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Measurement of prompt D^0, Λ_c^+, and $\Sigma_\mathrm{c}^{0,++}(2455)$ production in proton–proton collisions at $\sqrt{s} = 13$ TeV

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Abstract

The p_T-differential production cross sections of prompt D^0, Λ_c^+, and $\Sigma_\mathrm{c}^{0,++}(2455)$ charmed hadrons are measured at midrapidity ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 13$ TeV. This is the first measurement of $\Sigma_\mathrm{c}^{0,++}$ production in hadronic collisions. Assuming the same production yield for the three $\Sigma_\mathrm{c}^{0,+,++}$ isospin states, the baryon-to-meson cross section ratios $\Sigma_\mathrm{c}^{0,+,++}/\mathrm{D}^0$ and $\Lambda_\mathrm{c}^+/\mathrm{D}^0$ are calculated in the transverse momentum (p_T) intervals $2 < p_\mathrm{T} < 12$ GeV/c and $1 < p_\mathrm{T} < 24$ GeV/c. Values significantly larger than in $\mathrm{e}^+\mathrm{e}^-$ collisions are observed, indicating for the first time that baryon enhancement in hadronic collisions also extends to the Σ_c. The feed-down contribution to Λ_c^+ production from $\Sigma_\mathrm{c}^{0,+,++}$ is also reported and is found to be larger than in $\mathrm{e}^+\mathrm{e}^-$ collisions. The data are compared with predictions from event generators and other phenomenological models, providing a sensitive test of the different charm-hadronisation mechanisms implemented in the models.

*See Appendix A for the list of collaboration members

The formation of hadrons out of quarks ("hadronisation") represents a fundamental process in nature that can be investigated at particle colliders where, at high collision energies, quarks represent the relevant degrees of freedom for a very short time of the order of 10^{-23} s. The measurement of the relative production rates of different charm hadron species allows to study how charm quarks, produced only in initial hard scatterings, combine with other quarks, which may either exist in the system before hadronisation or be produced in the strong-force potential at hadronisation time. Recent measurements of Λ_c^+-, Ξ_c^0- and Λ_b^0-baryon production in pp collisions at $\sqrt{s}$ = 5.02, 7, and 13 TeV [1–8] indicate that the production of charm and beauty baryons relative to that of charm and beauty mesons is enhanced in pp with respect to e^+e^- and ep collisions [9–15]. Several models tuned to reproduce the e^+e^- data significantly underestimate the ratios measured in pp collisions and do not describe the observed transverse-momentum (p_T) trends. These measurements also set kinematic boundaries to the validity of the assumption made in perturbative-QCD calculations like FONLL [16, 17] and GM-VFNS [18–23] that fragmentation functions tuned on e^+e^- and ep data can be used in pp collisions.

The $\Sigma_c^{0,+,++}$ baryon triplet is the isospin $I = 1$ partner of the singlet ($I = 0$) Λ_c^+ baryon. All these states are composed of a charm quark and a pair of light (u, d) quarks. In e^+e^- collisions, while in the light-flavour sector the mass dependence of the yields of the Σ and Λ states is well described by a single exponential function, the yields of the $\Sigma_c^{0,+,++}$ states are about a factor 4 smaller than those of the Λ_c^+-states [24]. In the framework of hadronisation via string fragmentation, this suppression can be ascribed to the need to form $\Sigma_c^{0,+,++}$ via the combination of a heavy charm quark, which is always a string endpoint, and a diquark with spin $S = 1$ and $I = 1$ formed via the Schwinger tunnelling process [24, 25]. The large mass of $S = 1$ diquarks suppresses their formation with respect to $S = 0$ diquarks, hence the $\Sigma_c^{0,+,++}$ production yield is suppressed with respect to the Λ_c^+ yield. In the models that provide a fair description of the Λ_c^+/D^0 ratio in pp collisions (here denoted as "CR-BLC" [25], "SHM+RQM" [26], "Catania" [27, 28], "QCM" [29]) this suppression mechanism is absent or heavily reduced, and a sizeable contribution to Λ_c^+ production from strong decays of $\Sigma_c^{0,+,++}$ states is expected. Therefore, the measurement of the ground-state $\Sigma_c^{0,+,++}(2455)$ production is fundamental to understand the dynamics of heavy-flavour baryon formation, providing a key test for the different scenarios proposed in the mentioned models. Among these, the CR-BLC model is a version of PYTHIA 8 in which terms beyond the leading-colour approximation (BLC) are considered in string formation, representing more accurately the QCD SU(3) algebra and de facto enhancing effects from colour reconnection (CR). These terms cause confining potentials to also arise between quarks not produced in the same hard scattering and are relevant to hadronic collisions at high energies, where multiple-parton interactions produce an environment rich in quarks and gluons. Moreover, they give rise to "junction topologies" that favour the production of baryon states and do not penalise the formation of $\Sigma_c^{0,+,++}$ with respect to Λ_c^+ states. The production of $\Sigma_c^{0,+,++}(2455)$ is expected to increase by large factors, up to 25, and become even larger than that of direct Λ_c^+. The SHM+RQM model predicts a large feed-down contribution to the Λ_c^+ ground state from an enriched set of mostly unobserved excited charm-hadron states expected from the Relativistic Quark Model (RQM [30]). The branching fractions of charm quarks to the various hadron species are assumed to follow the relative thermal densities calculated with the Statistical Hadronisation Model (SHM [31]), therefore to depend only on the state mass and spin-degeneracy factor. In the Catania model charm quarks can hadronise via "vacuum"-like fragmentation as well as recombine (coalesce) with surrounding light quarks from the underlying event. The Wigner formalism is used to calculate the probability to form a baryon (meson) given the phase-space distribution of three (two) quarks. A different formalism is implemented in the QCM ("quark (re-)combination mechanism") model, in which charm quarks form hadrons by combining with equal-velocity light quarks. In this model, the relative abundances of the different baryon species are fixed by thermal weights.

