Letter

Observation of strangeness enhancement with charmed mesons in high-multiplicity pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV

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The production of prompt D_s^+ and D^+ mesons is measured by the LHCb experiment in proton-lead (pPb) collisions in both the forward ($1.5 < y^* < 4.0$) and backward ($-5.0 < y^* < -2.5$) rapidity regions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\rm NN}} = 8.16$ TeV. The nuclear modification factors of both D_s^+ and D^+ mesons are determined as a function of transverse momentum, $p_{\rm T}$, and rapidity. In addition, the D_s^+ to D^+ cross section ratio is measured as a function of the primary charged particle multiplicity in the event. An enhanced D_s^+ to D^+ production in high-multiplicity events is observed for the whole measured $p_{\rm T}$ range, in particular at low $p_{\rm T}$ and backward rapidity, where the significance exceeds six standard deviations. This constitutes the first observation of strangeness enhancement in charm quark hadronization in high-multiplicity pPb collisions. The results are also qualitatively consistent with the presence of quark coalescence as an additional charm quark hadronization mechanism in high-multiplicity proton-lead collisions.

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At hadron colliders, charm quarks are mainly produced by hard parton-parton interactions in the initial stages of the collisions, which are well described by perturbative quantum chromodynamics calculations. These calculations are based on the factorization theorem, according to which the charmed hadron cross sections are dependent on the parton distribution functions (PDFs) of the incoming nucleons, the hard parton-parton scattering cross section, and the fragmentation functions [1,2].

In proton-lead collisions, various effects could modify the charmed hadron cross sections compared to pp collisions. In the initial state, the charmed hadron production can be affected by the modification of the parton distribution functions of bound nucleons (nPDFs) [3,4] compared to those of free nucleons. Furthermore, the increased gluon density at small momentum fraction x leads to nonperturbative features, even if the coupling constant is weak. The color-glass condensate (CGC) effective theory [5,6] provides an appropriate theoretical framework in this regime. A recent measurement from the LHCb experiment has shown a discrepancy with the theoretical calculations based on nPDFs [7]. In the final state, the fragmentation functions are typically parametrized based on measurements performed in e^+e^- or ep collisions, assuming that the hadronization of charm quarks to charmed hadrons is a universal process independent of the colliding system [8]. A recent measurement from the ALICE experiment has shown that charm quark hadronization differs between e^+e^- and pp collisions [9,10]. This result suggests the existence of other hadronization mechanisms beyond fragmentation. An alternative mechanism is quark coalescence [11–14], where charm quarks recombine with other quarks to form charmed hadrons. This mechanism requires that multiple quarks overlap in velocity-position space. As a result, the fraction of charmed hadrons produced by coalescence is expected to be larger when the number of quarks produced in the collision is large, for example in relativistic heavy-ion collisions where quark-gluon plasma (QGP) is formed [15,16]. This mechanism is also expected to be more prominent at relatively low transverse momentum, $p_{\rm T}$, as most quarks or particles are produced in that kinematic region.

Relativistic heavy-ion collisions are often accompanied by strangeness enhancement, which was originally considered as a signature of QGP [17]. The enhanced strangeness production [18,19] and the coalescence mechanism result in an increased yield of strange charmed mesons relative to nonstrange charmed mesons compared to pp collisions [20,21]. Additionally, the ALICE collaboration observed the production enhancement of strange light hadrons in both high-multiplicity pp [22] and pPb [23,24] collisions. Although the origin of the strangeness enhancement in "small" systems (proton-proton or proton-nucleus collisions) is still under debate [25,26], it may

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indicate a common underlying physics mechanism which gradually compensates the strangeness suppression in fragmentation. If the coalescence mechanism contributes to the charm quark hadronization in small systems, the production rates of D_s^+ mesons ($c\bar{s}$) relative to D^+ mesons ($c\bar{d}$) could also increase with the event multiplicity.

