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Letter

Multiplicity dependence of charm baryon and charm meson production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$

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ABSTRACT

Measurements of the production yields of charm baryons (Λ_c^+) and charm mesons (D^0) in proton-lead collisions at a nucleon-nucleon center-of-mass energy of 8.16 TeV are presented. The data were collected in 2016 with the CMS experiment and correspond to an integrated luminosity of 186 nb^{-1}. The Λ_c^+ baryon is reconstructed from the decay channel $\Lambda_c^+ \to K_S^0 p$, while the D^0 meson is reconstructed via $D^0 \to K^-\pi^+$. The Λ_c^+ baryon and D^0 meson yields are extracted in several charged-particle multiplicity classes. No strong multiplicity dependence of the Λ_c^+-to-D^0 yield ratio is observed, unlike the observed strange baryon to strange meson yield ratio of $\Lambda/\overline{\Lambda}$ to K_S^0, which shows a strong multiplicity dependence. This observation indicates different mechanisms for the multiplicity evolution of hadronization processes for charm and strange quarks and provides new constraints to the understanding of heavy flavor production and collectivity in small collision systems.

1. Introduction

The quark-gluon plasma (QGP), a deconfined phase of quarks and gluons, is formed in ultra-relativistic heavy ion collisions. The collective flow motion ("collectivity") of this strongly coupled medium in nucleus-nucleus (AA) collisions has been observed at the CERN LHC [1–4] and the BNL RHIC [5–8]. The observed azimuthal anisotropies of the particles emitted [9–14], such as the "elliptic flow," result from strong interactions between constituents inside the medium that initially has an asymmetric geometrical shape and can be well described by hydrodynamic models [15–17]. Similar observations of a common collective signature for charm mesons [18–20] and bottom mesons [21–23] indicate that heavy quarks may also be strongly coupled to the QGP, even though their interactions with the medium are expected to be much less frequent than for light quarks.

In recent years, unexpected strong collective flow signals were also observed in small systems such as proton-proton (pp) [24–27] and proton-lead (pPb) [28–38] collisions. The elliptic flow for prompt D^0 [19,39] and J/ψ [40,41] mesons in pPb collisions was found to be comparable to that of light-flavor hadrons at a given particle transverse momentum (p_T). On the other hand, no evidence for bottom hadron collective flow has been observed yet in small systems, such as pPb collisions [39,42]. Although effects of final-state partonic rescatterings in a dense medium can successfully explain a large variety of measurements for light quarks (see reviews in Refs. [43,44]), they alone cannot describe the large flow for charm quarks [45]. Meanwhile, calculations based on initial-state effects, such as gluon saturation models, can successfully describe experimental measurements for several charm and bottom mesons [46].

The study of heavy flavor meson and baryon production yields provides a powerful means to further elucidate the origin of heavy flavor collectivity in small systems, as hadronization processes are also influenced by the presence of final-state rescattering effects. The abundant deconfined quarks in the QGP can coalesce into bound states before fragmenting to low-energy hadrons, resulting in a different modification of the yields for baryons and mesons [47,48]. This parton coalescence effect is expected to be stronger with increasing system size and can enhance the baryon-to-meson yield ratio at an intermediate hadron p_T range (e.g., 2–6 GeV) [49,50]. Models in AA collisions incorporating parton coalescence have been able to describe measurements of heavy-flavor hadrons, such as the Λ_c^+-to-D^0 production yield ratio, at both RHIC and the LHC [51–53]. Because of its dependence on final-state effects, the study of this baryon-to-meson enhancement effect may also contribute to our understanding of the origin of collectivity in small systems.

Measurements of the charged-particle multiplicity dependence of the baryon-to-meson ratio for strange particles show an increasing trend from low to high multiplicity in the intermediate hadron p_T range [54],

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which is qualitatively consistent with models including final-state effects. Therefore, an enhancement of charm baryon-to-meson yield ratios should be expected for high multiplicity events, if final state effects are the origin of heavy flavor quark collectivity. For inclusive pp and pPb collisions, models assuming the presence of a QGP [55,56] are in agreement with measurements of Λ_c^+ baryon yields [57–59] when coalescence effects are incorporated. Over the limited range of charged multiplicities in pp collisions, the statistical hadronization model is able to describe the multiplicity dependence of the Λ_c^+-to-D^0 yield ratio as a function of p_T [60,61].

