



CERN-EP-2021-084
10 May 2021

Measurement of the cross sections of Ξ_c^0 and Ξ_c^+ baryons and of the branching-fraction ratio $\text{BR}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e)/\text{BR}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ in pp collisions at $\sqrt{s} = 13$ TeV

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Abstract

The p_T -differential cross sections of prompt charm-strange baryons Ξ_c^0 and Ξ_c^+ were measured at midrapidity ($|y| < 0.5$) in proton–proton (pp) collisions at a centre-of-mass energy $\sqrt{s} = 13$ TeV with the ALICE detector at the LHC. The Ξ_c^0 baryon was reconstructed via both the semileptonic decay ($\Xi^- e^+ \nu_e$) and the hadronic decay ($\Xi^- \pi^+$) channels. The Ξ_c^+ baryon was reconstructed via the hadronic decay ($\Xi^- \pi^+ \pi^+$) channel. The branching-fraction ratio $\text{BR}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e)/\text{BR}(\Xi_c^0 \rightarrow \Xi^- \pi^+) = 1.38 \pm 0.14$ (stat) ± 0.22 (syst) was measured with a total uncertainty reduced by a factor of about 3 with respect to the current world average reported by the Particle Data Group. The transverse momentum (p_T) dependence of the Ξ_c^0 - and Ξ_c^+ -baryon production relative to the D^0 -meson and to the $\Sigma_c^{0,+,\pi^+}$ - and Λ_c^+ -baryon production are reported. The baryon-to-meson ratio increases towards low p_T up to a value of approximately 0.3. The measurements are compared with various models that take different hadronisation mechanisms into consideration. The results provide stringent constraints to these theoretical calculations and additional evidence that different processes are involved in charm hadronisation in electron–positron (e^+e^-) and hadronic collisions.

arXiv:2105.05187v1 [nucl-ex] 11 May 2021

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Measurements of heavy-flavour hadron production in high-energy proton–proton (pp) collisions provide important tests of quantum chromodynamics (QCD). The cross sections of heavy-flavour hadrons are usually computed using the factorisation approach as a convolution of three factors [1]: i) the parton distribution functions (PDFs) of the incoming protons, ii) the hard-scattering cross section at partonic level, and iii) the fragmentation function of heavy quarks into a given heavy-flavour hadron. The D- and B-meson cross sections in pp collisions at several centre-of-mass energies at the LHC [2–7] are described within uncertainties by perturbative QCD (pQCD) calculations [8–12], which use fragmentation functions tuned on e^+e^- data, over a wide range of transverse momentum (p_T). Measurements of Λ_c^+ -baryon production at midrapidity in pp collisions at the centre-of-mass energy $\sqrt{s} = 5.02$ and 7 TeV were reported by the ALICE and CMS collaborations in Refs. [13–15]. The measured Λ_c^+/D^0 ratio is higher than previous measurements in e^+e^- [16–18] and e^-p [19, 20] collisions, suggesting that charm-hadronisation mechanisms are different in pp collisions at LHC energies. A similar observation was drawn from the measurement of the inclusive Ξ_c^0 -baryon production at midrapidity in pp collisions at $\sqrt{s} = 7$ TeV [21]. The charm-baryon cross sections measured in pp collisions are larger than next-to-leading order pQCD-based calculations [12], and larger than expectations from various event generators, namely POWHEG matched to PYTHIA 6 for the parton-shower and the hadronisation stages with Perugia tune [22], PYTHIA 8 with Monash tune [23], and HERWIG 7 [24]. On the other hand, PYTHIA 8 tunes including string formation beyond the leading-colour approximation [25] qualitatively describe the measured $\Sigma_c^{0,+}/D^0$ and Λ_c^+/D^0 cross section ratios [15, 26], but underestimate the Ξ_c^0/D^0 ratio [21]. A statistical hadronisation model (SHM) [27] based on charm-hadron states listed by the Particle Data Group (PDG) [28] underestimates the Λ_c^+/D^0 ratio. However this ratio is qualitatively described by the SHM when the presence of a large set of yet-unobserved higher-mass charm-baryon states is assumed in the calculation as prescribed by the relativistic quark model (RQM) and from lattice QCD [29, 30]. The observed enhancement of the charm-baryon production can also be explained by model calculations considering hadronisation of charm quarks via coalescence in pp collisions [31, 32]. The increased yield of charm baryons makes it mandatory to include their contribution for an accurate measurement of the $c\bar{c}$ production cross section in pp collisions at the LHC [33] and further provide evidence that the assumption of universality (colliding-system independence) of parton-to-hadron fragmentation is not valid.

