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Measurement of the Cross Sections of Ξ_c^0 and Ξ_c^+ Baryons and of the Branching-Fraction Ratio $\mathrm{BR}(\Xi_c^0 \to \Xi^- e^+ \nu_e)/\mathrm{BR}(\Xi_c^0 \to \Xi^- \pi^+)$ in pp Collisions at $\sqrt{s} = 13$ TeV

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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 center-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 $\mathrm{BR}(\Xi_c^0 \to \Xi^- e^+ \nu_e)/\mathrm{BR}(\Xi_c^0 \to \Xi^- \pi^+) = 1.38 \pm 0.14(\mathrm{stat}) \pm 0.22(\mathrm{syst})$ 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 $\Sigma_c^{0,+,++}$- and Λ_c^+-baryon production are reported. The baryon-to-meson ratio increases toward low p_T up to a value of approximately 0.3. The measurements are compared with various models that take different hadronization mechanisms into consideration. The results provide stringent constraints to these theoretical calculations and additional evidence that different processes are involved in charm hadronization in electron-positron (e^+e^-) and hadronic collisions.

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Measurements of heavy-flavor hadron production in high-energy proton-proton (pp) collisions provide important tests of quantum chromodynamics (QCD). The cross sections of heavy-flavor hadrons are usually computed using the factorization approach as a convolution of three factors [1]: (i) the parton distribution functions 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-flavor hadron. The D- and B-meson cross sections in pp collisions at several center-of-mass energies at the LHC [2–7] are described within uncertainties by perturbative QCD 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 center-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. 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].

PYTHIA8.2 tunes including string formation beyond the leading-color approximation [22] and a statistical hadronization model (SHM) [23] including a set of higher-mass charm-baryon states as prescribed by the relativistic quark model (RQM) and from lattice QCD [24,25] 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]. The observed enhancement of the charm-baryon production can also be explained by model calculations considering hadronization of charm quarks via coalescence in addition to the fragmentation in pp collisions [27,28]. 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 [29].

In this Letter, the measurements of the cross sections of the prompt (i.e., produced directly in the hadronization 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 $\Xi^- e^+ \nu_e$, $\mathrm{BR} = (1.8 \pm 1.2)\%$ and $\Xi^- \pi^+$, $\mathrm{BR} = (1.43 \pm 0.32)\%$ [30] together with their charge conjugates in the interval $1 < p_T < 12$ GeV/c. The Ξ_c^+ baryon was reconstructed via the decay channel $\Xi^- \pi^+ \pi^+$, $\mathrm{BR} = (2.86 \pm 1.21 \pm 0.38)\%$ [31], together with its charge conjugate, in the interval $4 < p_T < 12$ GeV/c.

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The ratio $\mathrm{BR}(\Xi_c^0 \to \Xi^- e^+ \nu_e)/\mathrm{BR}(\Xi_c^0 \to \Xi^- \pi^+)$ 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. [32,33]. 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. Pileup events (less than 1% [34]) containing multiple primary vertices were rejected. Only events with a reconstructed primary vertex position within ± 10 cm in the longitudinal direction from the nominal center of the detector were used. With these requirements, 1.9×10^9 pp events were selected, corresponding to an integrated luminosity of $\mathcal{L}_{\mathrm{int}} = 32.08 \pm 0.51\ \mathrm{nb}^{-1}$ [34].

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 energy loss (dE/dx) through the TPC gas, and with the flight-time measurement of the time-of-flight detector [35]. The Ξ^- baryons were reconstructed from the decay chain $\Xi^- \to \pi^- \Lambda$, $\mathrm{BR} = (99.887 \pm 0.035)\%$, followed by $\Lambda \to \pi^- p$, $\mathrm{BR} = (63.9 \pm 0.5)\%$ [30]. The Ξ^- and Λ baryons were reconstructed by exploiting their characteristic decay topologies as reported in Refs. [21,36].