In this Letter, the p_T spectra of the Λ_c^+ and D^0 particles and their ratios are measured in the range of 2–10 GeV in pPb collisions at a nucleon-nucleon center-of-mass energy $\sqrt{s_{NN}} = 8.16$ TeV, for the first time in different multiplicity intervals. Tabulated results are provided in the HEPData record for this analysis [62].

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Hadron forward (HF) calorimeters [63], made of steel and quartz fibers, extend the pseudorapidity ($\eta = -\ln(\tan(\theta/2))$, where the polar angle θ is defined relative to the counterclockwise beam) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [64].

The silicon tracker measures charged particles within the range $|\eta_{lab}| < 2.5$ in the laboratory frame. During the LHC running period when the data used in this Letter were recorded, the silicon tracker consisted of 1440 silicon pixels and 15 148 silicon strip detector modules. For particles of $1 < p_T < 10$ GeV and $|\eta_{lab}| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [65].

The event samples are collected by the CMS experiment with a two-level trigger system [66,67]. At Level-1, events are selected by custom hardware processors, while the high-level trigger (HLT) uses fast versions of the offline software. The pPb data used in this analysis were collected in 2016 at $\sqrt{s_{NN}} = 8.16$ TeV and correspond to an integrated luminosity of $186.0 \pm 6.5\,\text{nb}^{-1}$ [68]. The beam energies were 6.5 TeV for the protons and 2.56 TeV per nucleon for the lead nuclei. Because of the asymmetric beam conditions, the midrapidity range of $|y_{lab}| < 1$, which is used for particle selections, corresponds to the rapidity range $-1.46 < y_{cm} < 0.54$ in the nucleon-nucleon center-of-mass frame, with positive rapidity corresponding to the proton beam direction.

The event reconstruction, event selections, and trigger requirements for minimum bias and high-multiplicity events are identical to those described in Refs. [27,69,70]. The minimum bias (MB) 8.16 TeV pPb events are triggered by requiring energy deposits above 1 GeV in at least one of the two HF calorimeters and the presence of at least one track with $p_T > 0.4$ GeV reconstructed using hits from the pixel tracker only. To collect a large sample of high-multiplicity pPb collisions, a dedicated trigger is implemented. At Level-1, the total number of ECAL+HCAL towers having deposited energy above a threshold of 0.5 GeV in transverse energy (E_T) is required to be greater than 150. As part of the HLT trigger, the track reconstruction is performed online with the identical reconstruction algorithm used offline [65]. For each event selected at Level-1, the reconstructed vertex with the highest number of associated tracks is selected as the primary vertex (PV) at the HLT. The number of online tracks with $|\eta| < 2.4$, $p_T > 0.4$ GeV, and a distance of closest approach less than 0.12 cm along the beam axis to the PV is determined for each event and is required to exceed 185. The events are required to contain a PV within 15 cm of the nominal interaction point along the beam axis and 0.2 cm in the transverse direction. The integrated luminosity sampled by the minimum bias (high-multiplicity) trigger is 4.22 (97.8) nb^{-1}.

Table 1
The average multiplicity before (and after) corrections, $\langle N_{trk}^{offline} \rangle$ ($\langle N_{trk}^{corrected} \rangle$) with track $p_T > 0.4$ GeV and $|\eta_{lab}| < 2.4$ in each multiplicity interval. The uncertainties reported for $\langle N_{trk}^{corrected} \rangle$ are systematic uncertainties, as the statistical uncertainties have been found to be negligible.

Multiplicity interval ($N_{trk}^{offline}$)	$\langle N_{trk}^{offline} \rangle$	$\langle N_{trk}^{corrected} \rangle$
[2, 35)	16.4	20.0 ± 0.8
[35, 60)	46.3	56.4 ± 2.3
[60, 90)	73.0	88.7 ± 3.5
[90, 120)	102	124 ± 5
[120, 185)	140	170 ± 7
[185, 250)	202	245 ± 10

