \mu_{R,F} < 2.0\mu_0$ , with  $0.5\mu_0 < \mu_R/\mu_F < 2.0\mu_0$ . Results are also compared with recent GM-VFNS pQCD calculations [98]. With respect to previous GM-VFNS calculations [10,11], a new fragmentation function for  $\Lambda_c^+$  has been used, obtained from a fit to OPAL data [99] and measurements from Belle at  $\sqrt{s} = 10.52$  GeV [100]. The measured  $p_T$ -differential cross section is significantly underestimated by the POWHEG prediction, by a factor of up to 15 in the lowest  $p_T$  interval of the measurements, and around a factor 2.5 in the highest. While the discrepancy between the data and calculation decreases as the  $p_T$  increases, the measured cross section at  $8 < p_T < 12$  GeV/ $c$  is still  $\sim 50\%$  larger than the upper edge of the POWHEG uncertainty band. The discrepancy between the data and POWHEG is similar to what was observed in  $pp$  collisions at  $\sqrt{s} = 7$  TeV [14]. The GM-VFNS predictions also significantly underestimate the data, by about a factor of 3–4 at low  $p_T$  and by about a factor of 1.5 at high  $p_T$ .

In Fig. 6, the  $\Lambda_c^+$ -production cross section in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV is compared with the measurement at  $\sqrt{s} = 7$  TeV [14]. For a direct comparison, the intervals  $4 < p_T < 5$  GeV/ $c$  and  $5 < p_T < 6$  GeV/ $c$  of the  $\sqrt{s} = 5.02$  TeV analysis have been merged. When merging, the systematic uncertainties were propagated considering the uncertainty due to the raw-yield extraction as fully uncorrelated and all the other sources as fully correlated between  $p_T$  intervals. In the lower panel of the same figure, the ratio of the cross sections is shown. In this case, the systematic uncertainties on feed-down,  $p_T$  shape, and branching ratio were assumed to be fully correlated, while all the other sources were considered as uncorrelated between the results at the two collision energies. The relative statistical uncertainties in the measurement at  $\sqrt{s} = 5.02$  TeV are on average smaller than those in the measurement at  $\sqrt{s} = 7$  TeV by a factor  $\sim 1.5$ . As expected, a lower  $\Lambda_c^+$ -production cross section is observed at the lower collision energy. The difference between the cross sections at the two  $\sqrt{s}$  values increases with increasing  $p_T$ , indicating a harder  $p_T$  shape at the higher collision energy. This behavior is consistent with that observed for the  $D$ -meson cross section ratios at  $\sqrt{s} = 7$  TeV and  $\sqrt{s} = 5.02$  TeV, which is described by pQCD calculations [9].

Figure 7 shows the  $p_T$ -differential cross section averaged among the decay channels and analysis techniques in  $p$ -Pb

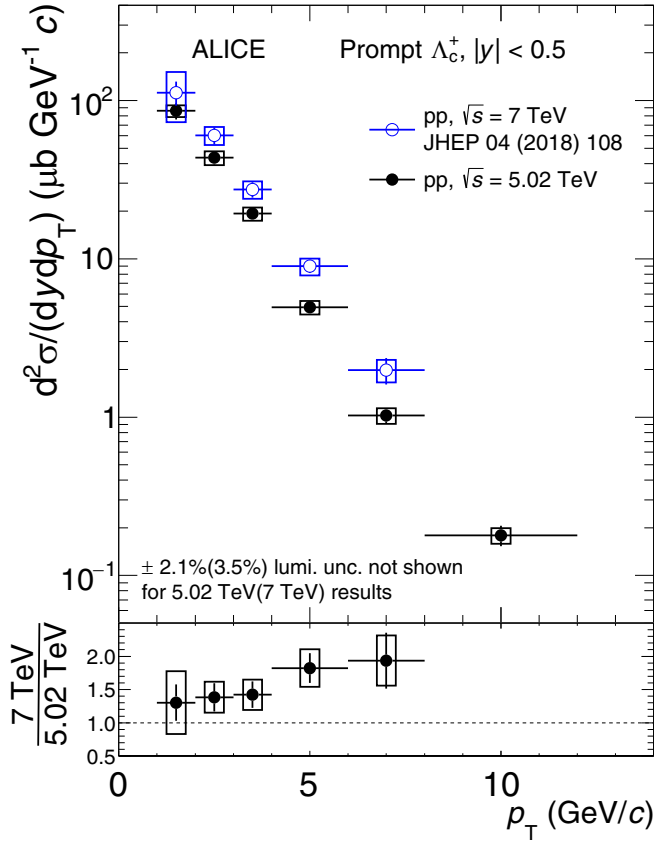


FIG. 6. Comparison between the  $p_T$ -differential production cross section of prompt  $\Lambda_c^+$  baryons in  $pp$  collisions at  $\sqrt{s} = 7$  TeV [14] and  $\sqrt{s} = 5.02$  TeV. The ratio between the cross sections is shown in the lower panel. The statistical uncertainties are shown as vertical bars and the systematic uncertainties are shown as boxes.

collisions. The cross section is compared to the POWHEG event generator, where the generator settings, the parton shower, and the set of parton distribution functions are the same as used in the calculations for  $pp$  collisions, and the nuclear modification of the parton distribution functions is modelled with the EPPS16 nPDF parametrization [48]. The theoretical uncertainty includes the uncertainty on the factorization and renormalization scales (estimated as done for POWHEG predictions for  $pp$  collisions), while the uncertainties on the parton distribution functions and EPPS16 nPDF are not included in the calculation as they are smaller than the scale uncertainties. The cross section is underestimated by the POWHEG prediction by a factor of up to 15 in the lowest  $p_T$  intervals, similar to what is observed for  $pp$  collisions. The difference between the POWHEG predictions and the measured cross section decreases with increasing  $p_T$  and in the highest  $p_T$  interval of the measurement ( $12 < p_T < 24$  GeV/c) the data point lies on the upper edge of the POWHEG uncertainty band. The Run 2  $p$ -Pb results are compatible with our previous results from the sample of  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV collected in LHC Run 1 [14]. The statistical uncertainties have been reduced by approximately a factor of two for all