In this letter, the measurements of the cross sections of the prompt (i.e produced directly in the hadronisation of charm quarks and in the decays of directly produced excited charm states) charm-strange baryons Ξ_c^0 and Ξ_c^+ at midrapidity ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 13$ TeV are reported. The Ξ_c^0 baryon was reconstructed via the decay channels $\Xi^- e^+ \nu_e$, $\text{BR} = (1.8 \pm 1.2)\%$ and $\Xi^- \pi^+$, $\text{BR} = (1.43 \pm 0.32)\%$ [28] together with their charge conjugates, using the Kalman-Filter vertexing algorithm [34] in the interval $1 < p_T < 12$ GeV/ c . The Ξ_c^+ baryon was reconstructed via the decay channel $\Xi^- \pi^+ \pi^+$, $\text{BR} = (2.86 \pm 1.21 \pm 0.38)\%$ [35], together with its charge conjugate, in the interval $4 < p_T < 12$ GeV/ c . The ratio $\text{BR}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e)/\text{BR}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ was also measured. In the following, the notation Ξ_c is used to refer to both Ξ_c^0 and Ξ_c^+ states, if not differently specified.

A description of the ALICE detector and its performance are reported in Refs. [36, 37]. The data used for these analyses were recorded with a minimum-bias trigger, based on coincident signals in the two scintillator arrays (V0) located on both sides of the interaction vertex. Offline selections, based on the V0 and Silicon Pixel Detector signals [3], were applied to remove background from beam–gas collisions. Pile-up events (less than 1%) containing multiple primary vertices were rejected. Only events with a reconstructed primary vertex position within ± 10 cm in the longitudinal direction from the nominal centre of the detector were used. With these requirements, 1.9×10^9 pp events were selected, corresponding to an integrated luminosity of $\mathcal{L}_{\text{int}} = 32.95 \pm 1.65$ nb $^{-1}$.

Charged-particle tracks and particle-decay vertices were reconstructed in the central barrel using the Inner Tracking System (ITS) and the Time Projection Chamber (TPC), which are located inside a

solenoidal magnet of field strength 0.5 T. The hadron (electron) selection criteria are the same as those reported in Ref. [3] ([21]). Particle identification (PID) was performed using the information on the specific energy loss (dE/dx) through the TPC gas, and with the flight-time measurement of the Time-Of-Flight detector (TOF) [38]. The Ξ^- baryons were reconstructed from the decay chain $\Xi^- \rightarrow \pi^- \Lambda$, BR = $(99.887 \pm 0.035)\%$, followed by $\Lambda \rightarrow \pi^- p$, BR = $(63.9 \pm 0.5)\%$ [28]. The Ξ^- and Λ baryons were reconstructed by exploiting their characteristic decay topologies as reported in Refs. [21, 39].