For the measurements in the hadronic decay channels, pions were selected according to the criteria described in Ref. [29]. The Ξ_c candidates were reconstructed combining one or two pions, with the correct electric charge, to the selected Ξ baryon. A Kalman-Filter vertexing algorithm [37] was used for the reconstruction of the $\Xi_c^0 \to \Xi^- \pi^+$ decay channel. The package allows us to set constraints on the mass and on the production point of the reconstructed particles, using also information about the errors of daughter particle trajectories improving reconstruction accuracy of the mother particle. The mass constraint improves the mass and momentum reconstruction of the particle, while the production point constraint helps to determine whether the particle is coming from a certain vertex. These constraints were applied to each vertex and particle (Λ and Ξ) in the decay chain reconstruction. In the case of the Ξ_c^+ baryon, the mean-proper lifetime $c\tau = 132\ \mu\mathrm{m}$ [30] was exploited. The Ξ_c^+ secondary vertex was reconstructed using only two pions having the same-sign charge, 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 adaptive boosted decision tree (BDT) algorithm in the Toolkit for Multivariate Data Analysis (TMVA) [38] was used. The BDT algorithm was trained using reconstructed signal candidates obtained by simulating pp collisions with PYTHIA8.2 [39] and propagating the generated particles through the detector using the GEANT3 transport code [40], including a realistic description of the detector response and alignment during the data taking period. The background candidates were taken from data by selecting candidates with invariant mass in the intervals $2.17 < M < 2.39\ \mathrm{GeV}/c^2$ and $2.55 < M < 2.77\ \mathrm{GeV}/c^2$. 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 modeled with a Gaussian and the background was described by a linear function.

The $\Xi_c^0 \to \Xi^- e^+ \nu_e$ analysis was performed using the technique reported in Ref. [21]. The Ξ_c^0 candidates were defined from opposite-sign charge $e\Xi$ pairs with an opening angle smaller than 90°. 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 [41,42]. Further rejection of background electrons originating from Dalitz decays of neutral mesons and photon conversions was performed using a technique based on the invariant mass of e^+e^- pairs [43,44]. The electron (positron) candidates were paired with opposite-sign charge tracks from the same event and are rejected if they form at least one e^+e^- pair with an invariant mass smaller than 50 MeV/c^2. A correction for the misidentification probability was implemented, estimated to be 2% by applying the algorithm to same-sign charge $e^\pm e^\pm$ pairs. The background in the $e^+\Xi^-$ pair distribution is estimated by exploiting the fact that Ξ_c^0 baryons decay into $e^+\Xi^-\bar{\nu}_e$, but not into $e^-\Xi^-\bar{\nu}_e$, while most of the background sources contribute equally to both samples. The yield of same-sign charge pairs is therefore used to estimate the background. The Ξ_c^0 raw yield was then obtained by subtracting the distribution of same-sign charge $e\Xi$-pairs from the distribution of opposite-sign charge pairs, and integrating the invariant-mass distribution for $M(e\Xi) < 2.5\ \mathrm{GeV}/c^2$. The procedure was verified with PYTHIA8.2 [39] simulations and the GEANT3 transport code. A similar procedure was adopted by the ARGUS and CLEO Collaborations [45,46]. The same-sign charge pairs also contain a contribution from $\Xi_b^{0,-} \to e^-\Xi^-\bar{\nu}_e X$ decays not present in the distribution of opposite-sign charge pairs, leading to an oversubtraction. It was corrected for based on the assumptions reported in Ref. [21] and ranges from 1% to 4%, depending on p_T. 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]. Additional information on the unfolding procedure is reported in the additional material [49].

The raw yields were divided by the acceptance-times-efficiency for prompt hadrons, $(\mathrm{acc} \times \varepsilon)_{\mathrm{prompt}}$, and were corrected for the beauty feed-down contribution. The $(\mathrm{acc} \times \varepsilon)_{\mathrm{prompt}}$ corrections were obtained from a Monte Carlo simulation with the same configuration of the one used for the BDT training. The simulated Ξ_c p_T distributions were modified by a two step iterative procedure in order to mimic data. In the first step, the Ξ_c reconstruction efficiency is obtained with the p_T distribution generated with PYTHIA8.2. This $(\mathrm{acc} \times \varepsilon)_{\mathrm{prompt}}$ is then used to calculate a first estimate of the Ξ_c^0 p_T -differential spectrum. This first estimate is used to reweight the simulated Ξ_c p_T distributions, which is then used for the final computation of the $(\mathrm{acc} \times \varepsilon)_{\mathrm{prompt}}$. The $(\mathrm{acc} \times \varepsilon)_{\mathrm{prompt}}$ 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 PYTHIA8.2 generator [39], 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 (f_{prompt}) 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 2 to obtain the particle-antiparticle averaged yields, by the BR, by the widths of the p_T and y intervals considered, and by $\mathcal{L}_{\mathrm{int}}$, as shown in Eq. (1).