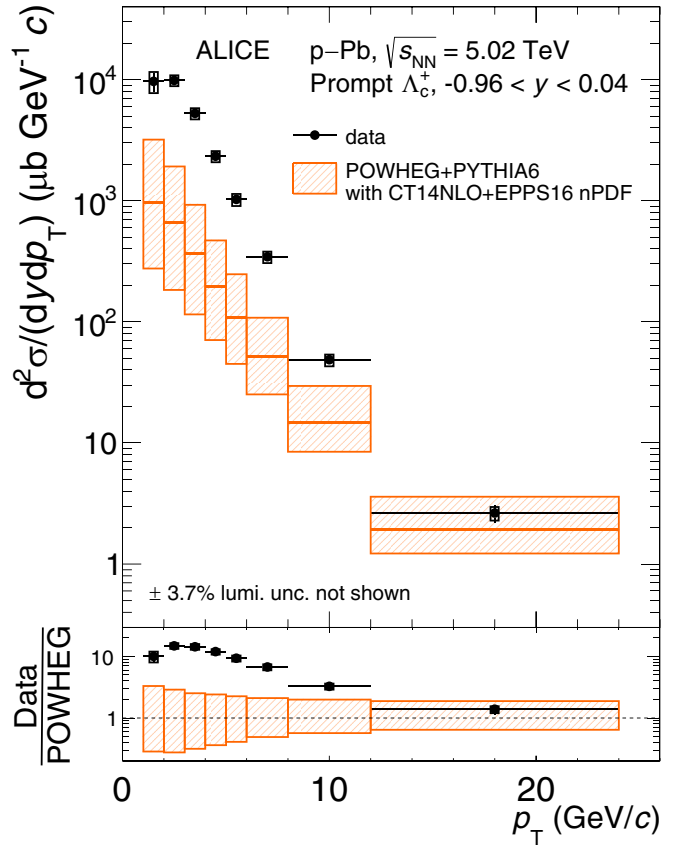


FIG. 7.  $p_T$ -differential prompt  $\Lambda_c^+$ -baryon production cross section in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV in the interval  $1 < p_T < 24$  GeV/c compared to predictions from the POWHEG event generator [96]. The statistical uncertainties are shown as vertical bars and the systematic uncertainties are shown as boxes. The orange boxes represent the uncertainties of POWHEG due to the choice of pQCD scales. See text for details on the POWHEG event generator settings.

$p_T$  intervals, and the systematic uncertainties improved by approximately 30% at low  $p_T$  and 10% at high  $p_T$ .

### B. Nuclear modification factor

The nuclear modification factor  $R_{pPb}$  was calculated as the  $p_T$ -differential  $\Lambda_c^+$  cross section in  $p$ -Pb collisions divided by the reference measurement of the  $p_T$ -differential  $\Lambda_c^+$  cross section in  $pp$  collisions scaled by the lead mass number  $A = 208$ ,

$$R_{pPb} = \frac{1}{A} \frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T}, \quad (6)$$

where  $d\sigma_{pp}/dp_T$  was obtained from the cross section measured in  $pp$  collisions in  $|y| < 0.5$  applying a correction factor to account for the different rapidity coverage of the  $pp$  and  $p$ -Pb measurements. The correction factor is calculated with FONLL and ranges from 0.995 (in  $1 < p_T < 2$  GeV/c) to 0.983 (in  $8 < p_T < 12$  GeV/c). Figure 8 (left) shows the  $R_{pPb}$  of  $\Lambda_c^+$  baryons in the  $p_T$  interval  $1 < p_T < 12$  GeV/c compared to the  $R_{pPb}$  of nonstrange  $D$  mesons from Ref. [101]. With respect to the previous measurement of the  $\Lambda_c^+$ -baryon

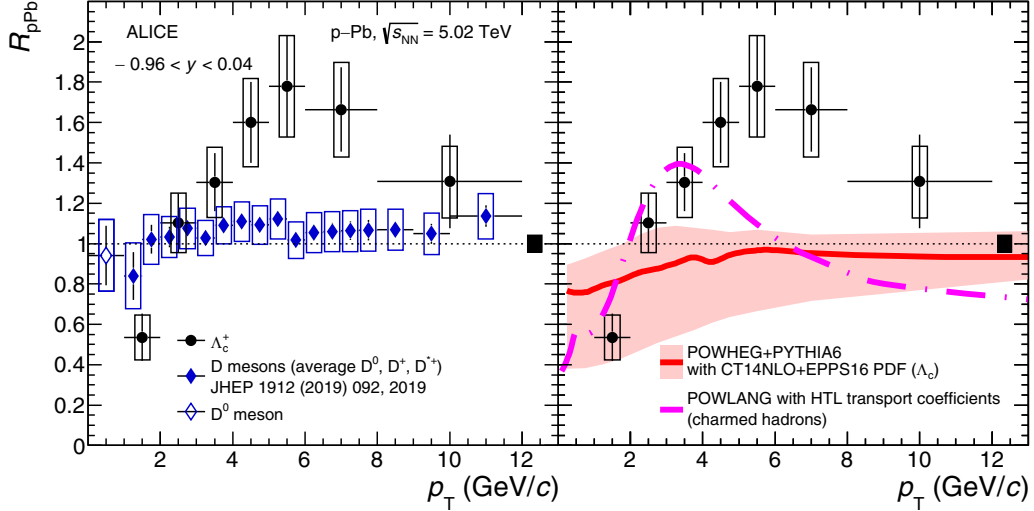


FIG. 8. The nuclear modification factor  $R_{pPb}$  of prompt  $\Lambda_c^+$  baryons in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV as a function of  $p_T$ , compared to the  $R_{pPb}$  of  $D$  mesons [101] (average of  $D^0$ ,  $D^+$ , and  $D^{*+}$  in the range  $1 < p_T < 12$  GeV/ $c$  and  $D^0$  in  $0 < p_T < 1$  GeV/ $c$ ) (left), as well as to POWHEG+PYTHIA 6 [96] with EPPS16 [48] simulations, and POWLANG [60] predictions (right). The black-filled box at  $R_{pPb} = 1$  represents the normalization uncertainty.