This Letter reports LHCb measurements of the prompt $D_{(s)}^+$ (D_s^+ and D^+) differential production cross sections, of their nuclear modification factors and forward-backward cross section ratio in pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV. Additionally, the cross section ratio, $\sigma_{D_s^+}/\sigma_{D^+}$, as a function of the primary charged particle multiplicity of the events is reported.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [27,28]. The present measurement covers the forward rapidity range of $1.5 < y^* < 4.0$ when the proton beam points towards the LHCb arm, and the backward rapidity range of $-5.0 < y^* < -2.5$ when the lead beam does. Here, y^* is the rapidity in the nucleon-nucleon center-of-mass frame. The center-of-mass frame does not coincide with the laboratory frame due to the asymmetry of the colliding beam energies, with a constant boost of $y_{\bf lab} - y^* = 0.5\log(A/Z) = 0.465$ in the direction of the proton beam, where $A = 208$ is the lead nucleus mass number and $Z = 82$ is the lead nucleus atomic number. The corresponding integrated luminosity for the forward (backward) rapidity data sample is 12.18 ± 0.32 nb^{-1} (18.57 ± 0.46 nb^{-1}).

Simulation is used to model the effects of detector acceptance and selection requirements. The $D_{(s)}^+$ mesons are generated using PYTHIA 8 [29] and embedded into minimum-bias (MB) pPb events using the EPOS generator [30], calibrated with LHC data [31]. The decays of unstable particles are described by EVTGEN [32], in which final-state radiation is generated using PHOTOS [33]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT8 toolkit [34] as described in Ref. [35]. The simulated $D_{(s)}^+$ event multiplicity distribution is weighted to match the background-subtracted distribution that is extracted from data using the *sPlot* method [36].

The double-differential cross section in a given ($p_{\rm T}$, y^*) interval is defined as

$$\frac{{\rm d}^2\sigma_{p{\rm Pb}}}{{\rm d}p_{\rm T}{\rm d}y^*} = \frac{N}{\mathcal{L}\times\epsilon^{\rm acc}\times\epsilon^{\rm trig}\times\epsilon^{\rm PID}\times\epsilon^{\rm rec\&sel}\times\mathcal{B}\times\Delta p_{\rm T}\times\Delta y^*}, \quad (1)$$

where N is the observed number of prompt $D_{(s)}^+$ and $D_{(s)}^-$ mesons, $\mathcal{L}$ the integrated luminosity, $\mathcal{B}$ the branching fraction of the corresponding $D_{(s)}^+$ meson decay, $\epsilon^{\rm acc}$, $\epsilon^{\rm trig}$, $\epsilon^{\rm PID}$, $\epsilon^{\rm rec\&sel}$ are the LHCb acceptance, trigger, particle identification (PID), reconstruction and selection efficiencies, respectively, and $\Delta p_{\rm T}$ and Δy^* are the $p_{\rm T}$ and y^* interval widths. The $D_{(s)}^+$ mesons are reconstructed through the $D^+ \to K^-\pi^+\pi^+$ and $D_s^+ \to K^-K^+\pi^+$ decay channels, where the mass of the K^+K^- pair is required to be within 20 MeV$/c^2$ of the known mass of the $\phi(1020)$ meson. The corresponding branching fractions are $\mathcal{B} = (2.24 \pm 0.13)\%$ for the $D_s^+ \to K^-K^+\pi^+$ decay [37], and $\mathcal{B} = (9.38 \pm 0.16\%)$ for the $D^+ \to K^-\pi^+\pi^+$ decay [38].

The selection criteria applied to $D_{(s)}^+$ candidates are similar to those used in the recent D^0 production measurements in pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV [7].