3. Data analysis

Similar to previous measurements [28,31,34,35], hadronic events are selected by requiring the presence of at least one energy deposit greater than 3 GeV in each of the two HF calorimeters. The pPb data are analyzed in several charged-particle multiplicity classes, and defined according to the number of selected offline tracks ($N_{trk}^{offline}$) with $|\eta_{lab}| < 2.4$ and $p_T > 0.4$ GeV that originate from the PV [27,65]. If more than one vertex is found in an event, the vertex associated with the highest number of offline tracks is considered as the PV. During the data taking, the average number of collisions per bunch crossing (pileup) varied from 0.10 to 0.25. The average number of tracks in each $N_{trk}^{offline}$ range before and after correcting for inefficiencies and misidentification rates in the tracking system is denoted as $\langle N_{trk}^{offline} \rangle$ and $\langle N_{trk}^{corrected} \rangle$, respectively. The statistical uncertainty in $\langle N_{trk}^{corrected} \rangle$ has been found to be negligible, while the systematic uncertainty is 4% resulting from the uncertainty of tracking efficiency estimated based on simulated events. The $\langle N_{trk}^{offline} \rangle$ and $\langle N_{trk}^{corrected} \rangle$ values in each $N_{trk}^{offline}$ range are summarized in Table 1; for minimum bias pPb events, these values are 50 and 59.5 ± 0.5, respectively. To optimize the signal significance and efficiency, a sample of simulated signal events is generated using hard processes in PYTHIA 8.209 [71], using the CUETP8M1 tune [72]. These signal events are embedded into pPb events generated with the EPOS LHC model [73]. The response of the CMS detector for generated events is simulated using the GEANT4 [74] toolkit. The decay kinematics for Λ_c^+ and D^0 particles are simulated using EVTGEN [75].

The Λ_c^+ baryons are reconstructed using the decay channel $\Lambda_c^+ \to K_S^0 p$ with the branching fraction of $(1.59 \pm 0.07)\%$ [76], where K_S^0 mesons are reconstructed via the $K_S^0 \to \pi^+\pi^-$ decays with the branching fraction of $(69.20 \pm 0.05)\%$ [76]. Throughout this Letter, charge-conjugate modes are implied unless explicitly noted otherwise. The decay vertex for each K_S^0 meson is reconstructed by fitting a common vertex with two oppositely charged particles inside the CMS tracking detector using a Kalman filter. Selections based on topological information are also applied to optimize the K_S^0 signal yield significance (over the non-signal hypothesis) of these signals, following the same procedures as Ref. [19]. The invariant mass of each K_S^0 candidate ($M_{\pi^+\pi^-}$) is required to be within $|M_{\pi^+\pi^-} - M_{K_S^0}| < 0.02$ GeV, where $M_{K_S^0}$ is the K_S^0 meson mass [76]. The secondary decay vertices of the Λ_c^+ baryon are reconstructed by combining a K_S^0 candidate with another charged track in the event. For the Λ_c^+ reconstruction, each K_S^0 candidate is treated as a particle with its kinematic parameters and covariance matrix taken from the K_S^0 vertex fit. In this step, the K_S^0 mass is fixed to the nominal PDG value [76], rather than using the reconstructed $\pi^+\pi^-$ invariant mass. This improves the mass resolution of the Λ_c^+ candidate. The Λ_c^+ candidates (including signals and backgrounds) with invariant mass falling within $|M_{K^0_S p} - M_{\Lambda_c^+}| < 0.2$ GeV, are considered in this analysis, where $M_{\Lambda_c^+}$ is the mass of the Λ_c^+ baryon [76]. A multilayer perceptron (MLP) is trained with the Toolkit for Multivariate Data Analysis (TMVA) package [77] using simulated signal events to suppress the combinatorial background. The training variables are: the candidate proton track momentum and η; the energy loss of the candidate proton track per unit length inside the tracker normalized by the expected mean value for the proton at the corresponding momentum; and the cosine of the pointing angle defined as the angle in three dimensions between the vector connecting the PV with the secondary decay vertex of Λ_c^+ baryons and the momentum of the Λ_c^+ candidate. The energy loss per unit length for each track is calculated with the "generalized mean" of grade–2, as described in Ref. [78].

Events populating the sideband region, defined as $0.06 < |M_{K^0_S p} - M_{\Lambda_c^+}| < 0.11$ GeV that is at least four standard deviations away from the peak of the signal distribution, are used as background samples in the TMVA training. The optimization of the Λ_c^+ signal significance is performed separately for event classes $2 \le N_{trk}^{offline} < 185$ (from the minimum bias trigger) and $185 \le N_{trk}^{offline} < 250$ (from the high-multiplicity trigger). The maximum statistical significance of these signals after optimization is much larger than 5 standard deviations.