$R_{pPb}$  [14], the  $p_T$  reach has been extended to higher and lower  $p_T$ . In addition, the  $pp$  reference at the same per-nucleon center-of-mass energy as the  $p$ -Pb sample eliminates the uncertainty originating from the  $\sqrt{s}$ -scaling of the  $pp$  cross section measured at  $\sqrt{s} = 7$  TeV that was present in the previous results. These improvements, along with the increased statistical precision, have allowed for a reduction of the overall uncertainty of the  $R_{pPb}$  by a factor of 1.7–2 compared with the previous measurement. The result is consistent with the  $D$ -meson  $R_{pPb}$  within the uncertainties in the  $p_T$  regions  $1 < p_T < 4$  GeV/ $c$  and  $p_T > 8$  GeV/ $c$ , but larger than the  $D$ -meson  $R_{pPb}$  in  $4 < p_T < 8$  GeV/ $c$  with a maximum deviation of  $1.9\sigma$  in  $5 < p_T < 6$  GeV/ $c$ , where  $\sigma$  is defined as the quadratic sum of the statistical and the lower(upper) systematic uncertainties for  $\Lambda_c^+$  baryons ( $D$  mesons). For  $p_T > 2$  GeV/ $c$  the  $\Lambda_c^+$ -baryon  $R_{pPb}$  is systematically above unity, with a maximum deviation from  $R_{pPb} = 1$  reaching  $2.2\sigma$  in the  $p_T$  interval  $5 < p_T < 6$  GeV/ $c$ , where  $\sigma$  is defined as the quadratic sum of the statistical and the upper systematic uncertainty. In the  $p_T$  interval  $1 < p_T < 2$  GeV/ $c$  the  $R_{pPb}$  is lower than unity by  $2.6\sigma$ . This hints that  $\Lambda_c^+$  production is suppressed at low  $p_T$  and is enhanced at mid- $p_T$  in  $p$ -Pb collisions with respect to  $pp$  collisions. In Fig. 8 (right) the measured  $\Lambda_c^+$ -baryon  $R_{pPb}$  is compared to model calculations. The POWHEG+PYTHIA 6 simulations use the POWHEG event generator with PYTHIA 6 parton shower and EPPS16 parametrization of the nuclear modification of the PDFs [48]. The uncertainty band includes the uncertainties on the nuclear PDFs and on the choice of the pQCD scales. The POWLANG model [60] assumes that a hot deconfined medium is formed in  $p$ -Pb collisions, and the transport of heavy quarks through an expanding QGP is computed utilising the Langevin approach and Hard Thermal Loop (HTL) transport coefficients. The POWLANG model does not implement specific differences in hadronization mechanisms for baryons and mesons, and the same prediction holds for all charm hadron species.

The two models capture some features of the data, but neither of them can quantitatively reproduce the observed  $\Lambda_c^+$ -baryon  $R_{pPb}$  in the measured  $p_T$  interval.

### C. $p_T$ -integrated $\Lambda_c^+$ cross sections

The visible  $\Lambda_c^+$  cross section was computed by integrating the  $p_T$ -differential cross section in its measured range. In the integration, the systematic uncertainties were propagated considering the uncertainty due to the raw-yield extraction as fully uncorrelated and all the other sources as fully correlated between  $p_T$  intervals. The visible  $\Lambda_c^+$  cross section in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV is

$$d\sigma_{pp, 5.02 \text{ TeV}}^{\Lambda_c^+} / dy \Big|_{|y| < 0.5}^{1 < p_T < 12 \text{ GeV}/c} = 161 \pm 11 \text{ (stat.)} \pm 14 \text{ (syst.)} \pm 3 \text{ (lumi.)} \mu\text{b}. \quad (7)$$

The visible  $\Lambda_c^+$  cross section in  $p$ -Pb collisions is

$$d\sigma_{pPb, 5.02 \text{ TeV}}^{\Lambda_c^+} / dy \Big|_{-0.96 < y < 0.04}^{1 < p_T < 24 \text{ GeV}/c} = 29.0 \pm 2.0 \text{ (stat.)} \pm 3.6 \text{ (syst.)} \pm 1.1 \text{ (lumi.)} \text{ mb}. \quad (8)$$

The  $p_T$ -integrated  $\Lambda_c^+$  production cross section at midrapidity was obtained by extrapolating the visible cross sections to the full  $p_T$  range. The extrapolation approach used for  $D$  mesons [75], based on the  $p_T$ -differential cross sections predicted by FONLL calculations, is not applicable here because FONLL does not have predictions for  $\Lambda_c^+$  baryons. For  $pp$  collisions, PYTHIA 8 predictions with specific tunes implementing CR mechanisms were used for the extrapolation. The  $p_T$ -differential  $\Lambda_c^+$  cross section values in  $0 < p_T < 1$  GeV/ $c$  and for  $p_T \geq 12$  GeV/ $c$  were obtained by scaling the measured  $\Lambda_c^+$  cross section in  $1 < p_T < 12$  GeV/ $c$  for the fractions of cross section given by PYTHIA in  $0 < p_T < 1$  GeV/ $c$  and for  $p_T \geq 12$  GeV/ $c$  respectively. The PYTHIA 8 simulation with Mode 2 CR tune [24] including soft QCD processes, which gives the best description of both the magni-

tude and shape of the  $\Lambda_c^+$  cross section and  $\Lambda_c^+/D^0$  ratio, was used to calculate the central value of the extrapolation factors. The procedure was repeated considering the three modes defined in Ref. [24], with the envelopes of the corresponding results assigned as the extrapolation uncertainty. A second extrapolation method was also implemented as a cross-check. This consisted of multiplying the measured  $D^0$  cross section value in  $0 < p_T < 1$  GeV/c by the  $\Lambda_c^+/D^0$  ratio estimated with PYTHIA 8 (CR Mode 2) in the same  $p_T$  interval to get an estimate of the  $\Lambda_c^+$  cross section value in  $0 < p_T < 1$  GeV/c, and then integrating in  $p_T$ . The results obtained with the two methods were found to be compatible within the uncertainties.

The resulting  $p_T$ -integrated cross section of the  $\Lambda_c^+$  baryon in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV is

$$d\sigma_{pp, 5.02 \text{ TeV}}^{\Lambda_c^+}/dy|_{|y|<0.5} = 230 \pm 16 \text{ (stat.)} \pm 20 \text{ (syst.)} \\ \pm 5 \text{ (lumi.)}_{-10}^{+5} \text{ (extrap.)} \mu\text{b.} \quad (9)$$

In  $p$ -Pb collisions, the  $p_T$ -integrated  $\Lambda_c^+$ -production cross section was obtained using a different approach, since the  $p_T$  spectrum of  $\Lambda_c^+$  is not well described by PYTHIA or other event generators. In this case, the cross sections in  $0 < p_T < 1$  GeV/c and  $p_T > 24$  GeV/c were calculated as the product of the  $pp$  cross sections in these  $p_T$  intervals obtained from the extrapolation of the measured  $p_T$ -differential cross section, as described above; the Pb mass number; a correction factor to account for the different rapidity interval covered in  $pp$  and  $p$ -Pb collisions; and an assumption on the nuclear modification factor  $R_{pPb}$  as described hereafter. For  $0 < p_T < 1$  GeV/c, the  $R_{pPb}$  was taken as  $R_{pPb} = 0.5$  as in the  $1 < p_T < 2$  GeV/c interval, under the hypothesis that the trend of the  $\Lambda_c^+$   $R_{pPb}$  at low  $p_T$  is similar to that of  $D$  mesons. The uncertainty was estimated by varying the hypothesis in the range  $0.35 < R_{pPb} < 0.8$ , which incorporates the envelope of the available models (see Fig. 8) and the range defined by the combination of the statistical and systematic uncertainties of the  $\Lambda_c^+$   $R_{pPb}$  in  $1 < p_T < 2$  GeV/c. For  $p_T > 24$  GeV/c, the  $R_{pPb}$  was assumed to be equal to unity, with the range  $0.8 < R_{pPb} < 1.2$  used to define the uncertainty.

