



Measurement of Ξ_c^+ production in p Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV at LHCb

LHCb collaboration[†]

Abstract

A study of prompt Ξ_c^+ production in proton-lead collisions is performed with the LHCb experiment at a centre-of-mass energy per nucleon pair of 8.16 TeV in 2016 in p Pb and Pb p collisions with an estimated integrated luminosity of approximately 12.5 and 17.4 nb⁻¹, respectively. The Ξ_c^+ production cross-section, as well as the Ξ_c^+ to Λ_c^+ production cross-section ratio, are measured as a function of the transverse momentum and rapidity and compared to the latest theory predictions. The forward-backward asymmetry is also measured as a function of the Ξ_c^+ transverse momentum. The results provide strong constraints on theoretical calculation and are a unique input for hadronisation studies in different collision systems.

Submitted to Phys. Rev. C

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In hadronic collisions, heavy quarks are produced in hard scattering processes with large momentum transfer. Theoretical predictions based on perturbative Quantum Chromodynamics (pQCD) describe reasonably well the transverse momentum (p_T) differential charm production cross-sections in proton-proton (pp) collisions at different energies [1]. The heavy-flavour hadron cross-sections are usually computed using the factorisation approach as a convolution of three terms [2]: the parton distribution functions of the colliding particles, the hard-scattering cross-section, and the fragmentation function (FF) of heavy quarks into a given heavy-flavour hadron. It is assumed that the FFs are universal between collision systems and energies. At the LHC, the FFs used to describe the measurements of heavy-flavour hadron production in pp collisions at different centre-of-mass energies are tuned on e^+e^- collision data within the framework of pQCD over a wide p_T range. However, evidence of non-universal FFs was observed by the LHCb collaboration in a study of the Λ_b^0 baryon to B^- and \bar{B}^0 meson production ratio in pp collisions [3]. Multiple measurements of the relative production of different heavy-flavour hadron species have been made, as they are sensitive probes of FFs.

The measurements of heavy-flavoured hadron ratios in hadronic collisions, such as the Λ_c^+/D^0 cross-section ratio, in pp collisions at $\sqrt{s} = 5, 7$ and 13 TeV and in proton-lead (pPb) collisions at $\sqrt{s} = 5$ TeV [4–6] show an enhancement with respect to predictions from pQCD calculations with charm fragmentation based on e^+e^- [7, 8] and e^-p [9–11] measurements. Similar observations were made in the measurement of the Ξ_c^0 (Ξ_c^+)/ D^0 cross-section ratio in pp collisions at $\sqrt{s} = 7$ and 13 TeV [12, 13]. Multiple models explain the ratio enhancement. For example, colour reconnection [14] could be stronger in pp collisions than in e^+e^- collisions, resulting in an enhanced production of baryons relative to mesons. Other models predicts that hadronisation via coalescence [15] will take place.

This paper presents a study of the ratio of production of the Ξ_c^+ particle, a charm-strange baryon, to the production of the Λ_c^+ baryon in pPb collisions at the LHCb experiment. This measurement has the potential to shed light on the mechanism of hadronisation and its universality as it is the first one to be performed in proton-nucleus collisions, considered the best environment to study the so-called cold nuclear matter (CNM) effects, such as shadowing [16–18], energy loss [19] and nuclear break-up [20]. In nucleus-nucleus collisions, in addition to CNM effects, experimental results indicate the formation of a high-density colour-deconfined medium, the quark-gluon plasma (QGP), a state of matter with asymptotically free partons, which is expected to exist at extremely high temperature and density. The presence of QGP can be determined by observing the change in behaviour of the particles as they traverse the nuclear medium with respect to their behaviour in the absence of QGP [21]. In pPb collisions the energy density is not expected to be sufficient to produce a QGP medium; however, some theoretical models predict the formation of “QGP droplets” [22], which could partially induce in pPb the same behaviour, albeit less pronounced, as in PbPb collisions. Moreover, several QGP models predict that strange (s) quark production is enhanced in heavy-ion collisions, as first reported in Ref. [23]; thus, strangeness enhancement and strange antibaryon abundance are considered signatures for QGP formation [24–26], mainly due to the predominance of the gluonic production mechanism $gg \rightarrow s\bar{s}$. Strangeness enhancement is investigated at accelerators by studying the ratio of production rates of hadrons containing a strange quark to those without, as done, by experiments at CERN [27] and RHIC [28, 29]. The ratio of Ξ_c^+ to Λ_c^+ production measured in this paper, by comparing a baryon with strange content to one without, has the potential to test the presence of QGP formation from

QGP droplets in $p\text{Pb}$ collisions, which has not yet been established.