The sample of $D_{(s)}^+$ candidates includes $D_{(s)}^+$ mesons originating from the collision point and from the decay of b hadrons. These categories are referred to as "prompt" and "from-b," respectively. The inclusive signal yield is determined using an extended unbinned maximum-likelihood fit to the invariant-mass distributions of the $K^-K^+\pi^+$ or $K^-\pi^+\pi^+$ combinations. The invariant mass of the signal is described by the sum of a Crystal Ball function [39] and a Gaussian function, where both functions share a common mean, while the background shape is described by a linear function. The prompt signal yield is determined by fitting the distribution of $\log_{10}(\chi^2_{\rm IP})$ of the candidates, where $\chi^2_{\rm IP}$ is defined as the difference in the vertex-fit χ^2 of a given primary vertex (PV) reconstructed with and without the candidate under consideration. Combinatorial background in the $\log_{10}(\chi^2_{\rm IP})$ distribution is subtracted using the *sPlot* method with the charm meson invariant mass as discriminating variable. The shapes of the $\log_{10}(\chi^2_{\rm IP})$ distributions corresponding to the prompt and from-b components are described by Bukin functions [40]. The parameters of the function describing the from-b component are fixed from simulation, and the parameters describing the prompt component are allowed to float. Typical invariant mass and $\log_{10}(\chi^2_{\rm IP})$ distributions are shown in the Supplemental Material [41].

The LHCb acceptance, trigger, reconstruction, and selection efficiencies are evaluated with pPb simulated samples. The track reconstruction efficiency is calibrated with MB $J/\psi \to \mu^+\mu^-$ and $K^0_{\rm S} \to \pi^+\pi^-$ samples, using the tag-and-probe approach of Ref. [42]. The PID efficiencies are estimated using a tag-and-probe method [43,44].

The various sources of systematic uncertainties considered in this measurement are listed in Table I. The uncertainty from the invariant mass fit is determined by describing signal and background shapes with alternative models [45]. For the estimation of the uncertainty associated to the $\log_{10}(\chi^2_{\rm IP})$ fit, the data are fitted again with different models and after varying any fixed parameters to evaluate the change in signal yield. The uncertainties on the tracking and PID calibration are dominated by the limited size of calibration samples. The uncertainty associated to the simulation multiplicity correction is estimated by weighting simulated events using different multiplicity variables. The larger uncertainty from multiplicity

TABLE I. Systematic uncertainties on the measured double-differential cross section. Each range indicates the minimum and the maximum value across all kinematic intervals. The uncertainties due to the mass and $\log_{10}(\chi^2_{\mathrm{IP}})$ fits are uncorrelated across the intervals. The other sources of uncertainty are 100% correlated between the different intervals.

Uncertainty source	Forward [%]	Backward [%]
Mass fit	0.1–6.1	0.1–9.6
$\log_{10}(\chi^2_{\mathrm{IP}})$ fit	0.1–22.2	0.1–17.3
Tracking calibration	0.9–3.6	1.4–9.6
PID calibration	1.2–14.0	1.4–8.9
Multiplicity correction	0.5–3.5	4.9–11.3
Trigger efficiency	0.0–1.6	0.0–1.5
Luminosity	2.6	2.5
Branching fraction D_s^+	5.8	5.8
Branching fraction D^+	1.7	1.7

corrections in the backward region primarily stems from a worse agreement between simulation and data in that region. For the trigger efficiency, the difference between the efficiencies derived from simulation and from collision data [46] are considered as a systematic uncertainty. The uncertainties associated to the luminosity, the branching fractions and the simulated samples size are also included.

The double-differential cross sections for prompt D_s^+ (D^+) mesons are measured in the p_{T} range $1 < p_{\mathrm{T}} < 13$ GeV/c ($1 < p_{\mathrm{T}} < 14$ GeV/c) and the rapidity ranges $1.5 < y^* < 4.0$ and $-5.0 < y^* < -2.5$ for the forward and backward rapidity regions, respectively. The results and numerical values are given in the Supplemental Material [41]. The total prompt $D^+_{(s)}$ production cross sections, obtained by integrating the double-differential results in the measured kinematic ranges, are $42.83 \pm 0.29 \pm 3.45$ mb ($92.36 \pm 0.18 \pm 4.96$ mb) for the forward rapidity region, and $42.96 \pm 0.36 \pm 4.91$ mb ($84.09 \pm 0.17 \pm 8.39$ mb) for the backward rapidity region, where the first uncertainty is statistical and the second systematic.