The resulting  $p_T$ -integrated cross section of prompt  $\Lambda_c^+$  in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV is

$$d\sigma_{pPb, 5.02 \text{ TeV}}^{\Lambda_c^+}/dy|_{-0.96 < y < 0.04} \\ = 36.2 \pm 2.5 \text{ (stat.)} \pm 4.5 \text{ (syst.)} \\ \pm 1.3 \text{ (lumi.)}_{-2.7}^{+4.4} \text{ (extrap.)} \text{ mb.} \quad (10)$$

The visible cross sections make up 70% and 80% of the integrated cross sections in  $pp$  and  $p$ -Pb collisions, respectively. The  $p_T$ -integrated  $\Lambda_c^+$  cross sections in  $pp$  and  $p$ -Pb collisions can be used for the comparison of fragmentation fractions of charm quarks in different collision systems and rapidity intervals. They can also be used in the calculation of the  $c\bar{c}$  cross section together with the cross sections of  $D$  mesons and higher-mass charm baryons that do not decay into  $\Lambda_c^+$ . Due to the lack of measurements of higher-mass charm baryons ( $\Xi_c^{+,0}, \Omega_c$ ) at  $\sqrt{s} = 5.02$  TeV, which contribute to the  $c\bar{c}$  cross section, a calculation of the  $c\bar{c}$  cross section is beyond the scope of this work.

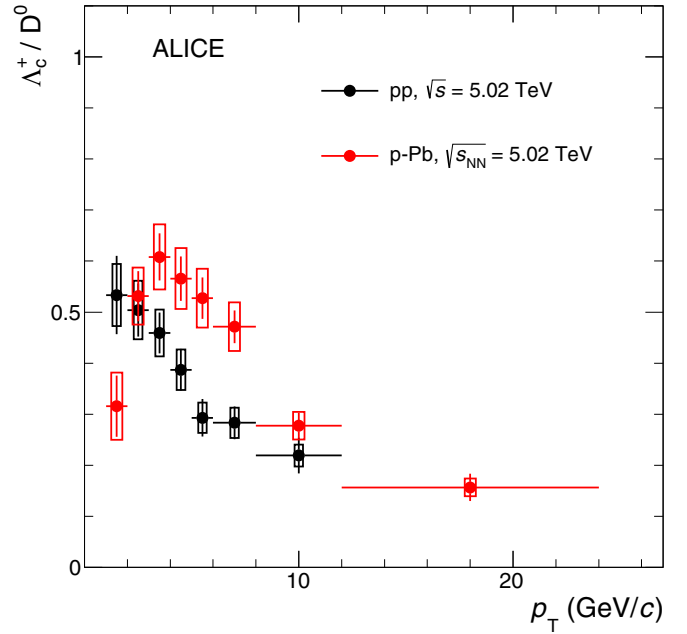


FIG. 9. The  $\Lambda_c^+/D^0$  ratio as a function of  $p_T$  measured in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV and in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV.

#### D. $\Lambda_c^+/D^0$ ratios

The ratios between the yields of  $\Lambda_c^+$  baryons and  $D^0$  mesons were calculated using the  $D^0$  cross sections reported in Ref. [9] for  $pp$  collisions and [101] for  $p$ -Pb collisions, respectively. The uncertainty sources assumed to be uncorrelated between the  $\Lambda_c^+$  and  $D^0$  production cross sections include those due to the raw-yield extraction, the selection efficiency, the PID efficiency, the generated  $p_T$  shape, the  $(A \times \epsilon)$  statistical uncertainties, and the branching ratios. The uncertainties assumed to be correlated include those due to the tracking, the beauty feed-down and the luminosity. The  $D^0$  cross section was measured in finer  $p_T$  intervals than the  $\Lambda_c^+$ , so it was rebinned such that the  $p_T$  intervals match between the two species.

The  $\Lambda_c^+/D^0$  ratio as a function of  $p_T$  in  $pp$  and  $p$ -Pb collisions is shown in Fig. 9. A clear decreasing trend with increasing  $p_T$  is seen in both  $pp$  and  $p$ -Pb collisions for  $p_T > 2$  GeV/c, and at high  $p_T$  the ratio reaches a value of about 0.2. The ratios measured in  $pp$  and  $p$ -Pb collisions are qualitatively consistent with each other, although a larger  $\Lambda_c^+/D^0$  ratio in  $3 < p_T < 8$  GeV/c and a lower ratio in  $1 < p_T < 2$  GeV/c are measured in  $p$ -Pb collisions with respect to  $pp$  collisions.

The values of the  $p_T$ -integrated  $\Lambda_c^+/D^0$  ratios are reported in Table III along with the values measured in  $e^+e^-$  and  $e^-p$  collisions by other experiments. The  $\Lambda_c^+/D^0$  ratios in  $pp$  and  $p$ -Pb collisions are consistent with each other within the experimental uncertainties. Comparing to previous measurements in other collision systems, the  $\Lambda_c^+/D^0$  ratio is significantly enhanced by a factor of about 3–5 in  $pp$  collisions and a factor of about 2–4 in  $p$ -Pb collisions, indicating that the fragmentation fractions of charm quarks into baryons

TABLE III. Comparison of the  $p_T$ -integrated  $\Lambda_c^+/D^0$  ratio measured in  $pp$  and  $p$ -Pb collisions and the same ratios in  $e^+e^-$  and  $e^-p$  collisions (reproduced from Ref. [14]). Statistical and systematic uncertainties are reported (from Refs. [15,17] it was not possible to separate systematics and statistical uncertainties). The ALICE measurements report an additional uncertainty source from the extrapolation procedure.