The Ξ_c^+ and Λ_c^+ candidates¹ in the analysis are reconstructed via the hadronic decay to the $pK^-\pi^+$ final state. The measurements are performed as a function of p_T and rapidity (y^*) of the baryons, using $p\text{Pb}$ and $\text{Pb}p$ collisions with an estimated integrated luminosity of approximately 12.5 and 17.4 nb^{-1} [30], respectively, collected by the LHCb detector at centre-of-mass energy per nucleon pair of $\sqrt{s_{\text{NN}}} = 8.16$ TeV. The rapidity y^* in the nucleon-nucleon centre-of-mass system is related to the rapidity in the laboratory frame (y_{lab}) via $y^* = y_{\text{lab}} \pm 0.4645$. Here, 0.4645 is the shift in rapidity in the direction of the proton beam due to the unequal mass of the two colliding objects. The proton beam and the lead beam have different energies per nucleon in the laboratory frame, with $E_p = 6.5$ TeV and $E_{\text{Pb}} = 2.56$ TeV. The particles are separated according to whether they originate from the collision point (prompt) or from the decay of b hadrons (nonprompt) using the impact parameter (IP), defined as the distance of closest approach of the particle trajectory to the collision point. Data are analysed separately in the $p\text{Pb}$ (forward) sample, covering a rapidity range $1.5 < y^* < 4.0$, and the $\text{Pb}p$ (backward) sample, covering the range $-5.0 < y^* < -2.5$.

The double differential cross-section for prompt Ξ_c^+ (Λ_c^+) production is measured as

$$\frac{d^2\sigma_{\Xi_c^+(\Lambda_c^+)}(p_T, y^*)}{dp_T dy^*} = \frac{N_{\Xi_c^+(\Lambda_c^+)}(p_T, y^*)}{\mathcal{L} \cdot \mathcal{B} \cdot \epsilon_{\text{tot}}(p_T, y^*) \cdot \Delta p_T \Delta y^*}, \quad (1)$$

where $N_{\Xi_c^+(\Lambda_c^+)}(p_T, y^*)$ is the measured signal yield of prompt Ξ_c^+ (Λ_c^+) decays produced in a given interval of p_T and y^* , Δp_T and Δy^* , respectively, and \mathcal{L} represents the integrated luminosity. The branching fractions \mathcal{B} are $(0.62 \pm 0.30)\%$ and $(6.28 \pm 0.32)\%$, for the decays $\Xi_c^+ \rightarrow pK^-\pi^+$ and $\Lambda_c^+ \rightarrow pK^-\pi^+$, respectively [31]. Finally, $\epsilon_{\text{tot}}(p_T, y^*)$ stands for the total signal efficiency determined in the Δp_T and Δy^* interval. The production ratio of Ξ_c^+ to Λ_c^+ , $R_{\Xi_c^+/\Lambda_c^+}(p_T, y^*)$, is defined as

$$R_{\Xi_c^+/\Lambda_c^+}(p_T, y^*) \equiv \frac{d^2\sigma_{\Xi_c^+}(p_T, y^*)/dp_T dy^*}{d^2\sigma_{\Lambda_c^+}(p_T, y^*)/dp_T dy^*}. \quad (2)$$

The forward-backward asymmetry, $R_{\text{FB}}(p_T, y^*)$, is measured in the overlapping rapidity range $2.5 < |y^*| < 4.0$ and is defined as

$$R_{\text{FB}}(p_T, y^*) \equiv \frac{d^2\sigma_{\Xi_c^+}(p_T, +|y^*|)/dp_T dy^*}{d^2\sigma_{\Xi_c^+}(p_T, -|y^*|)/dp_T dy^*}. \quad (3)$$

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [32, 33]. The detector elements that are most relevant to this analysis are a silicon-strip vertex detector (VELO) surrounding the $p\text{Pb}$ interaction region, which allows the determination of the position of the collision point, known as the primary vertex (PV), and the position of the short-lived particle decay vertices; a tracking system that provides a measurement of the momentum, p , of charged particles; and two ring-imaging Cherenkov detectors that can discriminate between different species of charged hadrons.