For the measurements in the hadronic decay channels, pions were selected according to the criteria described in Ref. [33]. The Ξ_c candidates were reconstructed combining one or two pions, with the correct electric charge, to the selected Ξ baryon. In the case of the Ξ_c^+ baryon, the mean proper life time $c\tau = 132 \mu\text{m}$ [28] was exploited. The Ξ_c^+ secondary vertex was reconstructed using only the two same charge-sign pions because the reconstructed Ξ trajectory has a much worse resolution when propagated to the primary vertex. Selections on the cosine of the pointing angle of the Ξ_c^+ to the primary vertex, the distance of closest approach between the two decay pions, and the decay length of the reconstructed secondary vertex were applied. For the Ξ_c^0 -baryon analysis, a multivariate technique based on the Boosted Decision Tree (BDT) algorithm [40] was used. The BDT algorithm was trained using reconstructed signal candidates obtained by simulating pp collisions with PYTHIA 8.243 [41] and propagating the generated particles through the detector using the GEANT3 transport code [42]. The background was taken from data by selecting candidates with invariant mass in the intervals $2.17 < M < 2.39 \text{ GeV}/c^2$ and $2.55 < M < 2.77 \text{ GeV}/c^2$. The conditions of all the ALICE detectors in terms of active channels, gain, noise level and alignment, and their evolution with time during the data taking, were taken into account in the simulation. The model was trained independently for each p_T interval with input variables related to the Ξ^- decay topology and to the PID information of the decay tracks. The Ξ_c raw yields were obtained from fits to the candidate invariant-mass distributions. The signal peak was modelled with a Gaussian and the background was described by a linear function. The $\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e$ analysis was performed using the technique reported in Ref. [21]. The Ξ_c^0 candidates were defined from opposite charge-sign $e\Xi$ pairs with an opening angle smaller than 90° . The Ξ_c^0 raw-yield was obtained by subtracting the same charge-sign $e\Xi$ -pair distribution from the opposite charge-sign pair yields, and integrating the invariant-mass distribution for $M(e\Xi) < 2.5 \text{ GeV}/c^2$. The same charge-sign pairs also contain a contribution from $\Xi_b^{0,-} \rightarrow e^- \Xi^- \bar{\nu}_e X$ decays not present in the opposite charge-sign distribution, leading to an oversubtraction. It was corrected for based on the assumptions reported in Ref. [21] and ranges from 1% to 8%, depending on p_T . In order to reject electrons from photon conversions occurring in the detector material, the electron-candidate tracks are required to have associated hits in the two innermost layers of the ITS [43, 44]. Further rejection of background electrons originating from Dalitz decays of neutral mesons and photon conversions was performed using an invariant-mass technique [45, 46]. A correction for the misidentification probability was applied, estimated to be 2% by applying the algorithm to same charge-sign $e^\pm e^\pm$ pairs. The p_T distribution of $e^+ \Xi^-$ pairs was corrected for the missing momentum of the undetected neutrino using the Bayesian unfolding technique [47] implemented in the RooUnfold package [48].

The raw yields were divided by the acceptance-times-efficiency for prompt hadrons $(\text{Acc} \times \epsilon)_{\text{prompt}}$ and were corrected for the beauty feed-down contribution. The $(\text{Acc} \times \epsilon)_{\text{prompt}}$ corrections were obtained from a Monte Carlo simulation analogous to the one used for the BDT training. The simulated Ξ_c p_T distributions were modified by an iterative procedure in order to mimic data. The $(\text{Acc} \times \epsilon)_{\text{prompt}}$ increases with p_T from 0.6% to 12% depending on the particle and decay channel. The contribution from beauty feed-down to the measured Ξ_c yields was subtracted. The cross section of feed-down Ξ_c is calculated from the one of Λ_c^+ originating from Λ_b^0 decays (as described in Ref. [15]) and scaled by the fraction of Ξ_b decaying in a final state with a Ξ_c , which is taken to be about 50% from the PYTHIA 8.243 generator [41], and by the ratio of the measured p_T -differential yields of inclusive Ξ_c and prompt Λ_c^+ baryons. This procedure relies on the assumptions that the p_T shape of the cross sections of feed-down Λ_c^+ and Ξ_c are similar, and that the ratio Ξ_c/Λ_c^+ is the same for inclusive and feed-down baryons. The

prompt fraction decreases with increasing p_T and it ranges from 0.99 at low p_T to 0.93 at high p_T . To obtain the prompt Ξ_c cross sections, the corrected yields were divided by a factor of two to obtain the particle-antiparticle averaged yields, by the BR, by the widths of the p_T and y intervals considered, and by \mathcal{L}_{int} .