In this letter, the measurement performed with the ALICE experiment of the p_T-differential cross sections of prompt D^0, Λ_c^+, and $\Sigma_c^{0,++}(2455)$ in pp collisions at $\sqrt{s} = 13$ TeV at midrapidity ($|y| < 0.5$) is reported. This is the first production measurement for $\Sigma_c^{0,++}(2455)$ in hadronic collisions. The baryon-to-meson ratios Λ_c^+/D^0 and $\Sigma_c^{0,+,++}(2455)/D^0$ as well as the fraction of Λ_c^+ feed-down from $\Sigma_c^{0,+,++}$ decays ($\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}/\Lambda_c^+$) are compared with expectations from the theoretical models described above. These ratios are calculated assuming the three $\Sigma_c^{0,+,++}(2455)$ isospin states to be equally produced. In what follows, the symbols $\Sigma_c^{0,++}$ and $\Sigma_c^{0,+,++}$ always refer to the ground-state $\Sigma_c^{0,+,++}(2455)$ baryons.

The ALICE apparatus is described in detail in Refs. [32, 33]. The D^0, Λ_c^+, and $\Sigma_c^{0,++}$ decays are reconstructed in the central barrel, which covers the pseudorapidity interval $|\eta| < 0.9$ and is embedded in a cylindrical solenoid providing a magnetic field of 0.5 T parallel to the beam direction. Charged particles are tracked with the Inner Tracking System (ITS) and the Time Projection Chamber (TPC). The ITS detector consists of six cylindrical silicon layers surrounding the beam pipe. The measurement of the specific energy loss ($\mathrm{d}E/\mathrm{d}x$) in the TPC gas and of the time difference between the collision time and the particle arrival time at the Time-Of-Flight (TOF) detector are exploited for particle identification (PID) [1, 34].

The data were collected with a minimum bias (MB) trigger requiring coincident signals in the two scintillator arrays covering the intervals $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C). Only events with a primary vertex reconstructed within ± 10 cm from the nominal interaction point along the beam line were analysed. Events with multiple primary vertices were rejected in order to remove collision pileup in the same bunch crossing. The remaining undetected pileup is negligible. The selected events correspond to an integrated luminosity of $\mathscr{L}_{\mathrm{int}} = 31.9 \pm 0.5\ \mathrm{nb}^{-1}$ [35].

The following hadronic decay channels are reconstructed to measure the production of the $\Sigma_c^{0,++}$, Λ_c^+, and D^0 particles and their anti-particles. The $\Sigma_c^{0,++}$ baryons decay strongly to a Λ_c^+ in the channel $\Sigma_c^{0,++} \to \pi^{-,+}\Lambda_c^+$ with a branching ratio (BR) of about 100% [36]. The Λ_c^+ baryons are reconstructed in two different final states: $\Lambda_c^+ \to pK^-\pi^+$, which occurs via multiple resonant and non-resonant decay channels, with a total BR of $(6.28 \pm 0.32)\%$ and $\Lambda_c^+ \to pK_S^0$, with a BR of $(1.59 \pm 0.08)\%$, followed by $K_S^0 \to \pi^+\pi^-$ with a BR of $(69.20 \pm 0.05)\%$. The D^0 mesons are reconstructed in the $D^0 \to K^-\pi^+$ decay channel, which has a BR of $(3.95 \pm 0.03)\%$.

The measurements of the D^0 and Λ_c^+ cross sections are based on an invariant-mass analysis of signal candidates selected for having the proper daughter-particle identities and a displaced decay topology. The analysis procedure, described only briefly here, closely follows that of previous measurements [1, 4, 37]. The D^0 candidates are formed by combining pairs of tracks with opposite charge, each with $|\eta| < 0.8$, $p_{\mathrm{T}} > 0.3\ \mathrm{GeV}/c$, and selected according to the track-quality criteria described in Ref. [37], which are adopted also in the Λ_c^+ and $\Sigma_c^{0,++}$ analyses. Pions and kaons are identified by requiring the $\mathrm{d}E/\mathrm{d}x$ and time-of-flight measured respectively with the TPC and TOF to be within three times the detector resolution from the expected values. The topological selections applied to reduce the combinatorial background are the same as those reported in Ref. [37]. For the $\Lambda_c^+ \to pK^-\pi^+$ decay channel, Λ_c^+ candidates are formed by combining tracks identified as p, K, or π, using the Bayesian PID approach with the "maximum-probability criterion" [38]. The reconstruction of the $\Lambda_c^+ \to pK_S^0$ decay is based on a machine-learning classification that makes use of the Boosted Decision Trees (BDT) algorithm [39]. For both decay channels, a complete description of the applied PID and topological selections can be found in Ref. [1]. A fiducial-acceptance selection $|y| < y_{\mathrm{fid}}(p_{\mathrm{T}})$ is applied to the D^0 and Λ_c^+ candidates, with y_{fid} smoothly increasing from about 0.6 at $p_{\mathrm{T}} = 1\ \mathrm{GeV}/c$ to the maximum value of 0.8 at $p_{\mathrm{T}} = 5\ \mathrm{GeV}/c$.