Simulation is used to model the reconstruction efficiency and the effects of the selection requirements. Charmed baryons are generated in pp collisions at $\sqrt{s} = 8.16$ TeV using

¹Charge conjugate decays are implied throughout this paper, unless otherwise stated.

the PYTHIA [34] generator and are embedded into the EPOS [35] generator, which simulates the environment of the proton-lead collision. Particle decays are described by EVTGEN [36], while the interaction of particles with the detector, and its response in simulation, are implemented using the GEANT4 toolkit [37,38].

The online event selection is performed by a trigger, which consists of a hardware stage followed by a two-level software stage. In between the two software stages, an alignment and calibration of the detector is performed in near real-time and their results are used in the trigger [39]. The same alignment and calibration information is propagated to the offline reconstruction, ensuring consistent and high-quality particle identification (PID) information between the trigger and offline software. The identical performance of the online and offline reconstruction offers the opportunity to perform physics analyses directly using candidates reconstructed in the trigger [40,41] which the present analysis exploits. The Ξ_c^+ and Λ_c^+ baryons are reconstructed by combining three tracks identified as proton, kaon and pion candidates. All the charged tracks are required to be well reconstructed and to have transverse momentum $p_T > 400$ MeV/ c and be incompatible with originating at the PV. The tracks must also be within the LHCb acceptance $2.0 < \eta < 5.0$ and in the kinematic range $3.2 < p < 100.0$ GeV/ c . The Ξ_c^+ and Λ_c^+ candidates are required to have a good quality secondary vertex and a reconstructed decay time between 0.1 and 10 ps. The angle between the reconstructed candidate momentum and the vector pointing from the PV to the secondary vertex is required to be close to zero. The $pK^-\pi^+$ invariant mass is required to be within ± 70 MeV/ c^2 of the known Ξ_c^+ (Λ_c^+) mass [31]. The invariant mass resolution for the reconstructed candidates is around 10 MeV/ c^2 .

The signal yields are determined using a maximum-likelihood fit to the $pK^-\pi^+$ invariant mass distributions, which were verified to be independent of the other kinematic variables. The signal component of the fit model is represented by a sum of a Crystal Ball function [42] and a Gaussian function, which share a common mean value. The background component is described by a linear function. The obtained signal yields are about 13.3k (12.6k) Ξ_c^+ decays and 119.2k (104.4k) Λ_c^+ decays in the $p\text{Pb}$ ($\text{Pb}p$) sample after background subtraction, achieved using the *sPlot* technique [43], with the $pK^-\pi^+$ invariant mass as the discriminating variable. The extracted signal contains promptly produced baryons and nonprompt signal from the decay of b -hadrons. To extract the prompt component, the method developed in Ref. [6] is used, with the variable χ_{IP}^2 discriminating between prompt and nonprompt production. The χ_{IP}^2 variable is defined as the difference in the vertex-fit χ^2 of a given PV reconstructed with and without the Ξ_c^+ (Λ_c^+) candidate under consideration. The prompt and nonprompt components are modelled with a Bukin function [44]. The asymmetry parameters of the Bukin function describing the prompt component are fixed using results from fits to simulated samples. The invariant-mass distributions fits and the $\log_{10}(\chi_{\text{IP}}^2)$ fits are given in the Supplemental Material [45]. The quantity $N^{\Xi_c^+(\Lambda_c^+)}(p_T, y^*)$ is obtained by performing the invariant mass and $\log_{10}(\chi_{\text{IP}}^2)$ fits in each (p_T, y^*) bin.

The simulation is used to determine the total efficiency, defined as the product of the geometrical acceptance of the detector, and the reconstruction, selection, PID and trigger efficiencies. The samples are weighted to match the background-subtracted data using the distributions of p_T , y^* , the number of VELO clusters and the invariant mass of the pK^- and $K^-\pi^+$ combinations. The PID efficiency is also measured with dedicated calibration data samples [46].

Several sources of systematic uncertainty are studied. A systematic uncertainty in the

signal yield determination is evaluated by changing the function used in the fit for the nonprompt component, switching from a Bukin function to a Gaussian. The difference in the signal yields obtained with the two fits is taken as a systematic uncertainty. The systematic uncertainty associated to the background determination, which is dominant, is evaluated by using a sideband subtraction technique, instead of the *sPlot* method. The uncertainties in reconstruction, selection and PID efficiencies are evaluated by varying the reweighting procedure by excluding the distributions of the invariant mass of the pK^- and $K^-\pi^+$ combinations. The uncertainties in the branching fractions are accounted for. A summary of the systematic uncertainties is provided in the Supplemental Material [45].