Systematic uncertainties were estimated considering several sources. For the hadronic decay channels, the systematic uncertainty on the raw-yield extraction was evaluated by repeating the fit of the invariant-mass distribution with varied fit interval, functional form of the background contribution, and width of the Gaussian function used to describe the signal peak. For the Ξ_c^0 in the semileptonic decay channel, the raw-yield extraction systematic uncertainty was estimated by varying the selection criteria on the opening angle and on the invariant mass of the pair. The systematic uncertainties were defined as the RMS of the distribution of the signal yields obtained from these variations. The relative uncertainty on raw-yield extraction ranges from 7% to 11% depending on the p_T . The uncertainty on the track reconstruction efficiency was evaluated by varying the track-selection criteria and by comparing the probability to prolong the tracks from the TPC to the ITS hits in data and simulations. A 5% (7%) uncertainty was assigned for the Ξ_c^0 (Ξ_c^+). The uncertainty on the selection efficiency originates mainly from imperfections in the description of the detector response and alignment in the simulation. It was estimated from the ratios of the corrected yields obtained by varying the BDT and topological selections applied; an uncertainty ranging from 2% to 5% was assigned. The systematic uncertainty due to the shape of the Ξ_c p_T distributions used for the calculation of $(\text{Acc} \times \epsilon)_{\text{prompt}}$ was estimated by considering different p_T shapes in the simulation, obtained by varying the weights mentioned above within their uncertainty [21] and it amounts to 1% for $p_T < 3$ GeV/ c . The systematic uncertainty on the subtraction of feed-down from beauty-hadron decays was evaluated as in Ref. [15] and additionally by scaling up the Ξ_c/Λ_c^+ ratio by a conservative factor of two and scaling it down to the Ξ_b^-/Λ_b^0 ratio measured by the LHCb collaboration [49], important in the case that $\text{BR}(\Xi_b^0 \rightarrow \Xi_c^- X)$ is the same as $\text{BR}(\Lambda_b^0 \rightarrow \Lambda_c^+ X)$. The assigned uncertainty ranges from 1% to 9% depending on p_T . Additional uncertainties related only to the Ξ_c^0 semileptonic decay channel were estimated as follows. The uncertainties related to the unfolding procedure were estimated by varying the number of iterations of the algorithm, the p_T range and the widths of the p_T intervals used in the Bayesian unfolding procedure, and the unfolding method itself to the Singular Value Decomposition [50], and ranges from 2% to 12% depending on p_T . The systematic uncertainty related to the oversubtraction due to the Ξ_b contribution in the same charge-sign $e\Xi$ pairs was estimated by scaling the assumed Ξ_b momentum distribution by a conservative 50% [51]. A maximum of 2% uncertainty was assigned at high p_T . A 2% uncertainty was assigned to account for possible differences in the acceptance of $e^+\Xi^-$ pairs in data and simulation, which is evaluated by performing the measurement in different rapidity intervals between $|y| < 0.5$ and 0.8. The cross sections have an additional global normalisation uncertainty due to the uncertainties on the integrated luminosity and the BRs [28, 35].

The Ξ_c^0 measurements in the two decay channels agree within statistical and uncorrelated systematic uncertainties. The results from the two decay channels were combined to obtain a more precise measurement of the prompt p_T -differential Ξ_c^0 -baryon cross section. The tracking and feed-down systematic uncertainties were propagated as correlated between the two measurements. Figure 1 shows the average of the cross sections, computed considering as weights the inverse square of the relative statistical and p_T -uncorrelated systematic uncertainties [52]. The prompt Ξ_c^+ -baryon cross section, also shown in Fig 1, is compatible within the uncertainties with the Ξ_c^0 measurement.

