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Open heavy flavor production in pPb and PbPb collisions at LHCb

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Heavy quarks are produced in the early stage of heavy ion collisions due to their large mass, and experience the entire evolution of the QCD medium. The baryon-to-meson ratio provides valuable information on charm hadronisation mechanisms, testing the role of coalescence in the Quark-Gluon Plasma created in PbPb collisions. In pPb collisions, heavy quarks are essential to study cold nuclear matter effects, which include the modification of nuclear parton distribution functions, energy loss in the nucleus, and other effects, providing a crucial baseline for interpreting PbPb measurements. Here, we present precision measurements of open charm production from a set of charmed hadrons in pPb collisions at 5.02 and 8.16 TeV, including the first measurement of Ξ_c^+ baryons in heavy ion collisions. The nuclear modification factor $R_{p\mathrm{Pb}}$, forward-backward ratio R_{FB} and particle production ratios of charm baryons and mesons are discussed and compared to models.

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1. Introduction

In hadronic collisions, charm quarks are produced at the early stage of the collision. The mass of the charm quark allows one to perform the calculation of charm production in the context of pertubative QCD down to very low transverse momenta. However, interactions with the nucleus can affect heavy flavour production rates and, consequently, the measured production rate will be modified. Therefore, to describe charm production in pp collisions, QCD factorisation approaches are introduced. The single inclusive charm production can be written as a three-term convolution: (1) the parton distribution function (PDF) of nucleons, (2) the parton-parton hard scattering cross section into a pair of quarks, calculated using pertubative QCD and (3) the fragmentation function of a charm quark into a charm flavoured hadron. The precise determination of PDFs of protons and nuclear PDFs is an extremely active area of research of a wide variety of experimental hard-process data. The measurement of the particle production ratio in pPb to pp, called "nuclear modification factor", is sensitive to nuclear PDFs, as hard scattering cross section and hadronisation, if it is not modified in pp compared to pPb, components will cancel out in the ratio. Such ratio will allow to study the modification of hadron production in nuclear collisions, commonly called Cold Nuclear Matter effects. Likewise, the production ratio of two charm hadrons is sensitive to the fragmentation functions. It was assumed that hadronisation is universal across different collision systems and energies. However, the evidence of non-universality of the fragmentation functions was reported first by LHCb in a study of the Λ_b^0 baryon to B^- and $\bar{B}^0$ meson production ratio in pp collisions [1]. Later, many experimental data confirmed that the production ratio in pp is greatly enhanced compared to ratios in e^+e^- and pe^-. Nowadays, hadronisation is studied in many experimental facilities and vast of phenomenological models have been proposed.

The LHCb detector is a single-arm forward spectrometer with a unique pseudorapidity coverage ($2 < \eta < 5$). It was designed to study heavy flavour physics at Large Hadron Collider (LHC) and showed excellent performance in heavy-ion collisions, allowing to study Cold Nuclear Matter effects at very low bjorken-x region. In 2016, LHCb has collected data in pPb and Pbp collisions with an estimated integrated luminosity of approximately 12.5 and 17.4 nb^{-1} [2], respectively, at centre-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV.

2. Prompt Ξ_c^+ production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

The production of the charm-strange baryon, Ξ_c^+ (usc) is measured in heavy-ion collision for the first time at the LHCb experiment. The Ξ_c^+ candidates are reconstructed via the hadronic decay to the $p\,K^-\pi^+$ final state. The measurements are performed as a function of p_{T} and rapidity (y^*) of the baryon within a p_{T} range of [2,12] GeV/c and a rapidity range for the pPb data sample of 1.5 $< y^* <$ 4.0 and for the Pbp data sample of -5.0 $< y^* <$ -2.5.

The double-differential cross-sections of prompt Ξ_c^+ production times $\mathcal{B}(\Xi_c^+ \to p\,K^-\pi^+)$ is shown on Fig. 1 as a function of p_{T}. The data are compared with theoretical predictions [3–5] from the HELAC-Onia method[6, 7] called EPPS16 [8] with three factorisation scale choices. The data agree with the predictions and appear to be best described using the scale $0.5\mu_0$.