The double-differential cross-sections of prompt Ξ_c^+ production times $\mathcal{B}(\Xi_c^+ \rightarrow pK^-\pi^+)$ in proton-lead collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV are measured as a function of p_{T} integrated over y^* in the region $1.5 < y^* < 4.0$ and $-5.0 < y^* < -2.5$, and as a function of y^* integrated over the p_{T} range between 2.0 and 12.0 GeV/ c . The double-differential cross-sections of prompt Ξ_c^+ production are shown in Fig 1. The data are compared with theoretical predictions [47–49] from the HELAC-Onia method [50, 51] called EPPS16 [52] with three factorisation scale choices. The data agree with the predictions and appear to be best described using the scale $0.5\mu_0$. For the forward and backward regions, the integrated cross-sections are

$$\begin{aligned}\sigma_{\Xi_c^+}^{p\text{Pb}}(2 < p_{\text{T}} < 12 \text{ GeV}/c, 1.5 < y^* < 4.0) &= 9.69 \pm 0.12 \pm 0.26 \pm 4.72 \text{ mb}, \\ \sigma_{\Xi_c^+}^{\text{Pb}p}(2 < p_{\text{T}} < 12 \text{ GeV}/c, -5.0 < y^* < -2.5) &= 8.10 \pm 0.11 \pm 0.72 \pm 3.95 \text{ mb},\end{aligned}$$

where the first uncertainty is statistical, the second is the uncorrelated systematic uncertainty and the third is the systematic uncertainty fully correlated among bins.

The forward-backward ratio R_{FB} , measured as a function of p_{T} , is shown in Fig. 2. The ratio is independent of p_{T} and agrees with the theoretical prediction within one standard deviation. The differential ratio of Ξ_c^+ to Λ_c^+ production is measured as a function of the number of clusters reconstructed in the VELO ($N_{\text{clusters}}^{\text{VELO}}$) and given in the Supplemental Material [45]. The ratios are constant as a function of p_{T} , similarly for the $p\text{Pb}$ and $\text{Pb}p$ data, and the results show no indication of strangeness enhancement.

Since LHCb has already measured the D^0 production cross-section in $p\text{Pb}$ collisions at $\sqrt{s} = 8.16$ TeV [53], it is also possible to compute the Ξ_c^+/D^0 production ratio. The differential ratios of Ξ_c^+ to Λ_c^+ production and Ξ_c^+ to D^0 production are shown in Fig. 3 as a function of p_{T} . Both the Ξ_c^+/Λ_c^+ and Ξ_c^+/D^0 ratios show no significant p_{T} dependence, similarly for the $p\text{Pb}$ and $\text{Pb}p$ data samples. This result provides a strong indication that the same processes govern hadronisation in $p\text{Pb}$ and $\text{Pb}p$ collisions. This is the first time they are measured in this system. The data are compared with EPPS16 nPDF calculation [52], which uses the cross-section measured in pp collisions by ALICE [13] as input for their calculation. The EPPS16 model shows a similar trend, but significantly overestimates the data. The measurements are also compared with results from the PYTHIA 8.3 event generator with a tune that implements colour reconnection (CR) beyond the leading-colour approximation [14] and the computation obtained with EPOS4HQ, the heavy quark extension of the new EPOS4 framework [4]. Both calculations are based on results in pp collisions. The Ξ_c^+/Λ_c^+ cross-section ratio is best described by the EPOS4HQ model within uncertainties, despite showing a different trend, especially at low p_{T} . This behaviour is even more pronounced in the Ξ_c^+/D^0 cross-section ratio. The Ξ_c^+ to D^0 production ratio is also compared with the result of ALICE at $\sqrt{s} = 13$ TeV at $|y| < 0.5$