The nuclear modification factor $R_{p\mathrm{Pb}}$ is defined as the ratio of differential cross sections

$$R_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*)/(\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*)}{\mathrm{d}^2\sigma_{pp}(p_{\mathrm{T}}, y^*)/(\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*)}, \tag{2}$$

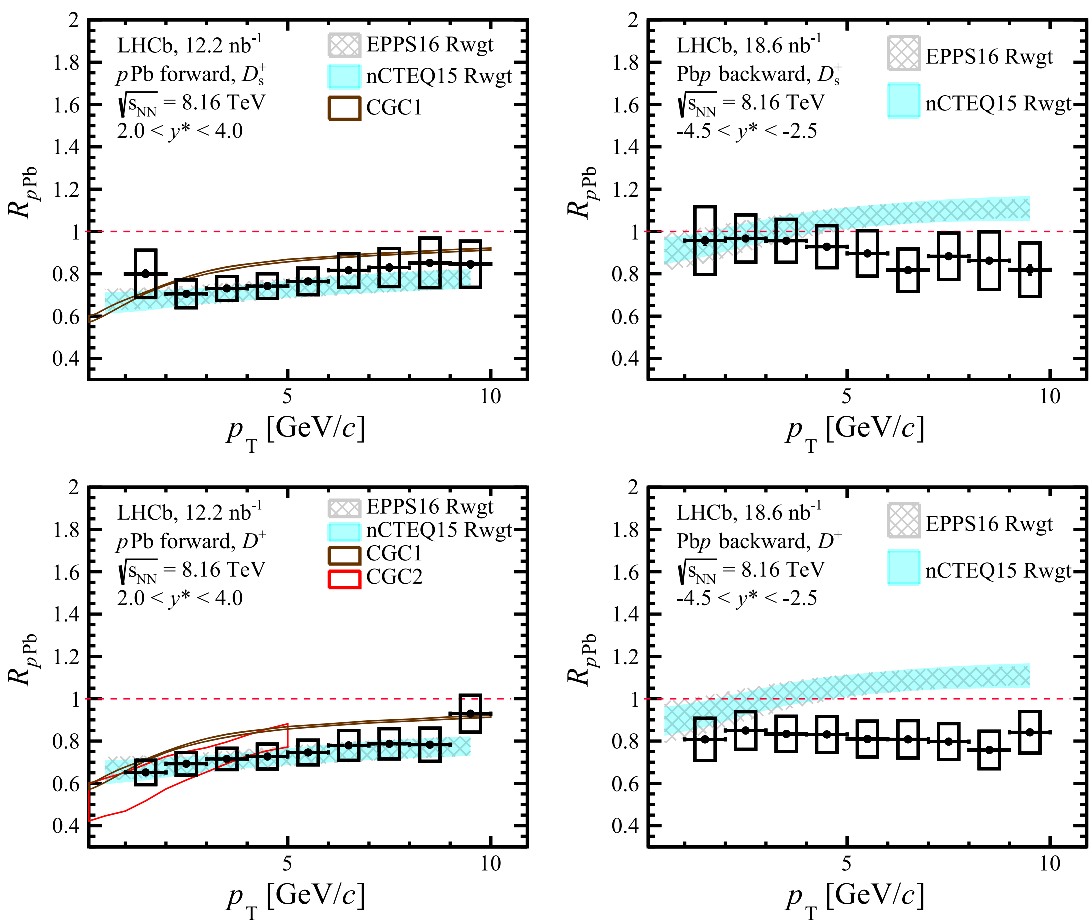

FIG. 1. Nuclear modification factor $R_{p\mathrm{Pb}}$ as a function of p_{T} for prompt (upper) D_s^+ and (lower) D^+ mesons. Forward rapidity results are shown on the left and backward rapidity on the right. The vertical error bars show the statistical uncertainties and the boxes show the systematic uncertainties. The theoretical calculations are also shown [49–53].