The p_T -integrated cross sections in the measured p_T interval for the Ξ_c are $d\sigma_{\text{pp}, 13 \text{ TeV}}^{\Xi_c^0}/dy|_{|y|<0.5}^{(1 < p_T < 12 \text{ GeV}/c)} = 149 \pm 21$ (stat) ± 35 (syst) ± 7 (lumi) μb and $d\sigma_{\text{pp}, 13 \text{ TeV}}^{\Xi_c^+}/dy|_{|y|<0.5}^{(4 < p_T < 12 \text{ GeV}/c)} = 15 \pm 2$ (stat) ± 7 (syst) ± 1 (lumi) μb . In calculating the p_T -integrated cross section and the ratio of the branching fractions, the systematic uncertainty related to unfolding, for the $\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e$, was considered as p_T uncorrelated and the other uncertainties as fully p_T correlated. For the hadronic decay channels, the uncertainty related

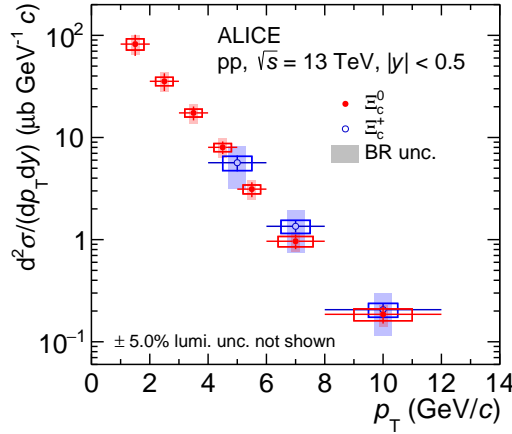


Figure 1: Cross sections of prompt Ξ_c^0 (full circles) and Ξ_c^+ (open circles) baryons as a function of p_T in pp collisions at $\sqrt{s} = 13$ TeV. The error bars and empty boxes represent the statistical and systematic uncertainties, respectively. The systematic uncertainties on the BR are shown as shaded boxes.

to the raw-yield extraction was considered p_T uncorrelated, because the signal-over-background ratio is observed to largely vary as a function of p_T , while the others as fully p_T correlated. The p_T -integrated Ξ_c^0 cross section at midrapidity was obtained by extrapolating the visible cross section to the full p_T range. The Catania model [32], that better describe the shape of the measured cross section, was used to calculate the extrapolation factor, which is $1.36^{+0.05}_{-0.15}$. The systematic uncertainty was estimated considering calculations [25, 27, 31] that describe the shape of the cross section in the measured p_T interval. The p_T -extrapolated cross section for the Ξ_c^0 is $d\sigma_{pp, 13 \text{ TeV}}^{\Xi_c^0}/dy|_{|y|<0.5} = 202 \pm 28$ (stat) ± 48 (syst) ± 10 (lumi) $^{+7}_{-22}$ (extrap) μb .

The measurement of the Ξ_c^0 -baryon cross sections, not corrected by the BRs, in the two different decay channels allowed the computation of the $\text{BR}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e)/\text{BR}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ ratio. The p_T -dependent ratio of the two measurements, which was observed to be flat in p_T , was averaged using the inverse uncorrelated relative uncertainties as weights [52]. The final systematic uncertainty on the ratio was obtained by summing in quadrature the p_T -correlated and uncorrelated systematic uncertainties. The measured ratio is $\text{BR}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e)/\text{BR}(\Xi_c^0 \rightarrow \Xi^- \pi^+) = 1.38 \pm 0.14$ (stat) ± 0.22 (syst). The result is consistent with the global average reported by the PDG (1.3 ± 0.8) [28] and has a total uncertainty reduced by a factor of three. The result is also consistent with the one released by the Belle collaboration [53].