For the $\Sigma_c^{0,++}$ study, separate analyses are carried out with candidates obtained from the two Λ_c^+ decay channels: averages are then taken of the resulting cross sections and particle cross section ratios. For the study of the $\Lambda_c^+ \leftarrow \Sigma_c^{0,++}$ feed-down, the analysis is performed as a function of Λ_c^+ p_{T}, rather than $\Sigma_c^{0,++}$ p_{T}. The $\Sigma_c^{0,++}$ candidates are built by pairing Λ_c^+ candidates with invariant mass in the interval $2.26 \lesssim M(\Lambda_c^+) \lesssim 2.31\ \mathrm{GeV}/c^2$ with charged particles with $|\eta| < 0.9$ and $p_{\mathrm{T}} > 0.12\ \mathrm{GeV}/c$. The decay tracks are further selected for having a distance from the primary vertex smaller than 650 μm in the transverse plane ($d_{r\varphi}$) and 1.5 mm along the beam axis. The signal-to-background ratio for the $\Sigma_c^{0,++}$

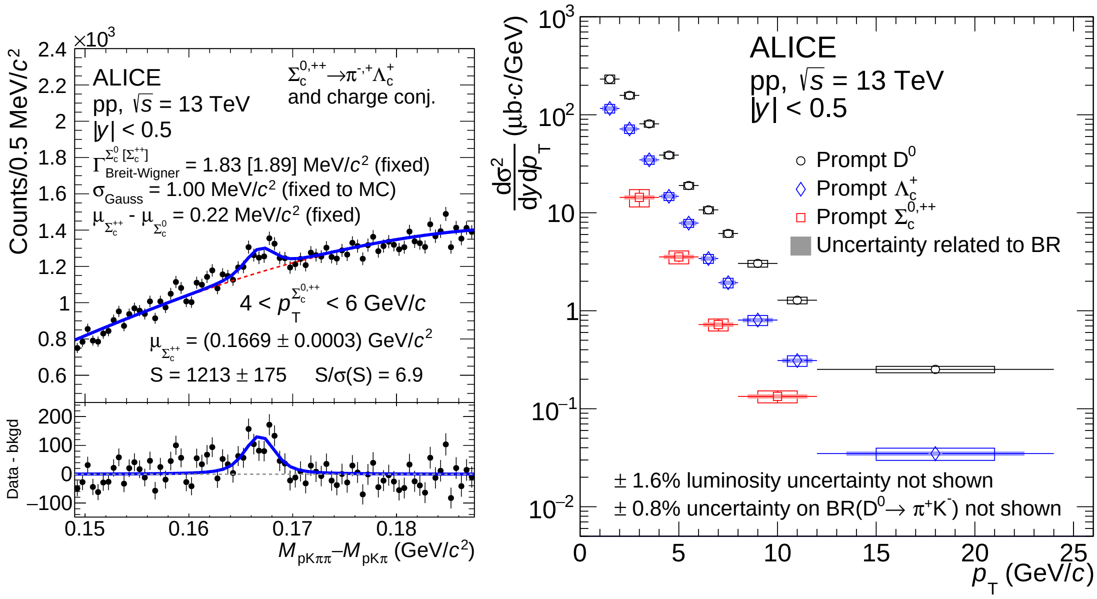

Figure 1: Left: distribution of $\pi^+\mathrm{K}^-\mathrm{p}\pi^\pm$ to $\pi^+\mathrm{K}^-\mathrm{p}$ (and charge conjugate) invariant-mass difference in $4 < p_\mathrm{T}^{\Sigma_c} < 6\,\mathrm{GeV}/c$. Right: p_T-differential cross section of prompt D^0, Λ_c^+, and $\Sigma_c^{0,++}$ in pp collisions at $\sqrt{s} = 13$ TeV. The statistical and systematic uncertainties are shown as vertical lines and boxes, respectively.

reconstructed with $\Lambda_c^+ \to \mathrm{pK}^-\pi^+$ candidates is improved by requiring $|d_{r\varphi} - d_{r\varphi}^{\mathrm{expected}}|/\sigma(d_{r\varphi}) < 2.5$ for $4 < p_\mathrm{T} < 6\,\mathrm{GeV}/c$ [40], and $\cos\theta_\mathrm{point} > 0.8$ for $2 < p_\mathrm{T} < 6\,\mathrm{GeV}/c$, where θ_point is the angle between the Λ_c^+ flight line and its reconstructed momentum vector.

The $\Sigma_c^{0,++}$ and $\Lambda_c^+ \leftarrow \Sigma_c^{0,++}$ raw yields are estimated in each p_T interval via a binned-likelihood fit to the distribution of the $\Sigma_c^{0,++}$ and Λ_c^+ candidate invariant-mass difference ΔM. An example of a ΔM distribution is shown in Fig. 1 (left) for the $\Lambda_c^+ \to \mathrm{pK}^-\pi^+$ decay channel for $4 < p_\mathrm{T}^{\Sigma_c^{0,++}} < 6\,\mathrm{GeV}/c$. The function used to fit the signal peak is

$$f(\Delta M) = \frac{C}{2}[\mathfrak{V}(\Delta M - \mu_{\Sigma_c^{++}}; \sigma, \Gamma_{\Sigma_c^{++}}) + \mathfrak{V}(\Delta M - \mu_{\Sigma_c^{++}} + \delta M; \sigma, \Gamma_{\Sigma_c^0})] \;, \tag{1}$$