	$\Lambda_c^+/D^0 \pm \text{stat.} \pm \text{syst.}$	System	$\sqrt{s}$ (GeV)	Notes
ALICE	$0.51 \pm 0.04 \pm 0.04^{+0.01}_{-0.02}$	$pp$	5020	$p_T > 0,  y  < 0.5$ $p_T > 0, -0.96 < y < 0.04$
ALICE	$0.42 \pm 0.03 \pm 0.06^{+0.05}_{-0.03}$	$p$ -Pb	5020	
CLEO [16]	$0.119 \pm 0.021 \pm 0.019$	$e^+e^-$	10.55	
ARGUS [15,17]	$0.127 \pm 0.031$	$e^+e^-$	10.55	
LEP average [18]	$0.113 \pm 0.013 \pm 0.006$	$e^+e^-$	91.2	
ZEUS DIS [21]	$0.124 \pm 0.034^{+0.025}_{-0.022}$	$e^-p$	320	$1 < Q^2 < 1000 \text{ GeV}^2,$ $0 < p_T < 10 \text{ GeV}/c, 0.02 < y < 0.7,$ $130 < W < 300 \text{ GeV}, Q^2 < 1 \text{ GeV}^2,$
ZEUS $\gamma p,$	$0.220 \pm 0.035^{+0.027}_{-0.037}$	$e^-p$	320	$p_T > 3.8 \text{ GeV}/c,  \eta  < 1.6$
HERA I [19]				
ZEUS $\gamma p,$	$0.107 \pm 0.018^{+0.009}_{-0.014}$	$e^-p$	320	$130 < W < 300 \text{ GeV}, Q^2 < 1 \text{ GeV}^2,$ $p_T > 3.8 \text{ GeV}/c,  \eta  < 1.6$
HERA II [20]				

are different with respect to  $e^+e^-$  and  $e^-p$  collisions. This is consistent with the previous ALICE measurements [14], where the  $p_T$ -integrated  $\Lambda_c^+/D^0$  ratios were restricted to  $1 < p_T < 8 \text{ GeV}/c$  in  $pp$  collisions, and to  $2 < p_T < 12 \text{ GeV}/c$  in  $p$ -Pb collisions.

Figure 10 shows the  $\Lambda_c^+/D^0$  ratio in  $pp$  collisions compared with models from MC generators, and a statistical hadronization model. The MC generators include PYTHIA 8 with Monash tune and color reconnection tunes as described above; PYTHIA 8 with color reconnection plus rope hadronization [24,102] where color charges can act coherently to form a rope, increasing the effective string tension; HERWIG 7.2 [27] where hadronization is implemented via clusters; and POWHEG pQCD generator matched to PYTHIA

6 to generate the parton shower, as described above. The measured points are also compared to predictions from GM-VFNS pQCD calculations, which were computed as the ratios of the  $\Lambda_c^+$  and  $D^0$  cross sections obtained with the same choice of pQCD scales [98]. The left panel shows the predictions of the  $\Lambda_c^+/D^0$  ratio from PYTHIA 8 (Monash tune), HERWIG 7, POWHEG, and GM-VFNS, which all implement fragmentation processes tuned on charm production measurements in  $e^+e^-$  collisions, and therefore all predict a value of the  $\Lambda_c^+/D^0$  ratio around 0.1, with a very mild  $p_T$  dependence. These predictions significantly underestimate the data at low  $p_T$  by a factor of about 5–10, while at high  $p_T$  the discrepancy is reduced to a factor of about 2. The right panel shows models which include processes that enhance baryon

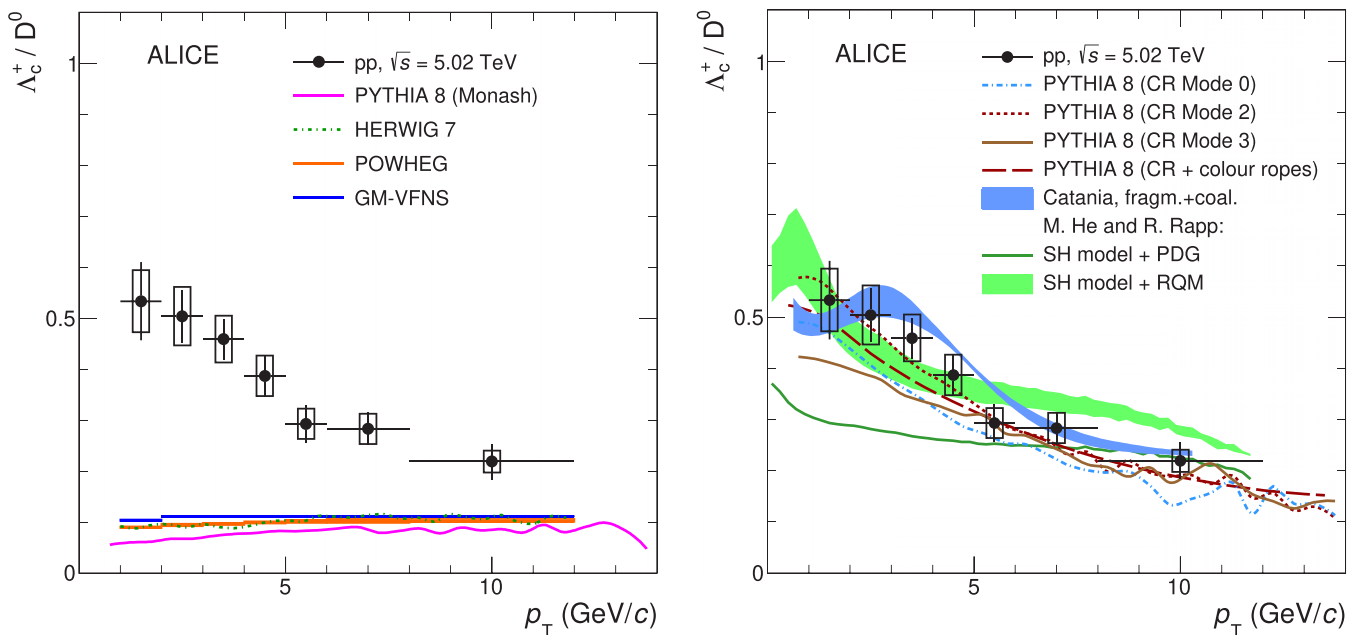


FIG. 10. The  $\Lambda_c^+/D^0$  ratio measured in  $pp$  collisions at  $\sqrt{s} = 5.02 \text{ TeV}$ , compared to theoretical predictions. The measurement is compared with predictions from MC generators (PYTHIA 8 [23,24], HERWIG 7 [27], POWHEG [96]), GM-VFNS [98], a statistical hadronization model [72] (“SH model” in the legend) and a model which implements hadronization via coalescence and fragmentation [104]. See text for model details.