The D^0 candidates are reconstructed using the decay channel $D^0 \to K^-\pi^+$ with the branching fraction of $(3.947 \pm 0.030)\%$ [76]. The boosted decision tree (BDT) method is used to reject combinatorial backgrounds and to optimize the D^0 signal yield significance. Details about the reconstruction, candidate selection, and correction are reported in Ref. [39].

The Λ_c^+ candidate mass spectra are modeled by a double Gaussian function with a common mean and different widths for the signal contribution and a third-order Chebyshev polynomial for the background. The widths of the signal distributions are constrained to those found in simulation to improve the fit stability. Fig. 1 shows the mass spectra of the Λ_c^+ candidates for the multiplicity ranges of $2 \le N_{trk}^{offline} < 35$ and $185 \le N_{trk}^{offline} < 250$. The invariant mass of D^0 candidates is modeled by several components: a double Gaussian function with a common mean for the D^0 signal; an additional Gaussian function to describe the invariant mass shape of D^0 candidates with swapped pion and kaon tracks ("swapped component"); two Crystal Ball (CB) functions [79] to describe the processes $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$; and a third-order polynomial to model the combinatorial background. Examples of fits to the D^0 invariant mass are shown in Ref. [39].

The differential yields for Λ_c^+ and D^0 particles are computed using

$$\frac{dN}{dp_T} = \frac{f^{prompt} N^{sig}}{2\alpha\epsilon\Delta p_T}\frac{1}{\mathcal{B}}, \quad (1)$$

where N^{sig} is the raw yield from the fit to the invariant mass in each p_T and multiplicity bin, α is the acceptance, ϵ is the reconstruction efficiency, Δp_T is the width of p_T interval, $\mathcal{B}$ is the branching fraction, and f^{prompt} is the corresponding prompt component fraction for Λ_c^+ and D^0 hadrons, respectively. Prompt mesons are those directly produced in pPb collisions or from strong decays of excited charm hadrons, rather than from decays of bottom hadrons. The factor of two in the denominator takes into account the inclusion of both charge-conjugate particles in the raw yield. The acceptance and reconstruction efficiencies are obtained from simulated events in bins of p_T, where the resolution is much narrower than the bin width.

The fraction f^{prompt} for Λ_c^+ events is estimated following a procedure similar to the one described in Ref. [57]. The estimation of nonprompt Λ_c^+ contributions from bottom hadron decays considers inputs including the Λ_b^0 and B production cross sections and the inclusive decay branching fractions of Λ_b^0 and B (B^+, B^0) mesons to Λ_c^+, i.e., $\Lambda_b^0 \to \Lambda_c^+ + X$ and $B \to \Lambda_c^+ + X$. The Λ_b^0 production cross section is derived from that for B meson production, computed using the "fixed order next-to-leading logarithmic" (FONLL) perturbative quantum chromodynamics calculation [80] and rescaled according to the fragmentation fractions measured by the LHCb Collaboration [81]. It is then multiplied by $A = 208$, the atomic number of the lead nucleus, to map it to pPb collisions. Modifications due to nuclear effects are allowed at the level of 25% in the systematic uncertainties, as discussed in Section 4. The $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ X)$ value is set to 83%, as in the EVTGEN package, and it includes the contributions from unobserved decay channels [82]. The corresponding branching fractions for the B mesons are set to 5% by summing over all channels reported in Ref. [76]. The correlations between the kinematic distributions of b hadrons and Λ_c^+ particles are simulated using EVTGEN. The cross section of nonprompt Λ_c^+ baryon production is further corrected for the acceptance and reconstruction efficiency. The fraction of feed-down contribution is assumed to be multiplicity independent in the range $2 \le N_{trk}^{offline} < 185$, as the same candidate selection is applied in all the multiplicity ranges. A summary of the nonprompt Λ_c^+ baryon fraction (1-f^{prompt}), which has little dependence on p_T and $N_{trk}^{offline}$ within uncertainties, is given in Table 2.