$$\frac{d^2\sigma^{\Xi_c^0}}{dp_T dy} = \frac{1}{\mathrm{BR}} \times \frac{1}{2\Delta y \Delta p_T} \times \frac{f_{\mathrm{prompt}} \times N_{\mathrm{raw}}^{\Xi_c^0+\bar{\Xi}_c^0}}{(\mathrm{acc} \times \varepsilon)_{\mathrm{prompt}}} \times \frac{1}{\mathcal{L}_{\mathrm{int}}}. \quad (1)$$

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 $(\mathrm{acc} \times \varepsilon)_{\mathrm{prompt}}$ 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 2 and scaling it down to the Ξ_b^-/Λ_b^0 ratio measured by the LHCb Collaboration [50], important in the case that $\mathrm{BR}(\Xi_b^0 \to \Xi_c^- X)$ is the same as $\mathrm{BR}(\Lambda_b^0 \to \Lambda_c^+ X)$. 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 [51], 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-sign charge $e\Xi$ pairs was estimated by scaling the assumed Ξ_b momentum distribution by a conservative 50% [52]. 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 normalization uncertainty due to the uncertainties on the integrated luminosity [34] and the BRs [30,31].

The Ξ_c^0 measurements in the two decay channels agree within statistical and uncorrelated systematic uncertainties [49]. 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 [53]. The prompt Ξ_c^+-baryon cross section, also shown in

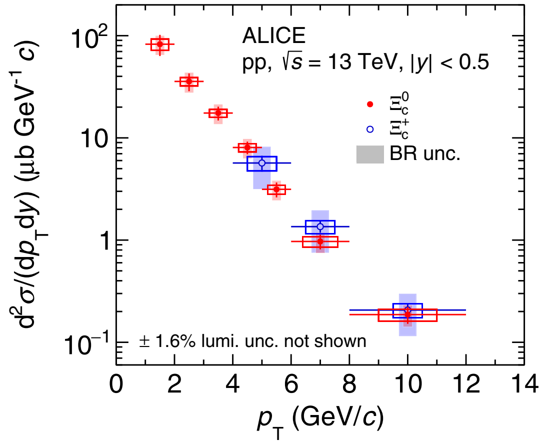

FIG. 1. Cross sections of prompt Ξ_c^0 (full circles) and Ξ_c^+ (open circles) baryons as a function of p_T in pp collisions at $\sqrt{s} = 13$ TeV. The error bars and empty boxes represent the statistical and systematic uncertainties, respectively. The systematic uncertainties on the BR are shown as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

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 $d\sigma^{\Xi_c^0}_{pp,13\ \mathrm{TeV}}/dy|^{(1<p_T<12\ \mathrm{GeV}/c)}_{|y|<0.5} = 149.6 \pm 20.8(\mathrm{stat}) \pm 35.6(\mathrm{syst}) \pm 2.4(\mathrm{lumi})$ μb and $d\sigma^{\Xi_c^+}_{pp,13\ \mathrm{TeV}}/dy|^{(4<p_T<12\ \mathrm{GeV}/c)}_{|y|<0.5} = 14.9 \pm 2.0(\mathrm{stat}) \pm 6.6(\mathrm{syst}) \pm 0.2(\mathrm{lumi})$ μb. In calculating the p_T -integrated cross section and the ratio of the branching fractions, the systematic uncertainty related to unfolding, for the $\Xi_c^0 \to \Xi^- e^+ \nu_e$, was considered as p_T uncorrelated and the other uncertainties as fully p_T correlated. For the hadronic decay channels, the uncertainty related 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 p_T dependence of the Catania model [28], which better describes the shape of the measured cross section with respect to other model calculations as seen in Fig. 2, was used to calculate the extrapolation factor, which is $1.29^{+0.12}_{-0.08}$. The systematic uncertainty was estimated considering calculations [22,23,27] 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 $d\sigma^{\Xi_c^0}_{pp,13\mathrm{TeV}}/dy|_{|y|<0.5} = 193.6 \pm 26.9(\mathrm{stat}) \pm 46.1(\mathrm{syst}) \pm 3.1(\mathrm{lumi})^{+17.5}_{-12.0}(\mathrm{extrap})$ 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 $\mathrm{BR}(\Xi_c^0 \to \Xi^- e^+ \nu_e)/\mathrm{BR}(\Xi_c^0 \to \Xi^- \pi^+)$ ratio. The p_T -dependent ratio of the two measurements, which was observed to be flat in p_T [49], was averaged over p_T using the inverse uncorrelated relative uncertainties as weights [53]. 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 $\mathrm{BR}(\Xi_c^0 \to \Xi^- e^+ \nu_e)/\mathrm{BR}(\Xi_c^0 \to \Xi^- \pi^+) = 1.38 \pm 0.14(\mathrm{stat}) \pm 0.22(\mathrm{syst})$. The result is consistent with the global average reported by the PDG (1.3 ± 0.8) [30] and has a total uncertainty reduced by a factor of 3. The result is also consistent with the one released by the Belle Collaboration [54].