where $\mathfrak{V}$ is a Voigt function defined as the convolution of a Gaussian function and a Breit-Wigner function. Two Voigt functions are used to account for Σ_c^0 ($M = 2453.75 \pm 0.14\,\mathrm{MeV}/c^2$, full width $\Gamma_{\Sigma_c^0} = 1.83^{+0.11}_{-0.19}\,\mathrm{MeV}/c^2$) and Σ_c^{++} ($M = 2453.97 \pm 0.14\,\mathrm{MeV}/c^2$, $\Gamma_{\Sigma_c^{++}} = 1.89^{+0.09}_{-0.18}\,\mathrm{MeV}/c^2$) isospin partners, whose invariant masses differ by $\delta M = 0.22\,\mathrm{MeV}/c^2$ [36]. The standard deviation of the Gaussian function, which accounts for the detector ΔM resolution, is fixed to values $\sigma \sim 1\,\mathrm{MeV}/c^2$, determined from Monte Carlo simulations. The free parameters of the fit are $\mu_{\Sigma_c^{++}}$, i.e. the Σ_c^{++} peak mean, and C, which represents the sum of Σ_c^0 and Σ_c^{++} (and charge conjugates) raw yields. Depending on the p_T interval, the background ΔM distribution is described with a 3rd-order polynomial function, a "threshold" function, or a template distribution, as described in Appendix B. The statistical uncertainty of the raw yields varies between 15% and 30% depending on the decay channel and p_T interval. It was verified that the Σ_c^0 and Σ_c^{++} raw yields are compatible within statistical uncertainties.

The p_T-differential cross sections of prompt D^0, Λ_c^+, $\Lambda_c^+ \leftarrow \Sigma_c^{0,++}$, and $\Sigma_c^{0,++}$ are calculated from the raw yields $N_{|y|<y_{\rm fid}}$, measured in the fiducial y acceptance in a $p_{\rm T}$ interval of width $\Delta p_{\rm T}$, as

$$\left.\frac{{\rm d}\sigma}{{\rm d}p_{\rm T}}\right|_{|y|<0.5} = \frac{1}{2}\frac{1}{\Delta p_{\rm T}} \times \frac{f_{\rm prompt} \times N_{|y|<y_{\rm fid}}}{c_{\Delta y} \times (A\times\varepsilon)_{\rm prompt}} \times \frac{1}{\rm BR} \times \frac{1}{\mathscr{L}_{\rm int}} \,. \quad (2)$$

The factor 2 in the denominator takes into account that both particles and antiparticles contribute to the measured raw yields. The term $c_{\Delta y}$ encompasses the correction for the rapidity coverage [40], and $(A \times \varepsilon)$ the detector acceptance as well as the reconstruction and selection efficiency for the signal. This is estimated from Monte Carlo simulations in which pp collisions are simulated with the PYTHIA 8.243 event generator [41, 42] and the generated particles are propagated through the apparatus using the GEANT3 package [43] via a simulation that reproduces the detector layout and data-taking conditions. For prompt $\Sigma_c^{0,++}$, $c_{\Delta y} \times (A\times\varepsilon)$ increases from 1% (4%) in $2 < p_{\rm T} < 4\,{\rm GeV}/c$ to 11% (22%) in $8 < p_{\rm T} < 12\,{\rm GeV}/c$ in the $\Lambda_c^+ \rightarrow {\rm pK}^-\pi^+$ ($\Lambda_c^+ \rightarrow {\rm pK}^0_{\rm S}$) analysis.

The fraction of prompt particles contributing to the measured raw yield, $f_{\rm prompt}$, is calculated using the reconstruction efficiencies of prompt and feed-down signals and the feed-down Λ_c^+ and D^0 cross sections, from Λ_b^0 and B-meson decays ("beauty feed-down"). The latter cross sections are estimated as reported in Refs. [4, 37], using computations based on FONLL calculations [16, 17], beauty-quark fragmentation fractions determined from LHCb data [8] for ${\rm b} \rightarrow \Lambda_b^0$ and from the averaged b-quark fragmentation fraction from LEP [12] for ${\rm b} \rightarrow {\rm B}$, and modelling the $\Lambda_b^0 \rightarrow \Lambda_c^+ + X$ and ${\rm B} \rightarrow {\rm D}^0 + X$ decay kinematics with PYTHIA 8 simulations [44]. The values of $f_{\rm prompt}$ range from 0.8 to 0.96 depending on $p_{\rm T}$ and the particle species. In the $\Sigma_c^{0,++}$ case, according to currently known decays [36] and to PYTHIA 8 simulations, a non-negligible feed-down contribution is only expected from Λ_b^0 decays. The probability for $\Lambda_b^0 \rightarrow \Sigma_c^{0,++} + X$ decays is estimated to be about 3% of the probability for $\Lambda_b^0 \rightarrow \Lambda_c^+ + X$ decays, resulting in $f_{\rm prompt} \geq 95\%$ for both $\Lambda_c^+ \leftarrow \Sigma_c^{0,++}$ and $\Sigma_c^{0,++}$ analyses.