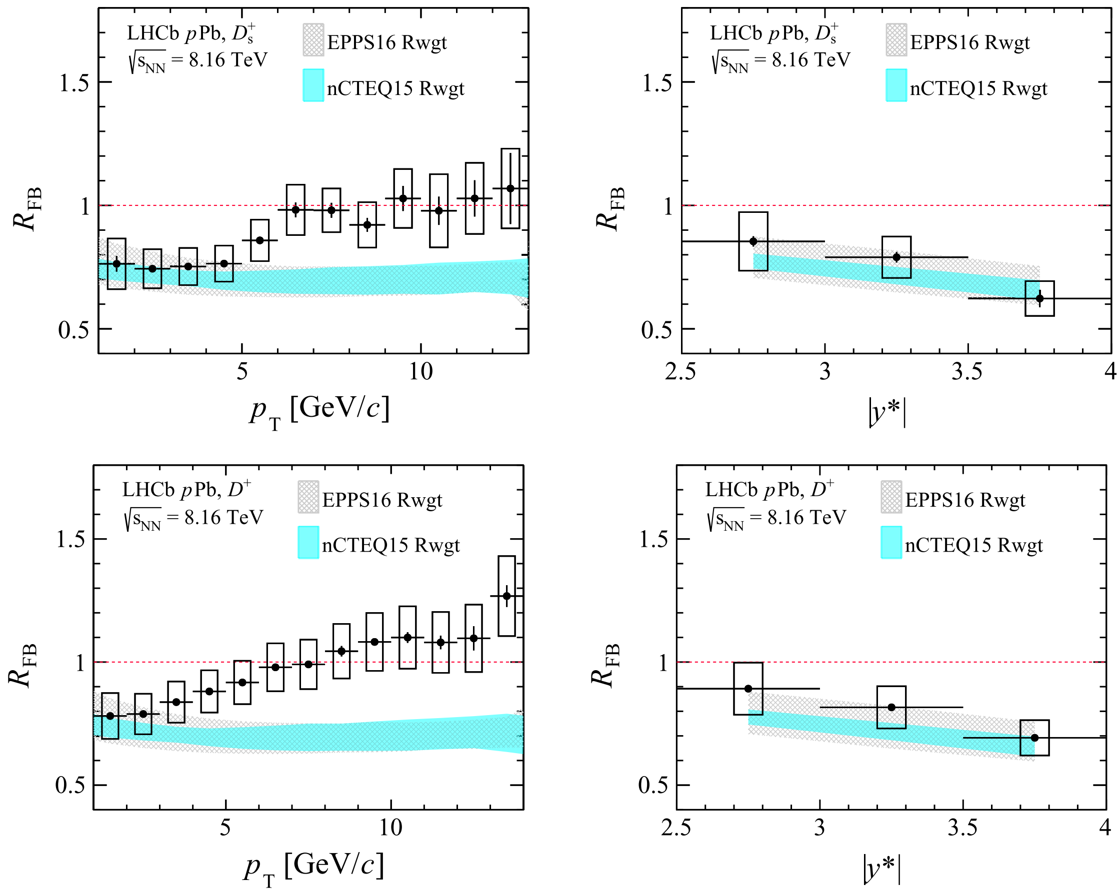

FIG. 2. Forward-backward cross-section ratio R_{FB} for prompt (upper) D_s^+ and (lower) D^+ mesons as a function of (left) p_T and (right) y^*. The vertical error bars show the statistical uncertainties and the boxes show the systematic uncertainties. The colored bands represent the theoretical calculations, incorporating nPDFs EPPS16 (gray) [52] and nCTEQ15 (cyan) [53].

where $A = 208$ is the lead nucleus mass number and σ_{pp} is the prompt $D_{(s)}^+$ meson cross section in pp collisions at $\sqrt{s} = 8.16$ TeV. The latter are obtained by an interpolation between LHCb measurements at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV [47,48]. The interpolation is performed within the common kinematic range $1 < p_T < 10\,\text{GeV}/c$ and $2.0 < y < 4.5$, using a power-law function. The difference obtained when using a linear function is assigned as a systematic uncertainty.

The nuclear modification factors for $D_{(s)}^+$ mesons as a function of p_T are displayed in Fig. 1, where the results are integrated over the rapidity range $2.0 < y^* < 4.0$ for the forward rapidity region and $-4.5 < y^* < -2.5$ for the backward region. A significant suppression of $D_{(s)}^+$ production in pPb collisions, with respect to those in pp collisions scaled by the lead mass number, is observed at forward rapidity. Figures showing $R_{p\text{Pb}}$ in different y^* intervals of width $\Delta y^* = 0.5$, as well as the numerical values, are given in the Supplemental Material [41].