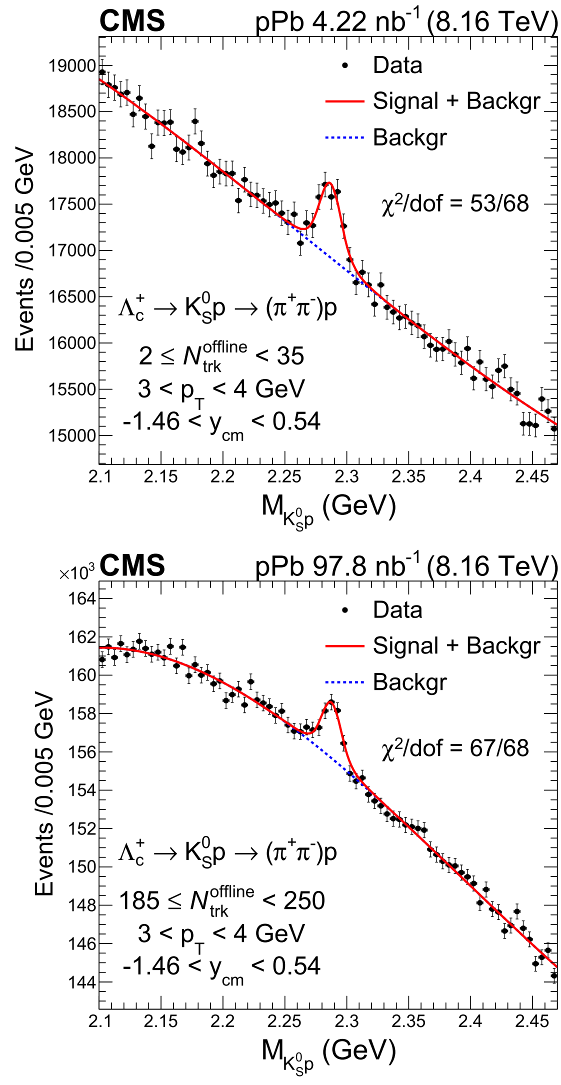

Fig. 1. The fitted mass spectra, along with the goodness-of-fit values, for Λ_c^+ candidates with $3 < p_T < 4$ GeV and $-1.46 < y_{cm} < 0.54$. The spectrum for the multiplicity class with $2 \le N_{trk}^{offline} < 35$ is shown in the upper plot, and the spectrum for $185 \le N_{trk}^{offline} < 250$ is shown in the lower plot.

The f^{prompt} fraction for D^0 mesons is obtained using a template fit method. The prompt and nonprompt D^0 mesons can be distinguished based on the distributions of their distance of closest approach (DCA) with respect to the PV of the event. A two-component fit with DCA tem-

Table 2
Summary table for the fraction of nonprompt Λ_c^+ baryons (1-f^{prompt}) relative to inclusive Λ_c^+ baryons. The fraction is evaluated in different multiplicity ranges. Details regarding the systematic uncertainties are described in Section 4.

p_T (GeV)	$2 \leq N_{\text{trk}}^{\text{offline}} < 185$ (%)	$185 \leq N_{\text{trk}}^{\text{offline}} < 250$ (%)
2–3	$6.8^{+11}_{-6.8}$	—
3–4	$4.1^{+5.8}_{-4.1}$	$4.3^{+6.0}_{-4.3}$
4–5	$3.3^{+5.5}_{-3.3}$	$3.4^{+5.7}_{-3.4}$
5–6	$3.6^{+2.9}_{-2.9}$	$3.6^{+3.0}_{-3.0}$
6–8	$3.5^{+3.8}_{-3.5}$	$3.1^{+3.4}_{-3.1}$
8–10	$3.9^{+5.5}_{-3.9}$	$4.3^{+6.2}_{-4.3}$

plates from simulated prompt and nonprompt D^0 samples is performed to the DCA distribution in data. Examples of the template fit to DCA distributions for D^0 mesons can be found in Ref. [39].

4. Systematic uncertainties

The candidate selection uncertainty is estimated by varying the MLP or BDT classifier cut over a wide range, which yields a relative uncertainty of 2–6% for Λ_c^+ baryons and 1–5% for D^0 mesons, respectively, depending on the $N_{\text{trk}}^{\text{offline}}$ and charm hadron p_T. The uncertainty of the fit procedure is estimated by changing the signal shape from a double Gaussian to a Gaussian+CB function for the Λ_c^+ baryon, and via changing the background function to a second- and fourth-order polynomial for both Λ_c^+ and D^0 particles. These variations yield a relative uncertainty of 6–28% for Λ_c^+ baryons and less than 2% for D^0 mesons.