Several sources of systematic uncertainties of the measured cross sections were studied, following similar procedures to those described in Refs. [4, 37] for the Λ_c^+ and D^0 analyses. The uncertainty of $N_{|y|<y_{\rm fid}}$, estimated by varying the invariant mass fit procedure, ranges from 2% to 4% for D^0 and from 5% to 11% for Λ_c^+, depending on $p_{\rm T}$. For $\Sigma_c^{0,++}$ and $\Lambda_c^+ \leftarrow \Sigma_c^{0,++}$, this source provides the largest contribution to the systematic uncertainty, which was estimated by repeating the ΔM fits varying the signal and background fit functions, as well as the fit ranges. The Γ and δM parameters were varied within their uncertainties, and the Gaussian width σ was changed by $\pm 20\%$. The estimated uncertainty decreases from 15–30% in the first $p_{\rm T}$ interval down to 8–10% in the last one. Imperfections in the description of the apparatus and detector conditions in the Monte Carlo simulations introduce an uncertainty on the determination of the $c_{\Delta y} \times (A\times\varepsilon)_{\rm prompt}$ correction factor: the systematic uncertainty of the track-reconstruction efficiency induces an uncertainty of about 4% for D^0, and 8% for Λ_c^+ and $\Sigma_c^{0,++}$, while the uncertainty related to the signal-selection efficiency, estimated by varying both topological and PID selections, ranges between 3% and 10% depending on the $p_{\rm T}$ interval and particle species. Variations of the simulated signal spectrum $p_{\rm T}$ shapes based on FONLL (for D^0) and CR-BLC (for Λ_c^+ and $\Sigma_c^{0,++}$) models alter the efficiency by 2% for D^0 with $p_{\rm T} < 2\,{\rm GeV}/c$ and, for the other analyses, by values decreasing from 10% to 1% with increasing $p_{\rm T}$. The systematic uncertainty of the prompt fraction is about 2–4% for D^0 and Λ_c^+. For the $\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}$ and $\Sigma_c^{0,+,++}$ analyses, the beauty feed-down contribution was varied according to the Λ_c^+ feed-down uncertainty, with the additional variation from 3% to 6% of the ratio of $\Sigma_c^{0,++}$ and Λ_c^+ feed-down estimated with PYTHIA 8 simulations as described previously. The resulting uncertainty of the cross section is within 2%. Further $p_{\rm T}$-independent uncertainties derive from the BR and the luminosity. All the uncertainty sources described above are assumed to be uncorrelated with respect to each other. The total uncertainty in each $p_{\rm T}$ interval is calculated as the quadratic sum of the values estimated for each source.

The $p_{\rm T}$-differential cross sections of D^0, Λ_c^+, and $\Sigma_c^{0,++}$ are shown in Fig. 1 (right). For Λ_c^+ and $\Sigma_c^{0,++}$ the weighted average of the results from the analyses of the two Λ_c^+ decay channels is calculated, using the in-

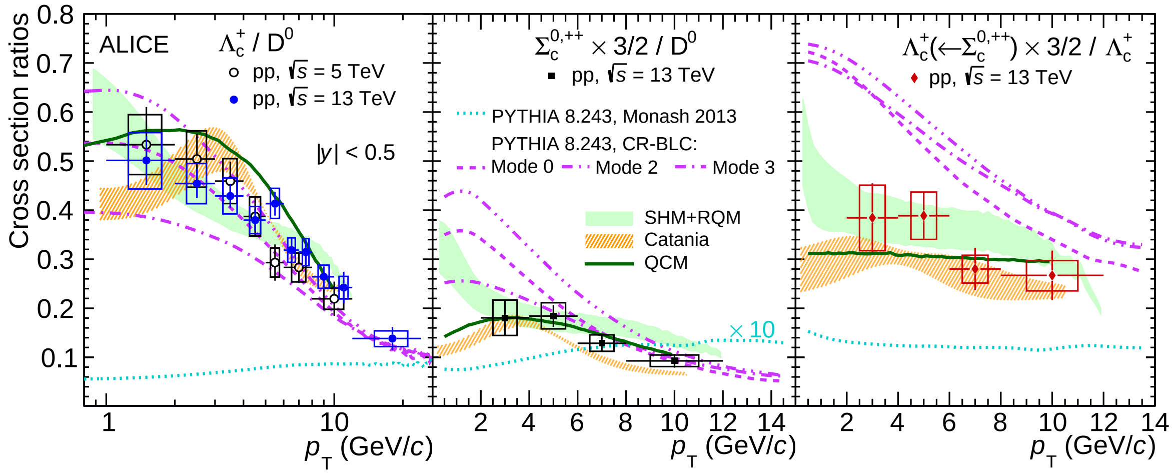

Figure 2: Prompt-charm-hadron cross-section ratios: Λ_c^+/D^0 (left), $\Sigma_c^{0,+,++}/D^0$ (middle), and $\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}/\Lambda_c^+$ (right), in pp collisions at $\sqrt{s} = 13$ TeV, compared with model expectations [25–27, 29] and (left) with data from pp collisions at $\sqrt{s} = 5.02$ TeV [3]. The horizontal lines reflect the width of the p_T intervals. The PYTHIA Monash 2013 curve is scaled by a factor of 10 in the middle panel.