The $R_{p\text{Pb}}$ results are compared with nPDF theoretical calculations. These calculations use the HELAC-Onia approach [54,55], which is based on a data-driven modeling of the scattering at partonic level folded with free proton PDFs [56]. They are first tuned by fitting the cross sections measured in pp collisions at the LHC. Then, the modified PDFs of nucleons in the Pb nucleus are introduced to calculate the cross sections in pPb collisions and to estimate the effect of nPDFs. Reweighted EPPS16 [52] or nCTEQ15 [53] nPDF sets, which incorporate LHC heavy-flavor data [57–60] in a Bayesian-reweighting analysis [61], are used in these calculations. This procedure leads to considerably reduced uncertainties with respect to calculations using the default nPDFs. The theoretical uncertainties shown in Fig. 1 are dominated by the nPDF parametrizations and correspond to a 68% confidence interval. At forward rapidity, the calculations are in satisfactory agreement with data. At backward rapidity, the data are lower than the calculations, indicating a weaker antishadowing effect or possible final-state effects that depend weakly on charm hadronization.

The nuclear modification factors in the forward rapidity region (small momentum fraction x) are also compared with two calculations based on the CGC effective field theory, CGC1 [49,50] and CGC2 [51]. The most significant theoretical uncertainty in CGC2 is the initial saturation scale of the target nucleus. The CGC1 predictions have much smaller uncertainties than the CGC2 predictions, as they include only variations of the charm quark mass and of the factorization scale, which largely cancel out in the $R_{p\text{Pb}}$ ratio. The CGC1 calculations are consistent with the upper bound of the CGC2 predictions and slightly overshoot the data. The CGC2 predictions show a stronger suppression than HELAC-Onia, especially for $p_{\text{T}} < 3\ \text{GeV}/c$.

The forward-backward cross section ratio R_{FB} is defined as

$$R_{\text{FB}}(p_{\text{T}}, |y^*|) = \frac{\mathrm{d}^2\sigma_{p\text{Pb}}(p_{\text{T}}, +|y^*|)/(\mathrm{d}p_{\text{T}}\mathrm{d}y^*)}{\mathrm{d}^2\sigma_{\text{Pb}p}(p_{\text{T}}, -|y^*|)/(\mathrm{d}p_{\text{T}}\mathrm{d}y^*)}, \quad (3)$$

and calculated in the common $|y^*|$ interval of the forward-backward acceptances, namely $2.5 < |y^*| < 4$. The measurements of R_{FB} are shown as a function of p_{T} and $|y^*|$ in Fig. 2, along with the nPDF calculations [52,53]. Good agreement with nPDF calculations is found at low p_{T}; however, the data show a clear rising trend with increasing p_{T}, reaching unity at the highest p_{T} values. This is in contrast to the nPDF calculations, which predict $R_{\text{FB}} \sim 0.7$ almost independently of p_{T}. This discrepancy originates from the observed suppression of high-p_{T} $D^+_{(s)}$ mesons at backward rapidity.

The cross-section ratio $\sigma_{D_s^+}/\sigma_{D^+}$, which is written as

$$\frac{\sigma_{D_s^+}}{\sigma_{D^+}} = \frac{N_{D_s^+}}{N_{D^+}} \times \frac{\mathcal{B}_{D^+}}{\mathcal{B}_{D_s^+}} \times \frac{\epsilon^{\text{acc}}_{D^+}}{\epsilon^{\text{acc}}_{D_s^+}} \times \frac{\epsilon^{\text{trig}}_{D^+}}{\epsilon^{\text{trig}}_{D_s^+}} \times \frac{\epsilon^{\text{PID}}_{D^+}}{\epsilon^{\text{PID}}_{D_s^+}} \times \frac{\epsilon^{\text{rec\&sel}}_{D^+}}{\epsilon^{\text{rec\&sel}}_{D_s^+}}, \quad (4)$$