Figure 2 (left) shows the Ξ_c/D^0 ratios measured as a function of p_T . The systematic uncertainties related to the track-reconstruction efficiency, feed-down subtraction, and luminosity were propagated as correlated in the ratio. The observed p_T dependence of the Ξ_c/D^0 ratio is similar to what was measured for the Λ_c^+/D^0 ratio [15]. This result provides strong indications that the fragmentation functions of baryons and mesons differ significantly. The PYTHIA 8 event generator with the Monash tune [23], and tunes that implement colour reconnection (CR) beyond the leading-colour approximation [25] were compared to the measurements. The Monash tune reproduces the charm fragmentation fractions measured in e^+e^- collisions and assumes that they are similar in pp collisions. The tunes implementing CR beyond the leading-colour approximation (Mode 0, 2, and 3) introduce new colour-reconnection topologies enhancing the contribution of “junctions” that fragment into baryons, leading to an increased baryon production. In the three considered tunes different constraints on the reconnection are applied, taking into account causal connection of dipoles involved in a reconnection and time-dilation effects caused by relative boosts between string pieces. The Monash tune significantly underestimates the data by a factor of 23–43 in the low- p_T region and by a factor of about 5 in the highest p_T interval. All three CR modes give a similar magnitude and p_T -dependence of Ξ_c/D^0 , and although they predict a larger baryon-to-

meson ratio with respect to the Monash tune, they still underestimate the measured Ξ_c/D^0 ratio by a factor 4–9 for $p_T < 4$ GeV/c. At higher p_T the measured Ξ_c/D^0 ratio is closer to the one obtained from calculations based on the charm fragmentation functions measured in e^+e^- collisions.

The measured Ξ_c/D^0 ratio was also compared to a SHM [27] that includes additional excited charm-baryon states not yet observed but predicted by the RQM [29] and by lattice QCD [30]. While this model describes the Λ_c^+/D^0 and $\Sigma_c^{0,+}/D^0$ ratios [15, 26], it underestimates the Ξ_c/D^0 ratio. The measured ratios were also compared with models that include hadronisation via coalescence. In the quark (re-)combination mechanism (QCM) [31] the charm quark can pick up a co-moving light antiquark or two co-moving quarks to form a single-charm meson or baryon. The model does not describe the Ξ_c/D^0 ratio. The Catania model [32, 54] implements charm-quark hadronisation via both coalescence and fragmentation, and it is the model that describes better the ratio over the full p_T interval. In the model, a blast wave parametrisation [55] for light quarks spectra at the hadronisation time with the inclusion of a contribution from mini-jets was considered, while for charm quarks the spectrum from fix-order-next-to-leading-log calculations was used [10]. The coalescence process of heavy quarks with light quarks is modelled using the Wigner function formalism and it was tuned to have all charm quarks hadronising via coalescence at $p_T \sim 0$. At finite p_T , charm quarks not undergoing coalescence are hadronised using fragmentation functions based on e^+e^- data.