verse of the quadratic sum of the relative statistical and uncorrelated systematic uncertainties as weights. The total systematic uncertainty of the averaged Σ_c cross section varies from 20% at low p_T to 13% at high p_T. The cross-section ratios Λ_c^+/D^0 and $\Sigma_c^{0,+,++}/D^0$ are compared with model expectations in Fig. 2 (left and middle panels). In the ratios, the systematic uncertainties of the track-reconstruction efficiency and luminosity, considered as fully correlated, cancel partly and completely, respectively. The feed-down uncertainty is propagated as partially correlated, while all other uncertainties are treated as uncorrelated. The Λ_c^+/D^0 ratio decreases with increasing p_T and is significantly larger than the ≈0.12 values observed in e^+e^- and ep collisions at several collision energies [12–15, 45–47]. The values measured in pp collisions at $\sqrt{s} = 13$ TeV are compatible, within uncertainties, with those measured at $\sqrt{s} = 5.02$ TeV [3, 4]. As shown in Fig. 2 (middle), the $\Sigma_c^{0,+,++}/D^0$ ratio is close to 0.2 for $2 < p_T < 6$ GeV/c, and decreases with p_T down to about 0.1 for $8 < p_T < 12$ GeV/c, though the uncertainties do not allow firm conclusions about the p_T dependence to be made. From Belle measurements (Table IV in Ref. [24]), the $\Sigma_c^{0,+,++}/\Lambda_c^+$ ratio in e^+e^- collisions at $\sqrt{s} = 10.52$ GeV can be evaluated to be around 0.17 and, thus, the $\Sigma_c^{0,+,++}/D^0$ ratio can be estimated to be around 0.02. Therefore, a remarkable difference is present between the pp and e^+e^- collision systems. Although rather approximate, such comparison is corroborated by the fact that a simulation performed with the default version of PYTHIA 6.2 reasonably reproduces Belle data [24], while the default version of PYTHIA 8.243 (Monash 2013 tune) severely underpredicts ALICE data, despite the very similar modelling of charm fragmentation in the two simulations. Figure 2 (right) shows the ratio $\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}/\Lambda_c^+$ as a function of p_T, which quantifies the fraction of Λ_c^+ feed-down from $\Sigma_c^{0,+,++}$. In order to better exploit the cancellation of correlated uncertainties, this is calculated as the weighted average of the ratios measured separately in the $\Lambda_c^+ \to pK^-\pi^+$ and $\Lambda_c^+ \to pK_S^0$ decay channels. The p_T-integrated value in the measured $p_T > 2$ GeV/c interval is $0.38 \pm 0.06(\text{stat}) \pm 0.06(\text{syst})$, significantly larger than the ratio $\Sigma_c^{0,+,++}/\Lambda_c^+ \sim 0.17$ from Belle data and the ∼0.13 expectation from PYTHIA 8 (Monash 2013) simulations. This indicates a larger increase for $\Sigma_c^{0,+,++}/D^0$ than for the direct-Λ_c^+/D^0 ratio from e^+e^- to pp collisions. The larger feed-down from $\Sigma_c^{0,+,++}$ partially explains the difference between the Λ_c^+/D^0 ratios in pp and e^+e^- collisions.

As shown in Figure 2, the CR-BLC (for which the three variations defined in Ref. [25] are considered), SHM+RQM, and Catania models describe, within uncertainties, both the Λ_c^+/D^0 and $\Sigma_c^{0,+,++}/D^0$ ratios. The QCM model uses the Λ_c^+/D^0 data in pp collisions at $\sqrt{s} = 7$ TeV to set the total charm baryon-to-meson ratio, but it predicts correctly the $\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}/\Lambda_c^+$ and the p_T-shape of all ratios. The $\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}/\Lambda_c^+$ ratio does not show a p_T trend as steep as that expected from the CR-BLC model, which significantly overestimates the Λ_c^+ feed-down from $\Sigma_c^{0,+,++}$ at low p_T. Therefore, the data suggest that further tuning of the model parameters involving the reconnection of quarks via junction topologies is needed to possibly validate this as the mechanism reducing the assumed suppression of $\Sigma_c^{0,+,++}$ formation in e^+e^- collisions [24, 25]. In the Catania, QCM, and SHM+RQM models, no specific penalty factor affects the formation of Σ_c states. The fact that the SHM+RQM model reproduces both the Λ_c^+/D^0 ratio and the fraction of Λ_c^+ feed-down from $\Sigma_c^{0,+,++}$ may suggest that yet-unobserved higher-mass charm-baryon states exist and are formed more frequently in pp collisions than in e^+e^- and ep collisions. Similarly, the success of the Catania and QCM models in reproducing the data may indicate that charm hadronisation in pp collisions involves coalescence of charm quark with light quarks.

The p_T-differential cross section of $\Sigma_c^{0,++}$ has been measured in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ in the range $2 < p_T < 12\,\text{GeV}/c$, the first measurement in hadron–hadron collisions, together with the Λ_c^+ and D^0 cross sections in the range $1 < p_T < 24\,\text{GeV}/c$. The charm baryon-to-meson cross section ratios were found to be larger than expectations based on e^+e^- measurements. The reported results confirm previous observations at $\sqrt{s} = 5.02\,\text{TeV}$ and $\sqrt{s} = 7\,\text{TeV}$ for the Λ_c^+ and show for the first time that the effect also extends to the $\Sigma_c^{0,++}$. The feed-down from $\Sigma_c^{0,+,++}$ decays to Λ_c^+ production amounts to $0.38 \pm 0.06(\text{stat}) \pm 0.06(\text{syst})$ in the range $2 < p_T < 12\,\text{GeV}/c$, which is significantly larger than measurements in e^+e^- collisions. The results presented provide important constraints on models aiming at explaining the observed increase of charm baryons in a parton-rich environment, either increasing baryon-formation probability via enhanced colour reconnection or coalescence mechanisms, or assuming feed-down from yet-unobserved higher-mass baryon states.