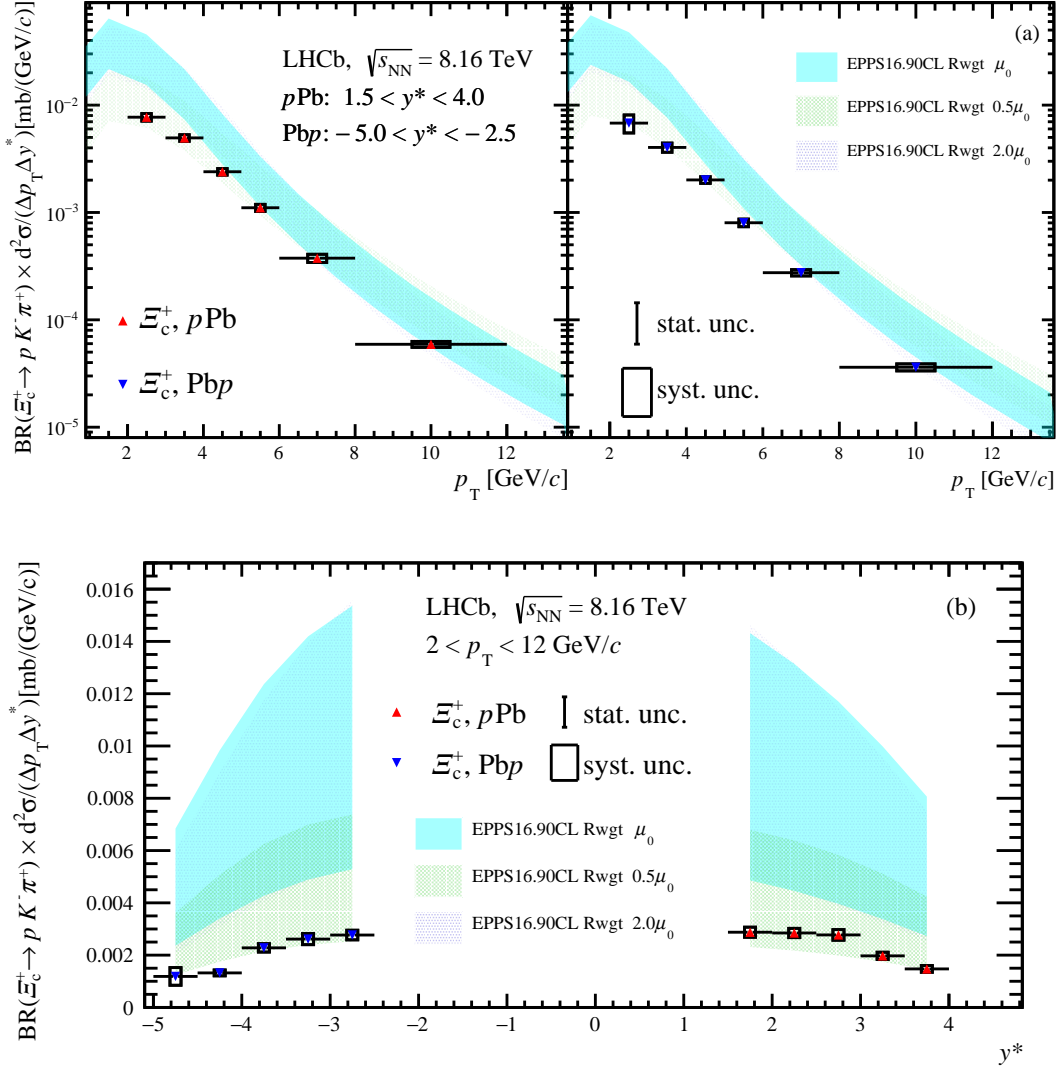


Figure 1: Double-differential cross-section of the prompt Ξ_c^+ baryon times $\mathcal{B}(\Xi_c^+ \rightarrow pK^-\pi^+)$ in proton-lead collisions as a function of (a) p_T and (b) y^* in $p\text{Pb}$ (red triangles) and Pbp (blue triangles) collisions. The error bars represent the statistical uncertainties, while the black squares represent the total systematic uncertainties which include correlations among bins.

in pp collisions [13]. The ALICE result is generally higher, but the two measurements agree within the uncertainties.

In summary, the prompt Ξ_c^+ production cross-section in $p\text{Pb}$ and Pbp collisions at a centre-of-mass energy of $\sqrt{s_{\text{NN}}} = 8.16$ TeV at the LHCb experiment is measured differentially for the first time as a function of p_T and y^* . The cross-section measurement provides new constraints for nPDF calculations, especially at low p_T , where the uncertainty on the factorisation scale is the largest. The forward-backward ratio R_{FB} is measured and found to be well described by nuclear shadowing calculations showing that there are no major final-state effects involved, in contrast to what has been observed in D^0 production studies in the same kinematic range at the same energy [53]. Prompt Ξ_c^+ production is compared to prompt Λ_c^+ production in the same kinematic region and their ratio is found