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], while the

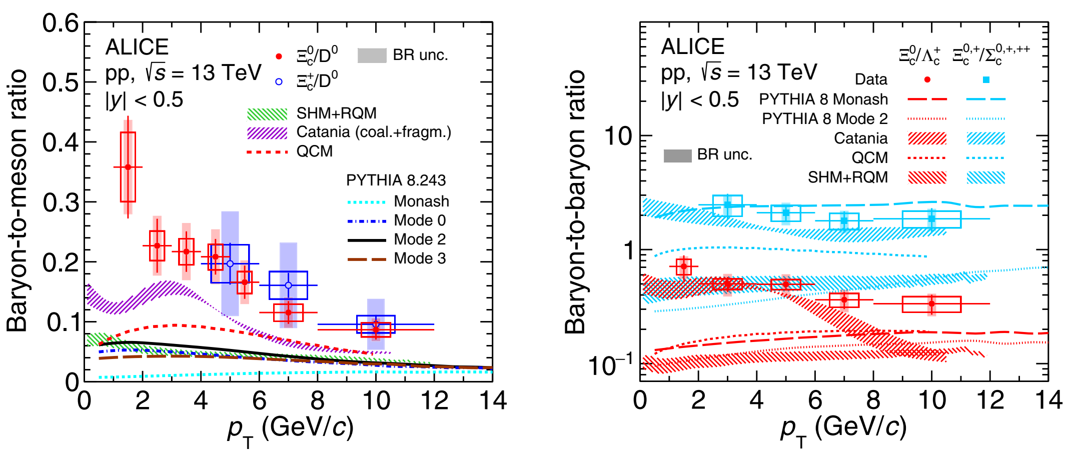

FIG. 2. Left panel: Ξ_c^0/D^0 and Ξ_c^+/D^0 ratios as a function of p_T in pp collisions at $\sqrt{s} = 13$ TeV. Right panel: Ξ_c^0/Λ_c^+ and $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ ratio as a function of p_T. The error bars and empty boxes represent the statistical and systematic uncertainties, respectively.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

Ξ_c/D^0 ratio is generally lower. This result provides strong indications that the fragmentation functions of baryons and mesons differ significantly. The PYTHIA8.2 event generator with the Monash tune [39], and tunes that implement color reconnection (CR) beyond the leading-color approximation [22], which lead to an increased baryon production, were compared to the measurements. 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. The measured Ξ_c/D^0 ratio was also compared to a SHM [23] that includes additional excited charm-baryon states not yet observed but predicted by the RQM [24] and by lattice QCD [25]. 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 hadronization via coalescence. In the quark (re-)combination mechanism (QCM) [27], the charm quark can pick up a comoving light antiquark or two comoving quarks to form a single-charm meson or baryon. The model does not describe the Ξ_c/D^0 ratio. The Catania model [28,55] implements charm-quark hadronization via both coalescence and fragmentation, and it is the model that is closer to the measured ratio over the full p_T interval.

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 PYTHIA8.2 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 2 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 PYTHIA8.2 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 pose important constraints to models of charm-quark hadronization in pp collisions. Finally, the ratio $\mathrm{BR}(\Xi_c^0 \to \Xi^- e^+ \nu_e)/\mathrm{BR}(\Xi_c^0 \to \Xi^- \pi^+)$ was measured with a total uncertainty reduced by a factor 3 with respect to the global average reported by the PDG [30].

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