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B Invariant-mass plots and fit procedures

The ΔM distributions from which the $\Sigma_c^{0,++}$ and $\Lambda_c^+ \leftarrow \Sigma_c^{0,++}$ raw yields are extracted and reported in Fig. B.1 for the analysis of the $\Sigma_c^{0,++} \rightarrow pK_S^0\pi^{-,+}$ decay channel, and in Fig. B.2 for the analysis of the $\Sigma_c^{0,++} \rightarrow pK^-\pi^+\pi^{-,+}$ decay channel. Different functional shapes are used for the background term in the fit of the ΔM distributions. For the analyses of the $\Sigma_c^{0,++} \rightarrow pK_S^0\pi^{-,+}$ decay channel the "threshold" function $c_0(\Delta M - M_\pi)^{c_1} e^{-c_2(\Delta M - M_\pi)}$ is used for $p_T < 6$ GeV/c, while a 3rd-order polynomial function is used at higher p_T. For the analyses of the $\Sigma_c^{0,++} \rightarrow pK^-\pi^+\pi^{-,+}$ decay channel, a 3rd-order polynomial function is used for $p_T > 4$ GeV/c, while a template distribution multiplied by a 2nd-order polynomial function is exploited in the interval $2 < p_T < 4$ GeV/c, which is characterised by a very low signal-to-background ratio. The template distribution is obtained by recalculating ΔM nine times for each $\Sigma_c^{0,++}$ candidate after rotating the pion momentum vector around the longitudinal direction. For both the $\Sigma_c^{0,++} \rightarrow pK^-\pi^+\pi^{-,+}$ and $\Sigma_c^{0,++} \rightarrow pK_S^0\pi^{-,+}$ analyses the same background functional shapes are used in the fits of the $\Sigma_c^{0,++}$ and $\Lambda_c^+ \leftarrow \Sigma_c^{0,++}$.

The difference obtained by using the template distribution for background candidates, the 3rd-order polynomial and the "threshold" function was taken into account in the estimate of the systematic uncertainty on the raw-yield extraction.