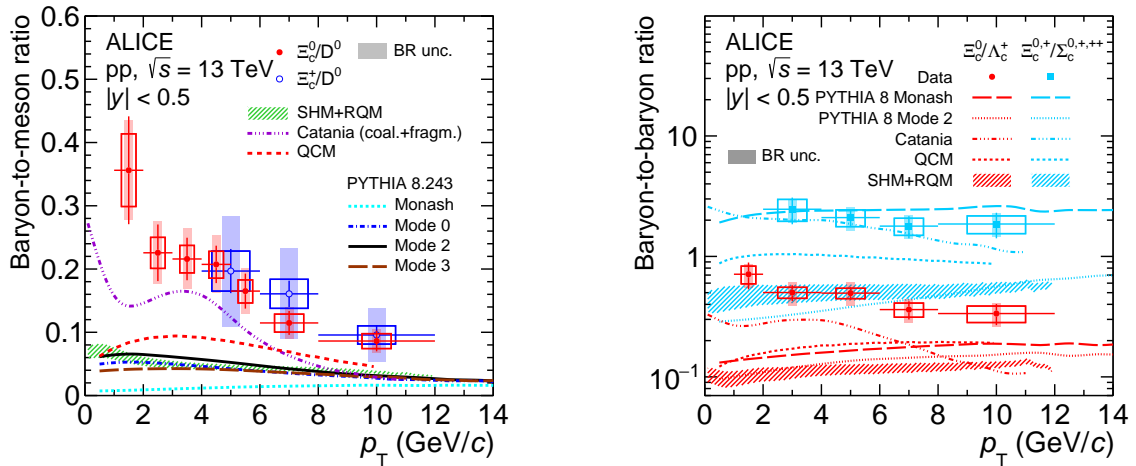


Figure 2: Left panel: Ξ_c^0/D^0 and Ξ_c^+/D^0 ratios as a function of p_T in pp collisions at $\sqrt{s} = 13$ TeV. Right panel: Ξ_c^0/Λ_c^+ and $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ ratio as a function of p_T . The error bars and empty boxes represent the statistical and systematic uncertainties, respectively. The systematic uncertainties on the BR are shown as shaded boxes. The measurements are compared with model calculations (see text for detail).

The Ξ_c^0/Λ_c^+ and $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ [26] cross section ratios are reported in the right panel of Fig. 2. The tracking, feed-down, and luminosity systematic uncertainties were propagated as correlated. The Ξ_c^0/Λ_c^+ ratio is approximately 0.5 and within the current uncertainties there is no significant p_T dependence. All the PYTHIA 8 tunes, as well as the QCM, Catania, and the SHM+RQM models, do not describe the measured ratio. To compute the $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$, the Ξ_c^0 was summed with the Ξ_c^+ for $p_T > 4$ GeV/c and scaled by a factor of two in the interval $2 < p_T < 4$ GeV/c. The ratio is at approximately 2 and it is compatible with the Monash tune, which underestimates by a similar amount the $\Xi_c^{0,+}$ and $\Sigma_c^{0,+,++}$ cross sections [21, 26]. The PYTHIA 8 tunes with CR and the SHM+RQM calculation also underestimate the measurement. The QCM model shows an almost flat value at unity, largely underestimating the measured ratio. The Catania model describes the data within the uncertainties.

In summary, measurements of the prompt charm-strange baryons Ξ_c^+ and Ξ_c^0 at midrapidity in pp collisions at $\sqrt{s} = 13$ TeV were presented. The results further provide evidence that the assumption of universality (colliding-system independence) of parton-to-hadron fragmentation is not valid, and they

pose important constraints to models of charm-quark hadronisation in pp collisions. Finally, the ratio $\text{BR}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) / \text{BR}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ was measured with a total uncertainty reduced by a factor 3 with respect to the global average reported by the PDG [28].

Acknowledgements

The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF): [M 2467-N36] and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (Finep), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Universidade Federal do Rio Grande do Sul (UFRGS), Brazil; Ministry of Education of China (MOEC), Ministry of Science & Technology of China (MSTC) and National Natural Science Foundation of China (NSFC), China; Ministry of Science and Education and Croatian Science Foundation, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research | Natural Sciences, the VILLUM FONDEN and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l’Energie Atomique (CEA) and Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS), France; Bundesministerium für Bildung und Forschung (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial Research (CSIR), India; Indonesian Institute of Science, Indonesia; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Institute for Innovative Science and Technology, Nagasaki Institute of Applied Science (IIST), Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Society for the Promotion of Science (JSPS) KAKENHI, Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Académico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Commission on Science and Technology for Sustainable Development in the South (COMSATS), Pakistan; Pontificia Universidad Católica del Perú, Peru; Ministry of Education and Science, National Science Centre and WUT ID-UB, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics and Ministry of Research and Innovation and Institute of Atomic Physics, Romania; Joint Institute for Nuclear Research (JINR), Ministry of Education and Science of the Russian Federation, National Research Centre Kurchatov Institute, Russian Science Foundation and Russian Foundation for Basic Research, Russia; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; Suranaree University of Technology (SUT), National Science and Technology Development Agency (NSDTA) and Office of the Higher

Education Commission under NRU project of Thailand, Thailand; Turkish Energy, Nuclear and Mineral Research Agency (TENMAK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and United States Department of Energy, Office of Nuclear Physics (DOE NP), United States of America.

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