The uncertainty in feed-down from b hadrons for Λ_c^+ is estimated from the following components. The associated systematic uncertainty from FONLL calculations is evaluated by varying its central values by its uncertainties [80]. Another variation is performed by comparing the FONLL calculations with PYTHIA. The value of the Pb-normalized FONLL calculations is also varied by 25% to account for potential nuclear effects. No significant nuclear modifications to the b-hadrons production cross sections in pPb collisions are observed within ±25% [83]. The uncertainty from the LHCb fragmentation fraction measurements is also considered [81]. The assumption that the feed-down is uniform across multiplicities is studied using D^0 mesons and assumed to have similar behavior for Λ_c^+ baryons, because both nonprompt Λ_c^+ and D^0 production originates from b hadrons. The maximum of the difference of f^{prompt} for D^0 mesons between different multiplicity classes is taken as an estimate for the systematic uncertainty in the Λ_c^+ measurements. The sum in quadrature of these sources yields a total relative uncertainty of 4–12% for the feed-down estimation. The uncertainty related to template fits in DCA for D^0 mesons is estimated by varying the DCA resolution of simulated samples to explore the discrepancy between simulated samples and data. This source yields an uncertainty of less than 15%.

The systematic uncertainty from the tracking efficiency is 2.3% per track [84], which is propagated to 7% for Λ_c^+ baryon yields and 5% for D^0 meson yields since the former are reconstructed from three tracks and the latter are from two. The uncertainty related to trigger efficiency is found to be negligible, as the main inefficiency affects mostly very low multiplicity events while those containing a heavy flavor hadron production are strongly biased toward higher average multiplicity within each class. The pileup effects are studied by requiring different minimum distances between multiple reconstructed PVs according to the final-state track multiplicity. The systematic uncertainty due to pileup effects turns out to be 3–6% (from low to high $N_{\text{trk}}^{\text{offline}}$) for Λ_c^+ baryons and < 1% for D^0 mesons. The total systematic uncertainty of the production yields is calculated by assuming all sources are independent and adding them in quadrature.

The relative systematic uncertainty for the yield ratio of Λ_c^+-to-D^0 is computed by adding in quadrature the relative Λ_c^+ and D^0 yield uncertainties including the effects of candidate selections, fit procedures,

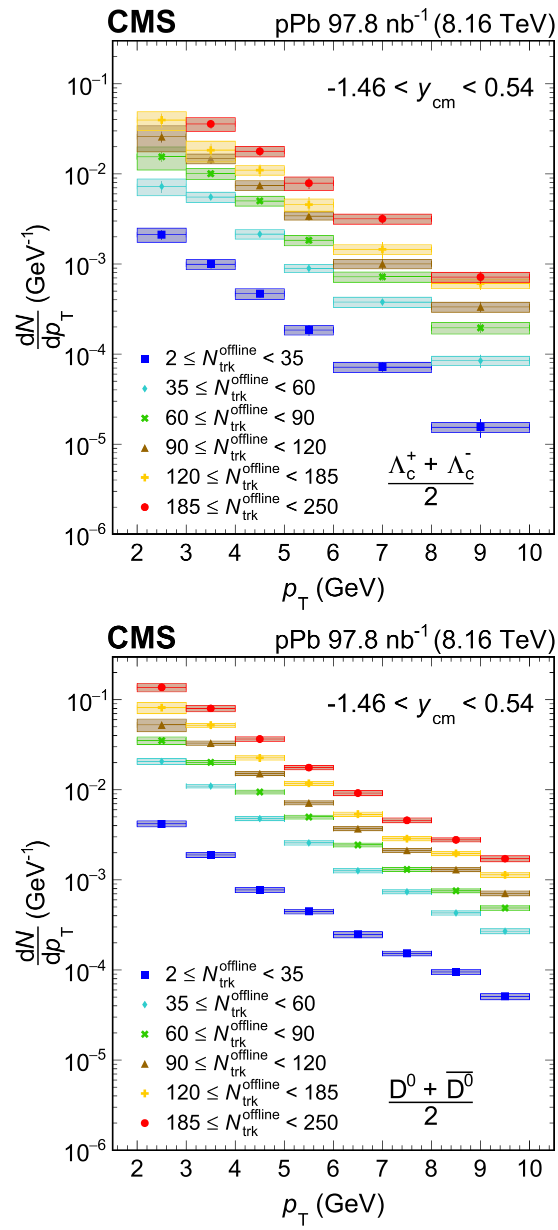

Fig. 2. Transverse momentum spectra for Λ_c^+ baryons (upper) and D^0 mesons (lower) with $-1.46 < y_{\text{cm}} < 0.54$ in different multiplicity classes. The vertical bars show the statistical uncertainties while the shaded areas represent the systematic uncertainties.

b hadron feed-down, and branching fractions. The uncertainties from tracking efficiency and pileup effects are taken to be fully correlated between the D^0 and Λ_c^+ samples, resulting in uncertainties of 2.3% and 2–4% for the Λ_c^+-to-D^0 ratio, respectively.