is more precisely measured thanks to a cancellation of systematic uncertainties. The dependence of $\sigma_{D_s^+}/\sigma_{D^+}$ versus the primary charged particle multiplicity is measured in the $D^+_{(s)}$ kinematic intervals $2 < p_{\text{T}} < 12\ \text{GeV}/c$ and $1.8 < y^* < 3.3$ $(-4.3 < y^* < -2.8)$ for forward (backward) rapidity. The primary charged particle multiplicity, denoted as N_{ch}, represents the number of charged particles originating from the collisions, including decay products. In this Letter, it is estimated within the forward-pseudorapidity region $(2 < \eta < 4.8)$ by measuring the number of tracks used to reconstruct the primary vertex, denoted as $N^{\text{PV}}_{\text{Tracks}}$. The correlation between the measured $N^{\text{PV}}_{\text{Tracks}}$ and N_{ch} is obtained from simulation.

Figure 3 shows the dependence of $\sigma_{D_s^+}/\sigma_{D^+}$ on primary charged particle multiplicity in four different p_{T} intervals (integrated over rapidity). Plots of $\sigma_{D_s^+}/\sigma_{D^+}$ in different y^* intervals and the derived numerical values are given in the Supplemental Material [41]. These measurements show that the $\sigma_{D_s^+}/\sigma_{D^+}$ ratio increases significantly as a function of the primary charged particle multiplicity, especially in the low-p_{T} and backward rapidity regions. They deviate