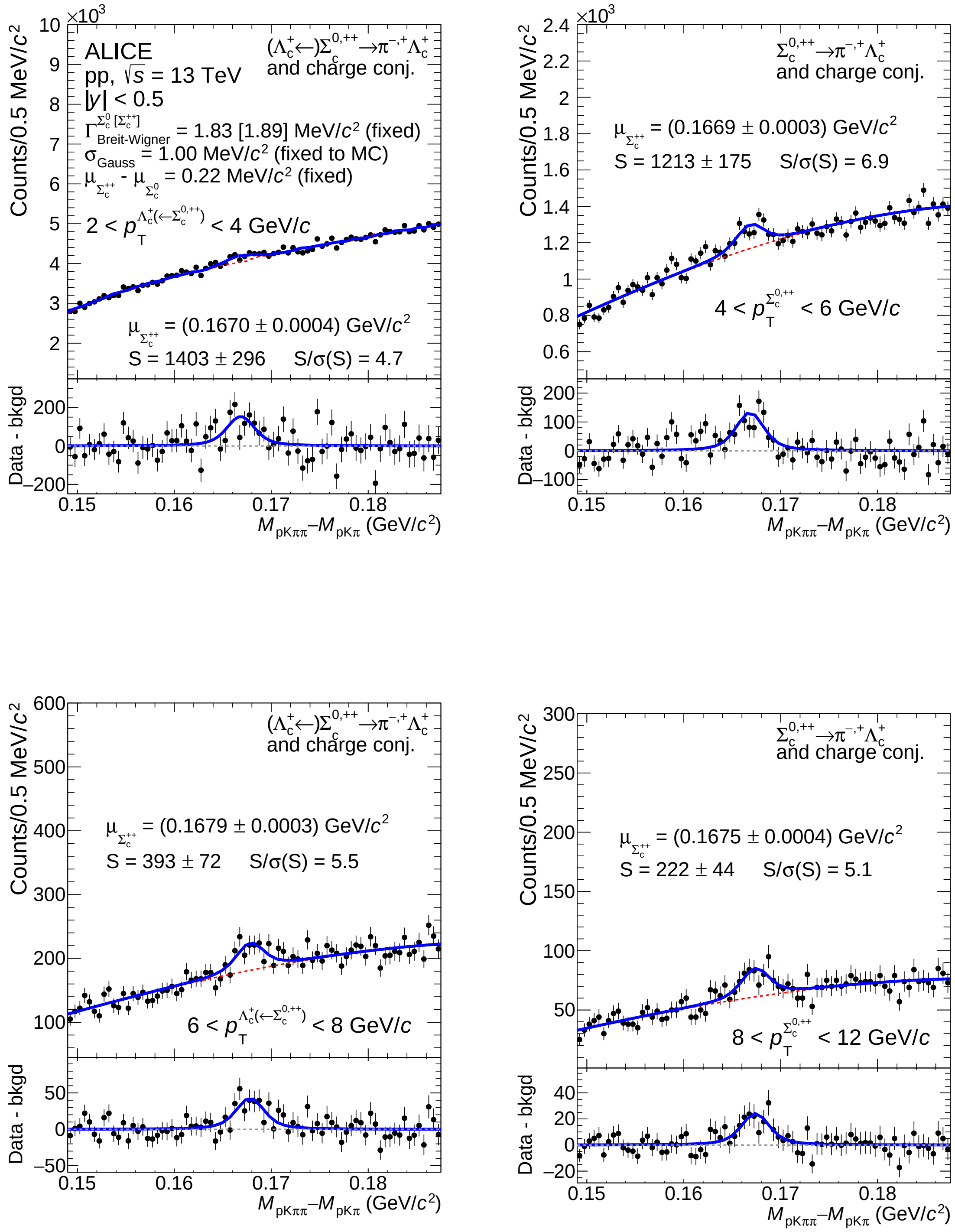

Figure B.1: Distribution of $pK^-\pi^+\pi^\pm$ to $pK^-\pi^+$ (and charge conjugate) invariant-mass difference in different $p_T^{\Lambda_c^+ \leftarrow \Sigma_c^{0,++}}$ (left column) and $p_T^{\Sigma_c}$ (right column) intervals in pp collisions at $\sqrt{s} = 13$ TeV. The residuals with respect to the background ("bkgd") are shown in the bottom sub-panels.

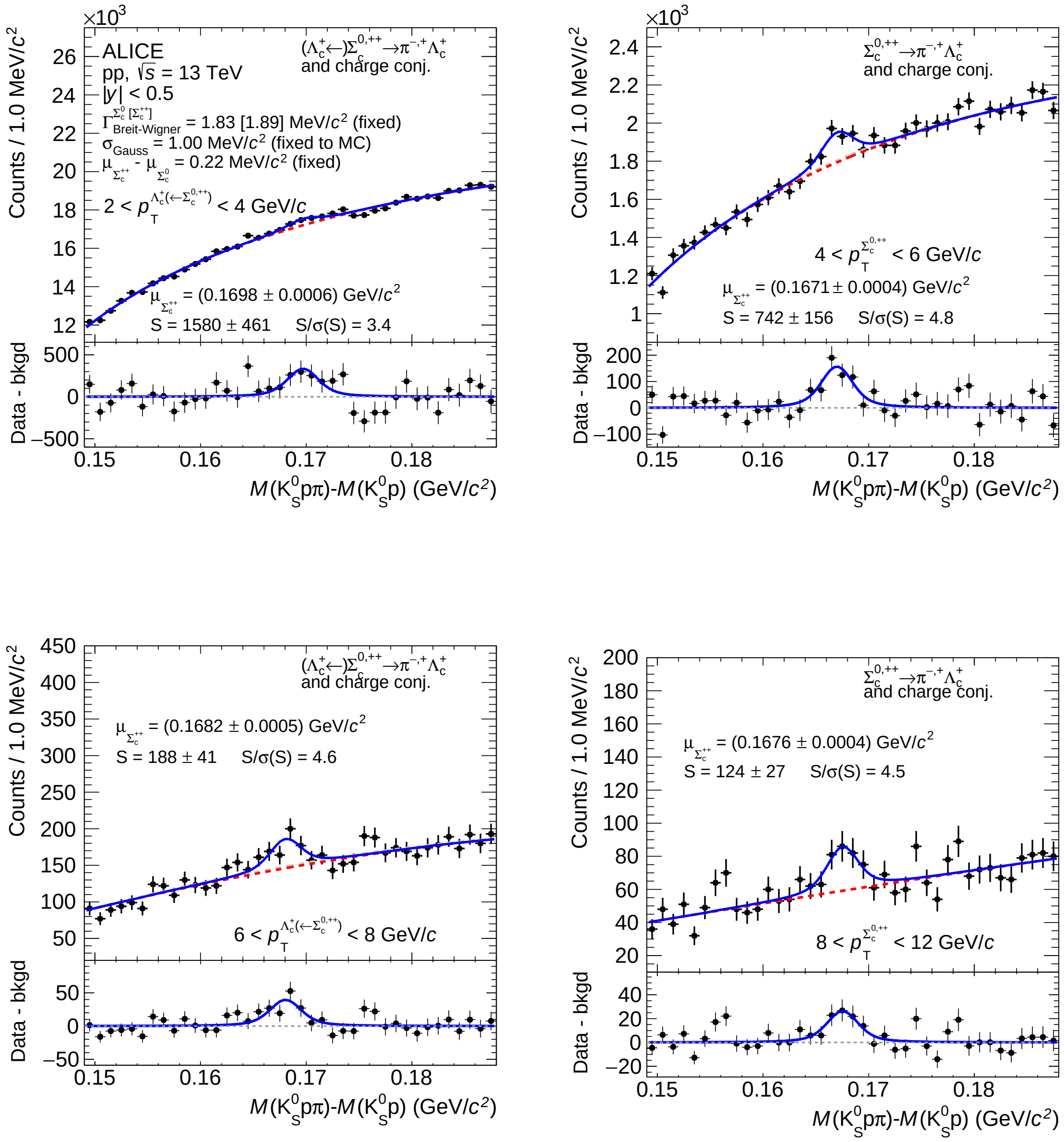

Figure B.2: Distribution of $K_S^0 p\pi^{\pm}$ to $K_S^0 p$ (and charge conjugate) invariant-mass difference in different $p_T^{\Lambda_c^+ \leftarrow \Sigma_c^{0,++}}$ (left column) and $p_T^{\Sigma_c}$ (right column) intervals in pp collisions at $\sqrt{s} = 13$ TeV. The residuals with respect to the background ("bkgd") are shown in the bottom sub-panels.