A summary of systematic uncertainties in measurements of the Λ_c^+ and D^0 differential yields can be found in Table 3.

5. Results

The p_T spectra for Λ_c^+ and D^0 hadrons in each multiplicity class are shown in Fig. 2. The production of charm hadron yield per event increases with multiplicity. The p_T spectra follow approximately an exponential falling trend for all multiplicity classes.

The corresponding Λ_c^+-to-D^0 ratios are presented in Fig. 3 for three multiplicity classes. The Λ_c^+-to-D^0 ratio tends to decrease with p_T, both for low- and high-multiplicity events. The ratios in Fig. 3 are also consistent with those obtained in inclusive pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Table 3
Summary of relative uncertainties in the differential yields.

Source	Λ_c^+ (%)	D^0 (%)
Selections	2–6	1–5
Fit	6–28	<2
b feed-down	3–11	<15
Tracking efficiency	7	5
Pileup effects	3–6	<1
Branching fraction	5	1
Total	10–32	5–16

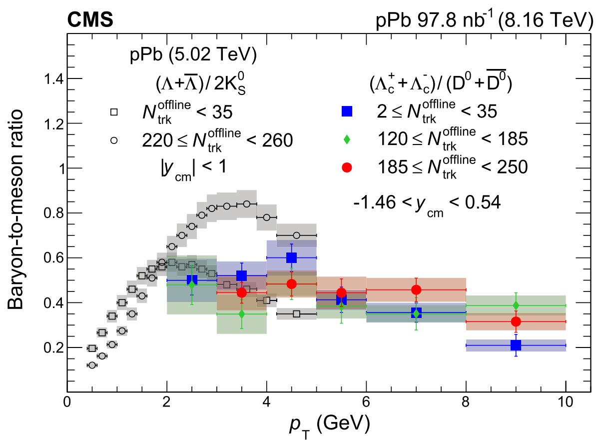

Fig. 3. Ratio of Λ_c^+ baryons to D^0 mesons production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with $2 \le N_{trk}^{offline} < 35$, $120 \le N_{trk}^{offline} < 185$ and $185 \le N_{trk}^{offline} < 250$. The vertical bars show the statistical uncertainties while the shaded areas represent the systematic uncertainties. The gray markers are for Λ baryon to (two times) K_S^0 meson production at $\sqrt{s_{NN}} = 5.02$ TeV from Ref. [54].

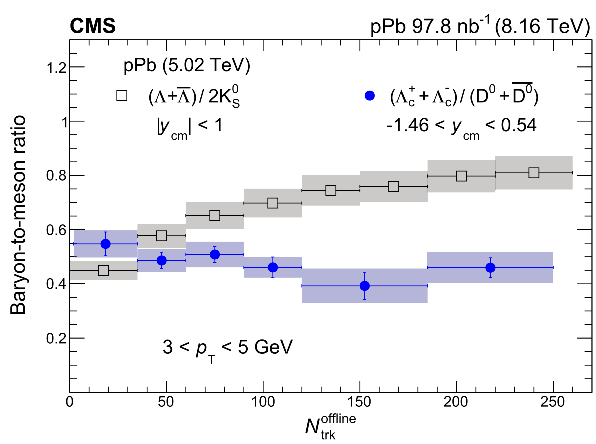

Fig. 4. Ratio of Λ_c^+ baryon to D^0 meson production with $-1.46 < y_{cm} < 0.54$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV as a function of $N_{trk}^{offline}$. The vertical bars show the statistical uncertainties while the shaded areas represent the systematic uncertainties. The ratio of Λ baryon to (two times) K_S^0 meson production at $\sqrt{s_{NN}} = 5.02$ TeV obtained from data in Ref. [54] is also shown for comparisons, denoted by gray markers.

reported in Refs. [57,59]. No strong multiplicity dependence is observed within one standard deviation, in contrast to the enhanced baryon-to-meson ratio for strange hadrons as the multiplicity increases [54].