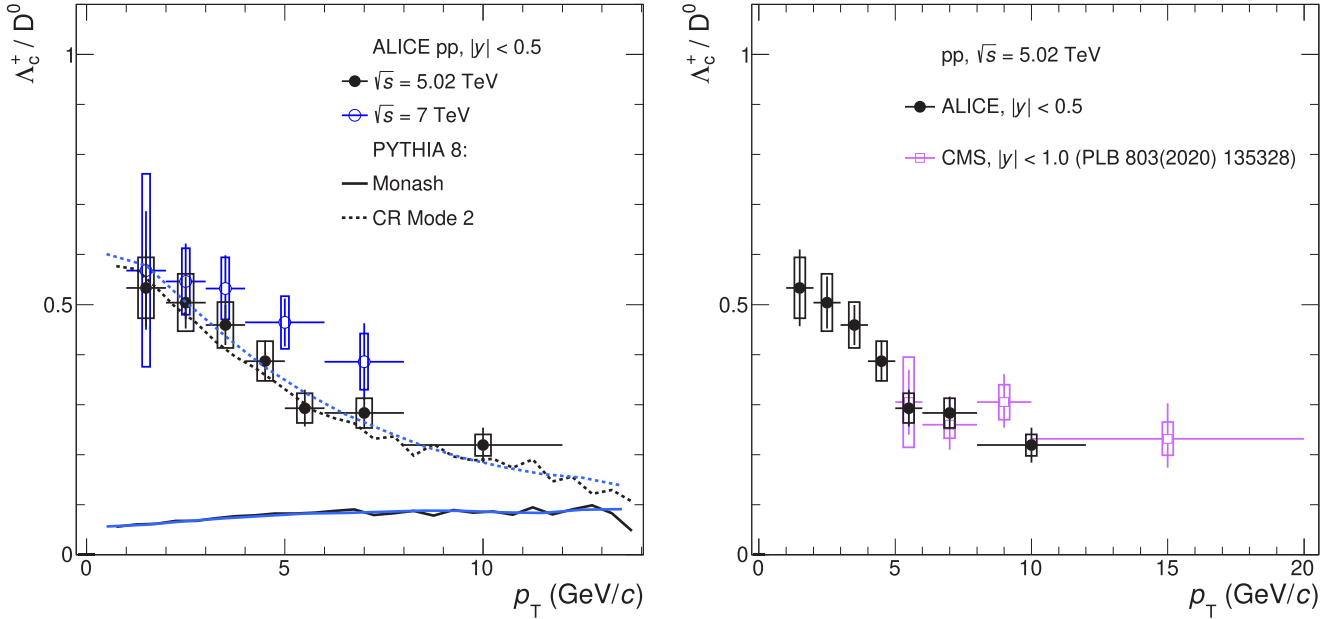


FIG. 11. Left: The  $\Lambda_c^+/D^0$  ratio measured in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV, compared to the measurement at  $\sqrt{s} = 7$  TeV [14]. PYTHIA 8 predictions are shown at both energies, for the Monash tune (solid lines) and with the Mode 2 CR tune (dotted lines). Right: the  $\Lambda_c^+/D^0$  ratio at  $\sqrt{s} = 5.02$  TeV compared with the measurement by the CMS Collaboration at  $|y| < 1$  [28].

production. A significant enhancement of the  $\Lambda_c^+/D^0$  ratio is observed with PYTHIA 8 simulations including CR beyond the leading-color approximation, with respect to the Monash tune. The results of these PYTHIA 8 tunes are consistent with the measured  $\Lambda_c^+/D^0$  ratio in  $pp$  collisions, also reproducing the decreasing trend of  $\Lambda_c^+/D^0$  with increasing  $p_T$ . Including rope hadronization in addition to color reconnection induces a small modification in the  $\Lambda_c^+/D^0$  ratio, suggesting that the increased string tension does not significantly affect the relative production of baryons with respect to mesons. The data is also compared with a statistical hadronization model [72] where the underlying charm baryon spectrum is either taken from the PDG, or augmented to include additional excited baryon states, which have not yet been observed but are predicted by the Relativistic Quark Model (RQM) [103]. For the former case, the model underpredicts the data at low  $p_T$ . For the latter case, the additional charm baryon states decay strongly to  $\Lambda_c^+$  baryons, contributing to the prompt  $\Lambda_c^+$  spectrum. This increases the  $\Lambda_c^+/D^0$  ratio and allows the model to describe both the magnitude and the  $p_T$  dependence of the measured ratio. Finally, the Catania model [104] is also presented, which assumes that a QGP is formed in  $pp$  collisions and that the hadronization occurs via coalescence as well as fragmentation. The light quark  $p_T$  spectrum is determined with a blast wave model, while the heavy quark  $p_T$  spectrum is determined with FONLL pQCD predictions, and coalescence is implemented via the Wigner formalism. Contrary to the implementation in Pb–Pb collisions [105], jet quenching mechanisms are not included in  $pp$  collisions. The model predicts that hadronization via coalescence is dominant at low  $p_T$ , while fragmentation dominates at high  $p_T$ . Both the magnitude and the  $p_T$  shape of the measured  $\Lambda_c^+/D^0$  ratio are described well by this model.

Figure 11 (left) shows the  $\Lambda_c^+/D^0$  ratio in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV compared with the previous measurement at  $\sqrt{s} = 7$  TeV, and with predictions from PYTHIA 8 simulations. The  $\Lambda_c^+/D^0$  ratio is found to be consistent between the two collision energies, within the experimental uncertainties; however, the wider  $p_T$  coverage and the improved statistical and systematic uncertainties on the new measurement reveal a clear decreasing trend in the  $\Lambda_c^+/D^0$  ratio in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV, which was not clearly visible in the result at  $\sqrt{s} = 7$  TeV. The predictions of PYTHIA 8 with Monash tune do not show a  $\sqrt{s}$ -dependence, while those with CR Mode 2 indicate a slight  $\sqrt{s}$ -dependence, where the  $\Lambda_c^+/D^0$  ratio is slightly larger at low  $p_T$  at  $\sqrt{s} = 7$  TeV than at  $\sqrt{s} = 5.02$  TeV. The right panel shows the  $\Lambda_c^+/D^0$  ratio in  $pp$  collisions, compared with the measurement by the CMS Collaboration in  $5 < p_T < 20$  GeV/c and  $|y| < 1$  [28]. In the  $p_T$  region covered by both experiments, the results are found to be consistent with one another.