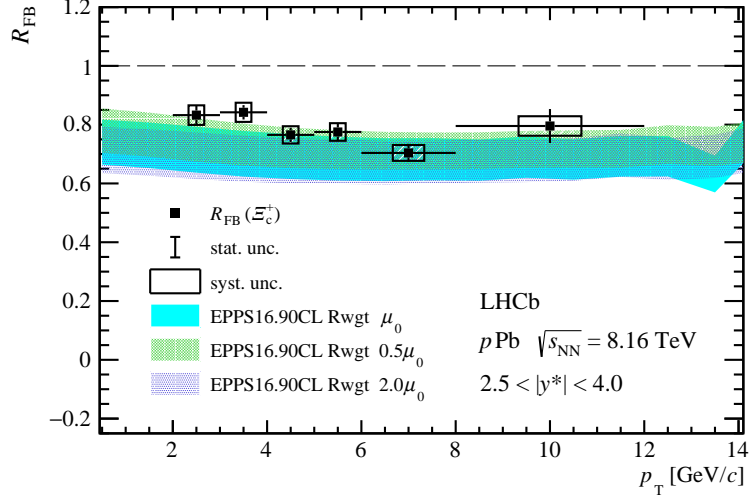


Figure 2: Forward-backward ratio of Ξ_c^+ production as a function of p_T . The error bars represent the statistical uncertainties, while the boxes indicate the systematic uncertainty.

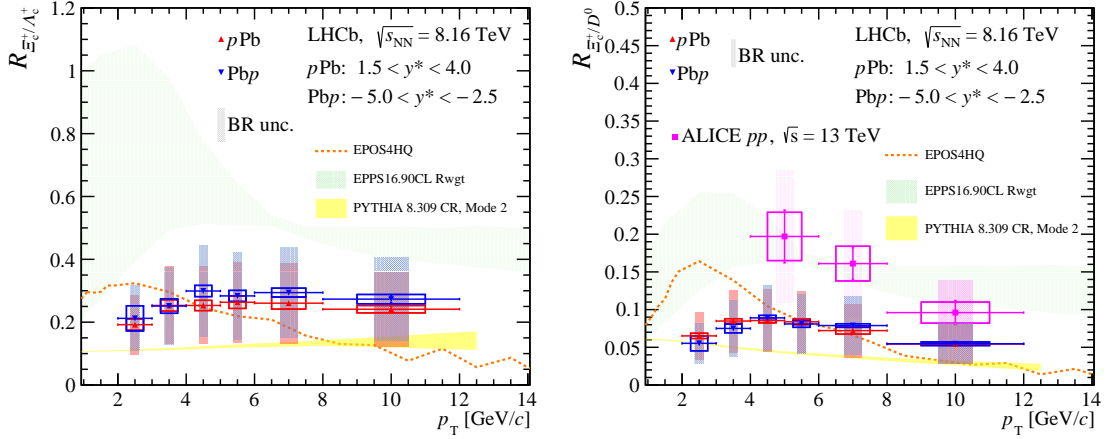


Figure 3: Ratio of (left) prompt Ξ_c^+ to Λ_c^+ production and (right) Ξ_c^+ to D^0 production in the p Pb (red triangles) and Pb p (blue triangles) data samples as a function of p_T . The error bars represent the statistical uncertainties, while the empty rectangles indicate the systematic uncertainty. Shaded rectangles denote the branching ratio uncertainty.

to be constant within the uncertainties as a function of p_T and multiplicity, which is an indication that similar effects govern both Ξ_c^+ and Λ_c^+ production. The ratio of Ξ_c^+ to D^0 production is also measured as a function of p_T . Both ratios are found to be similar in p Pb and Pb p collisions but they show different trends compared to pp theory calculations. Therefore, our results show that hadronisation in p Pb is not well understood and provides clear input for the hadronisation studies in p Pb collisions.

Acknowledgements

We would like to thank to Hua-Sheng Shao, Jiaying Zhao and Joerg Aichelin for providing LHCb-specific theoretical predictions. We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MICINN (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), Polish WLCG (Poland) and NERSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from ARC and ARDC (Australia); Minciencias (Colombia); AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union); A*MIDEX, ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central Universities, and Sci. & Tech. Program of Guangzhou (China); GVA, XuntaGal, GENCAT and Prog. Atracción Talento, CM (Spain); SRC (Sweden); the Leverhulme Trust, the Royal Society and UKRI (United Kingdom).

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



















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




























LHCb collaboration

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