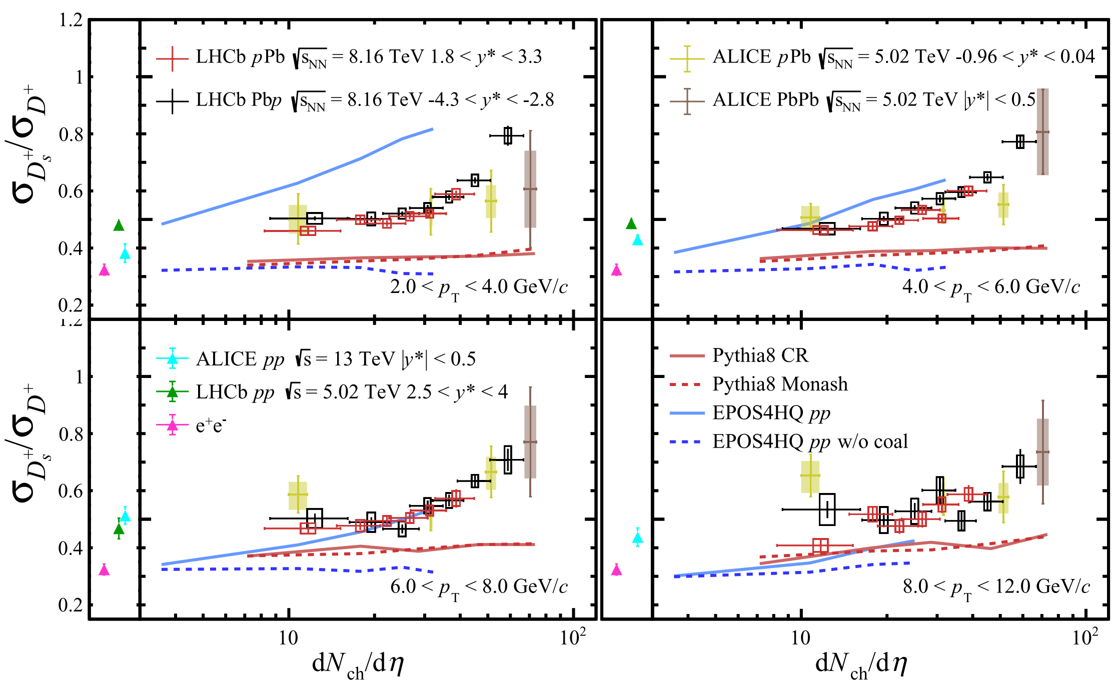

FIG. 3. Cross section ratio $\sigma_{D_s^+}/\sigma_{D^+}$ versus the primary charged particles per unit of pseudorapidity in e^+e^- [62], pp [10,63], pPb [64], PbPb [65] collisions in different $D^+_{(s)}$ p_{T} ranges. The vertical error bars show the statistical uncertainties and the boxes show the systematic uncertainties. The colored bands contain both statistical and systematic uncertainties. The calculations from PYTHIA 8 [66,67], EPOS4HQ [68,69], and EPOS4HQ without coalescence mechanism are also shown. These calculations are applicable to pp collisions at $\sqrt{s} = 8.16$ TeV within the rapidity range of $1.8 < y^* < 3.3$.

from a flat distribution, expected if only the fragmentation mechanism is considered, by 6.1 ($2 < p_T < 4$ GeV/c), 6.8 ($4 < p_T < 6$ GeV/c), 2.7 ($6 < p_T < 8$ GeV/c), and 3.2 ($8 < p_T < 12$ GeV/c) standard deviations in the forward rapidity region, and by 7.9 ($2 < p_T < 4$ GeV/c), 10.5 ($4 < p_T < 6$ GeV/c), 4.4 ($6 < p_T < 8$ GeV/c), and 1.1 ($8 < p_T < 12$ GeV/c) standard deviations at backward rapidity. As a comparison, the measured $\sigma_{D_s^+}/\sigma_{D^+}$ ratios in e^+e^- [62], pp [10,63], pPb [64], and PbPb [65] collisions are also shown in the Fig. 3. There are significant differences in the $\sigma_{D_s^+}/\sigma_{D^+}$ ratios between pp and PbPb collisions. The LHCb measurements reveal a trend where the ratio tends to resemble that of pp collisions in low-multiplicity pPb collisions, while it converges towards the behavior observed in PbPb collisions in high-multiplicity pPb collisions. In pPb collisions, the LHCb data are compatible with the ratio measured by ALICE within uncertainties. The $\sigma_{D_s^+}/\sigma_{D^+}$ pattern is similar in both the forward and backward rapidity regions. This suggests that the $\sigma_{D_s^+}/\sigma_{D^+}$ ratio is independent of rapidity, and the mechanism contributing to this ratio increase is strongly correlated with the charged particle density. Additionally, theoretical calculations are compared using PYTHIA 8 with Monash [66] and CR [67] tunes, along with EPOS4HQ [68,69]. EPOS4HQ extends the EPOS4 framework to include heavy quarks and incorporates a coalescence mechanism in hadronization. These calculations are applicable to pp collisions. Theoretical calculations from PYTHIA 8 underestimate experimental measurements and do not fully capture the trends dependent on multiplicity. While EPOS4HQ also exhibits some discrepancies with experimental data, it can depict the multiplicity-dependent trends across all p_T intervals by introducing a coalescence mechanism.

In summary, the prompt $D_{(s)}^+$ production cross sections are measured by the LHCb experiment in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV, both in the forward and backward rapidity regions. The nuclear modification factors are measured and found to be consistent with the previous results with D^0 mesons [7]. The results show a strong suppression of the $D_{(s)}^+$ cross sections at forward rapidity, consistent with the nPDF and CGC effective theory calculations. At backward rapidity, the $R_{p\mathrm{Pb}}$ values of $D_{(s)}^+$ mesons are lower than nPDF calculations at high p_T, indicating a weaker antishadowing effect than predicted by the models or additional hadronization-independent final-state effects. Moreover, the forward-backward cross-section ratio also shows a deviation from the nPDF calculations at high p_T. Combined with the nuclear modification factors, this deviation may arise from the observed suppression of high-p_T $D_{(s)}^+$ mesons at backward rapidity. The production of D_s^+ mesons is significantly enhanced relative to D^+ mesons in high particle multiplicity proton-lead collision events, in particular for low p_T and backward rapidity. This is the first observation of strangeness enhancement in charm quark hadronization in high-multiplicity small collision systems. The multiplicity-dependent trend is well understood within EPOS4HQ.

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