To further investigate the system size dependence, the charm baryon-to-meson ratio is also plotted as a function of $N_{trk}^{offline}$ in Fig. 4. In contrast to what is observed in the strange-quark sector, the charm baryon-to-meson ratio is approximately constant over a large range of multiplicity. This may indicate a possible mass dependence for the particle hadronization mechanism. If a coalescence process is present, it may happen earlier for charm quarks than for light quarks during the system evolution.

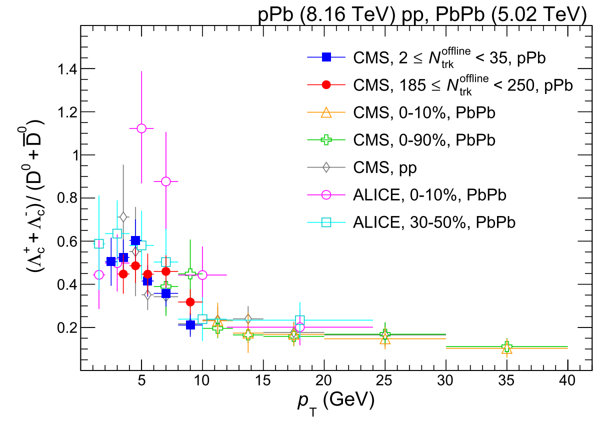

Fig. 5. Comparison between the Λ_c^+-to-D^0 ratio as a function of p_T in pp, pPb, and PbPb (different centrality ranges) collisions at the nucleon-nucleon center-of-mass energies of 5.02, 8.16, and 5.02 TeV, respectively [53,87]. The ratio is measured with the rapidity ranges $-1.46 < y_{cm} < 0.54$ in pPb collisions and $|y_{cm}| < 1$ in pp and PbPb collisions by the CMS Collaboration [87] and $|y_{cm}| < 0.5$ by the ALICE Collaboration [53]. The vertical bars indicate the uncertainties. For pPb, the uncertainty is the quadratic sum of statistical and systematic uncertainties; for pp and PbPb, the uncertainties are as reported in Ref. [53] and [87], respectively.

The observed independence of the Λ_c^+-to-D^0 ratio on the multiplicity might indicate a difference between heavy and light quarks, even though these particles show similar elliptic flow signals as a function of multiplicity [19,41]. In models of QGP formation, charm quarks are expected to experience kinetic propagation inside the liquid QGP [50,85], while light quarks are in general thermalized in the hot QGP. The larger mean free path of heavy quarks compared with light quarks in pPb collisions may lead to less pronounced effects from the dense medium. On the other hand, a model incorporating an initial-state gluon saturation scenario without QGP production shows agreement with the elliptic flow of D^0 mesons in pPb collisions [46,86].

The charm baryon-to-meson ratio as a function of p_T in pPb collisions at 8.16 TeV is also compared with that in pp and PbPb collisions at 5.02 TeV [53,87] in Fig. 5. The results in the range $2 < p_T < 10$ GeV are consistent with inclusive events in pp collisions and mid-central (e.g., 30–50% centrality) PbPb collisions. The decreasing trend with p_T for the charm baryon-to-meson ratio is also observed in these systems. Further studies of the multiplicity dependence of this ratio in pPb collisions for the very high-p_T regime are crucial to find out whether this convergence is universal across different colliding systems and event activities.

6. Summary

The first measurements of Λ_c^+ baryon and D^0 meson yields, as well as their yield ratios, as a function of the charged-particle multiplicity in proton-lead (pPb) collisions are presented. At a nucleon-nucleon center-of-mass energy of 8.16 TeV, the Λ_c^+ baryon is reconstructed using the decay channel $\Lambda_c^+ \to K_S^0 p$, while the D^0 meson is reconstructed from $D^0 \to K^-\pi^+$. The Λ_c^+ and D^0 production yields, and the Λ_c^+-to-D^0 yield ratio are studied as a function of transverse momentum and charged-particle multiplicity. No strong multiplicity dependence is observed within the experimental uncertainties. The absence of any significant multiplicity dependence of the yield ratio differs strikingly from that for strange hadrons, which is observed to increase with multiplicity. The difference between these results for charm quarks and those for strange quarks might indicate that the conjectured coalescence processes of heavy quarks happen earlier than those of strange quarks.

Declaration of competing interest

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Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

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