In Fig. 12, the  $\Lambda_c^+/D^0$  ratio in  $p$ –Pb collisions at midrapidity ( $-0.96 < y < 0.04$ ) is compared with the measurements by the LHCb Collaboration at forward ( $1.5 < y < 4$ ) and backward ( $-4.5 < y < -2.5$ ) rapidities [71]. The left panel shows the comparison of the  $\Lambda_c^+/D^0$  ratios in the different rapidity intervals as a function of  $p_T$ . For  $p_T < 8$  GeV/c the ratio measured at midrapidity is higher than the ones measured at forward and backward rapidities, whereas at higher  $p_T$  the measurements are consistent within uncertainties. The right panel shows the  $p_T$ -integrated  $\Lambda_c^+/D^0$  ratio as a function of rapidity. The  $p_T$  range of the integration of the ALICE data ( $2 < p_T < 12$  GeV/c) is chosen to be similar to the reported LHCb integrated  $p_T$  range ( $2 < p_T < 10$  GeV/c). The results suggest an enhancement of the ratio at midrapidity with respect to forward and backward rapidities. The difference between the  $\Lambda_c^+/D^0$  ratio at mid and forward (backward)



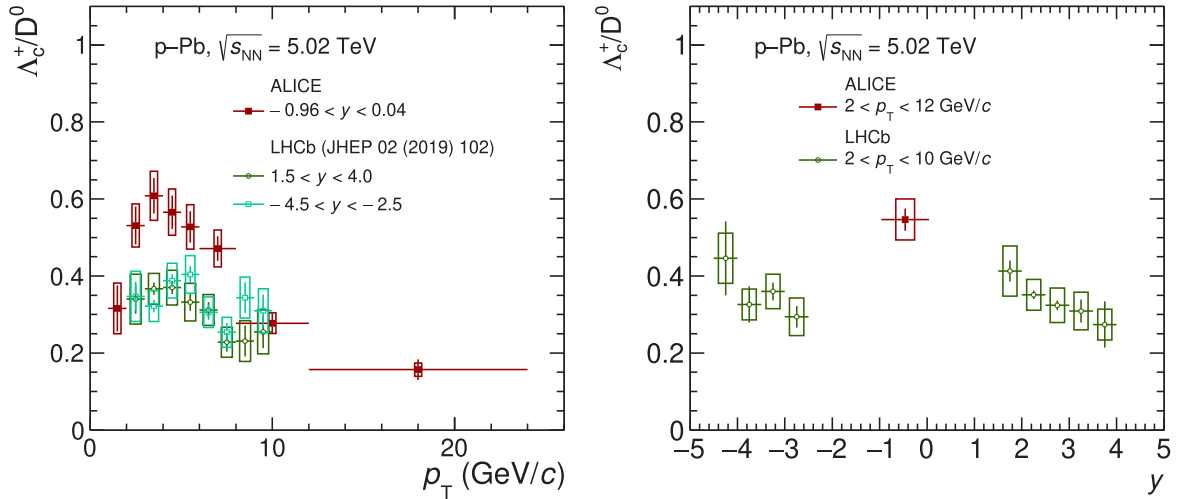


FIG. 12. The  $\Lambda_c^+/D^0$  ratio measured in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, compared with the measurement at forward and backward rapidity [71] by the LHCb collaboration. The measurements are shown as a function of  $p_T$  (left) and as a function of  $y$  (right).

rapidities is less pronounced in  $p$ -Pb collisions compared to the one observed in  $pp$  collisions at 7 TeV [14,29].

Figure 13 shows the  $\Lambda_c^+/D^0$  ratio in  $pp$  and  $p$ -Pb collisions, compared to the baryon-to-meson ratios in the light-flavor sector,  $p/\pi$  [68,106] and  $\Lambda/K_S^0$  [107,108]. The  $p/\pi$  ratio in  $pp$  collisions is shown at center-of-mass energies of 7 TeV and 5.02 TeV, and both results are fully consistent with each other. The  $\Lambda/K_S^0$  ratio in  $pp$  collisions is shown at  $\sqrt{s} = 7$  TeV. Comparing the  $\Lambda_c^+/D^0$  ratio to the light-flavor ratios, similar characteristics can be seen. All the baryon-to-meson ratios decrease with increasing  $p_T$  for  $p_T > 3$  GeV/c. In addition, the light-flavor hadron ratios show a distinct peak at intermediate  $p_T$  (around 3 GeV/c), while the  $\Lambda_c^+/D^0$  ratio shows a hint of a peak at  $2 < p_T < 4$  GeV/c in  $p$ -Pb

collisions, though a higher precision measurement would be needed to confirm this. Also shown in Fig. 13 are predictions from PYTHIA 8 with Monash and CR Mode 2 tunes. The PYTHIA 8 predictions for the light-flavor baryon-to-meson ratios are calculated at  $\sqrt{s} = 7$  TeV. It can be observed that the behaviors of the PYTHIA 8 predictions for light-flavor and charm baryon-to-meson ratios are similar. The measured  $\Lambda/K_S^0$  ratio in  $pp$  collisions is underestimated by the Monash tune, while for the CR Mode 2 tune both the magnitude and trend of the ratio are closer to data, despite predicting a slightly flatter trend with  $p_T$ . The  $p/\pi$  ratio is underestimated by PYTHIA 8 (Monash) at low  $p_T$  but overestimated at high  $p_T$ , while CR Mode 2 improves the agreement with data at low  $p_T$  but still overestimates the data at high  $p_T$ . Overall, the

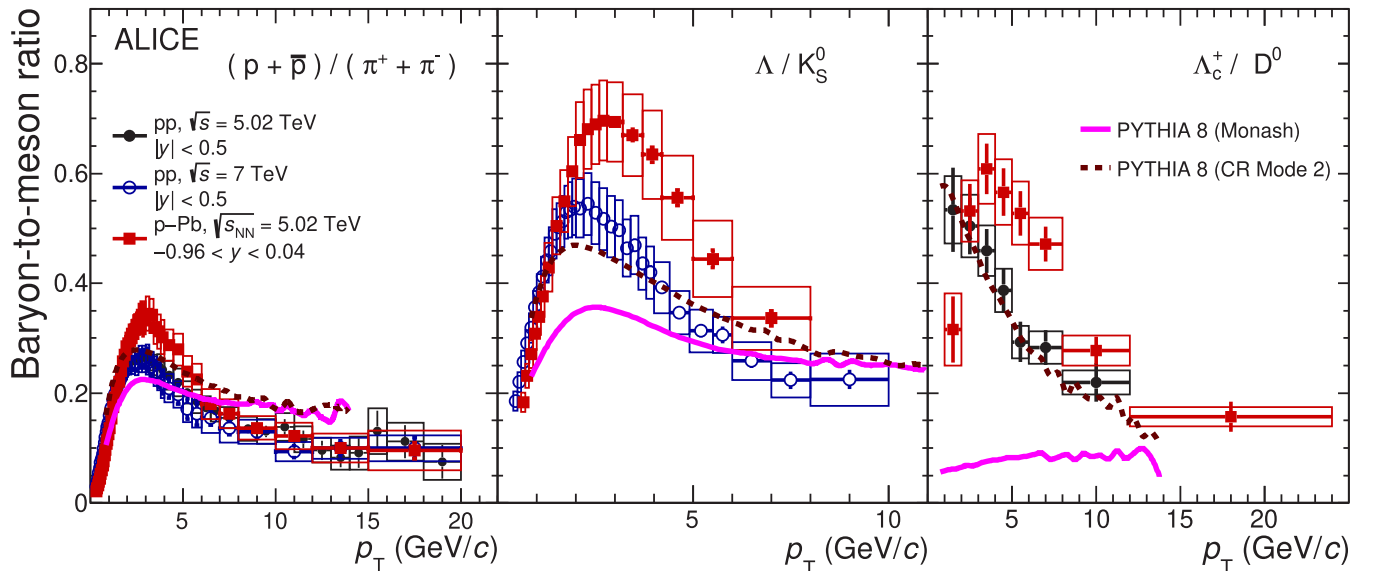


FIG. 13. The baryon-to-meson ratios in the light-flavor and charm sector;  $p/\pi$  in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV and 7 TeV and  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV [68] (left),  $\Lambda/K_S^0$  in  $pp$  collisions at  $\sqrt{s} = 7$  TeV and  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV [107,108] (middle), and  $\Lambda_c^+/D^0$  in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV and  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV (right). The data are compared to predictions from PYTHIA 8 [23,24]. See text for model details.

color reconnection modes in PYTHIA 8 generally provide a better description of the baryon-to-meson ratios in both the light-flavor and charm sector.

## VII. SUMMARY AND CONCLUSIONS

The measurements of the production of prompt  $\Lambda_c^+$  baryons at midrapidity in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV and in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV with the ALICE detector at the LHC have been reported. The measurement in  $pp$  collisions, in particular, was performed at a different center-of-mass energy with respect to the previous work in which  $\Lambda_c^+$ -baryon production was measured in  $pp$  collisions at  $\sqrt{s} = 7$  TeV [14]. The  $pp$  data sample at  $\sqrt{s} = 5.02$  TeV is the natural reference for measurements in  $p$ -Pb and Pb-Pb collisions at the same center-of-mass energy per nucleon pair. Moreover, with respect to Ref. [14], the uncertainties were significantly reduced, and the  $p_T$  range and the  $p_T$  granularity of the measurements were improved in both collision systems. The analysis was performed using two different decay channels,  $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $\Lambda_c^+ \rightarrow pK_S^0$ . The results were reported for  $pp$  collisions in the rapidity interval  $|y| < 0.5$  and the transverse-momentum interval  $1 < p_T < 12$  GeV/ $c$  and for  $p$ -Pb collisions in  $-0.96 < y < 0.04$  and  $1 < p_T < 24$  GeV/ $c$ . The  $p_T$ -differential production cross sections were obtained averaging the results from different hadronic decay channels.

The  $p_T$ -differential cross section was measured to be larger than predictions given by pQCD calculations in both  $pp$  and  $p$ -Pb collisions. The nuclear modification factor  $R_{pPb}$  of  $\Lambda_c^+$  baryons was found to be below unity in the interval  $1 < p_T < 2$  GeV/ $c$  and to peak above unity around 5 GeV/ $c$ . It is consistent with the  $R_{pPb}$  of  $D$  mesons in the  $p_T$  regions  $1 < p_T < 4$  GeV/ $c$  and  $p_T > 8$  GeV/ $c$  and larger than the  $D$ -meson  $R_{pPb}$  in  $4 < p_T < 8$  GeV/ $c$ . The current precision of the measurement is not enough to draw conclusions on the role of different CNM effects and the possible presence of hot-medium effects. As already observed in Ref. [14], the  $\Lambda_c^+/D^0$  baryon-to-meson ratio in  $pp$  collisions is larger than previous measurements obtained in  $e^+e^-$  and  $e^-p$  collision systems at lower center-of-mass energies. The increase of precision in this paper allowed to observe, for the first time, a clear decreasing trend as a function of transverse momentum in the  $\Lambda_c^+/D^0$  ratio. The  $\Lambda_c^+/D^0$  ratio was compared to  $pp$  event generators and models that implement different particle production and hadronization mechanisms: qualitative agreement with the measurement is obtained with PYTHIA 8 tunes including string formation beyond the leading-color approximation; a prediction based on the statistical hadronization model which includes unobserved charm baryon states that strongly decay to  $\Lambda_c^+$ ; and a prediction which assumes the formation of a QGP and implements hadronization via coalescence and fragmentation. The  $\Lambda_c^+/D^0$  ratio measured in  $pp$  collisions is consistent with the results by CMS at midrapidity in the common  $p_T$  regions of both measurements. The ratio in  $p$ -Pb collisions at midrapidity is higher than the one measured by LHCb at forward and backward rapidities in  $2 < p_T < 8$  GeV/ $c$ , while for  $p_T > 8$  GeV/ $c$  the measurements at central, forward and backward rapidities are

consistent within uncertainties. The measured  $\Lambda_c^+/D^0$  ratio was also compared with baryon-to-meson ratios measured in the light-flavor sector. The measured  $\Lambda/K_S^0$  ratio can also be described by PYTHIA 8 when including string formation beyond the leading-color approximation, although this PYTHIA 8 tune slightly overestimates the measured  $p/\pi$  ratio. The increased precision of this measurement with respect to the measurements made with the Run 1 data is crucial for providing further insight into charm baryon production in  $pp$  and  $p$ -Pb collisions. A more precise measurement is expected to be obtained during the LHC Runs 3 and 4 after the upgrade of the ALICE apparatus [109].

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