The differential ratio of Ξ_c^+ to Λ_c^+ (a) and D^0 (b) production times $\mathcal{B}(\Xi_c^+ \to p\,K^-\pi^+)$ is shown in Fig. 2 as a function of p_{T}. The ratio is roughly constant as a function of p_{T}, similarly for the

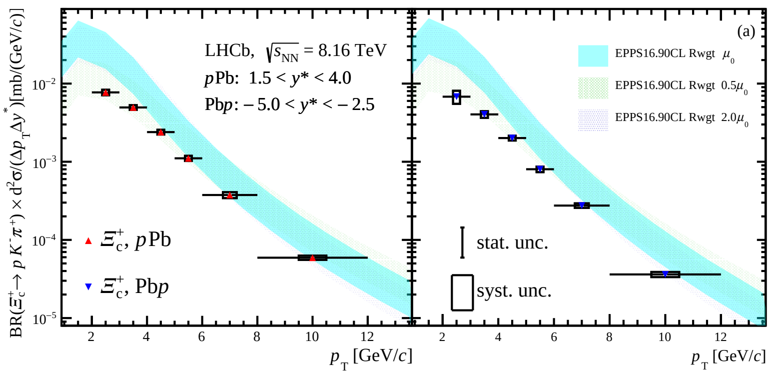
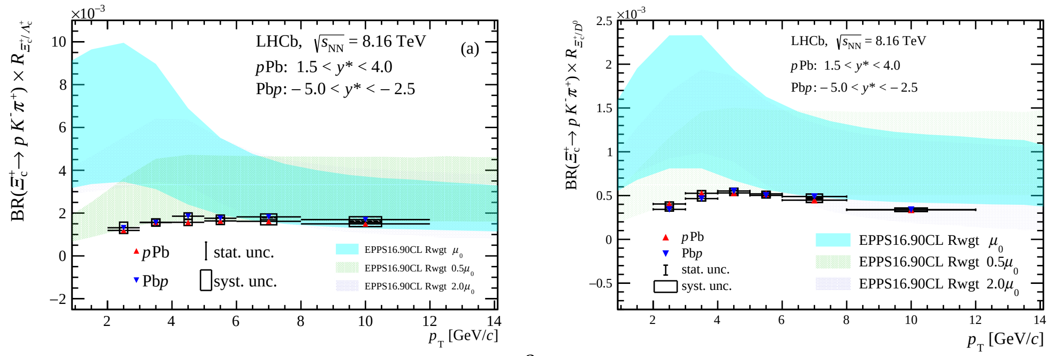


Figure 1: Double-differential cross-section of the prompt Ξ_c^+ baryon times $\mathcal{B}(\Xi_c^+ \to p\, K^-\pi^+)$ as a function of p_{T} in pPb (red triangles) and Pbp (blue triangles) collisions. The error bars represent the statistical uncertainties, while the black squares represent the total systematic uncertainties which include correlations among bins.

pPb and Pbp data samples. While it shows no p_{T} dependence in the region $p_{\mathrm{T}} \gtrsim 4\,\mathrm{GeV}/c$, the ratio seems to decrease by about 8% in the lower p_{T} region, a trend which is in agreement with the theoretical predictions with the choice of factorisation scale mentioned before.



a b

Figure 2: Production ratio of prompt Ξ_c^+ to Λ_c^+ (a) and D^0 (b) times $\mathcal{B}(\Xi_c^+ \to p\, K^-\pi^+)$ in pPb (red triangles) and Pbp (blue triangles) data samples as a function of p_{T}. The error bars represent the statistical uncertainties, while the squares indicate the systematic uncertainty.

The forward-backward ratio, R_{FB}, which is defined as production ratio in pPb collisions to Pbp, is measured in the overlapping rapidity range $2.5 < |y^*| < 4.0$. The results are shown in Fig. 3 as a function of p_{T}. R_{FB} is well described by nuclear shadowing showing that there are no major final-state effects involved.

3. Prompt D^0 production in pPb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV

The production of prompt D^0 mesons was studied in pPb and Pbp collisions. D^0 candidates were reconstructed via the hadronic decay to the $K^-\pi^+$ final state. The measurement is performed within a p_{T} range of [0,16] GeV/c and a rapidity range for the pPb data sample of $1.5 < y^* < 4.0$ and for the Pbp data sample of -5.0 $< y^* <$ -2.5.

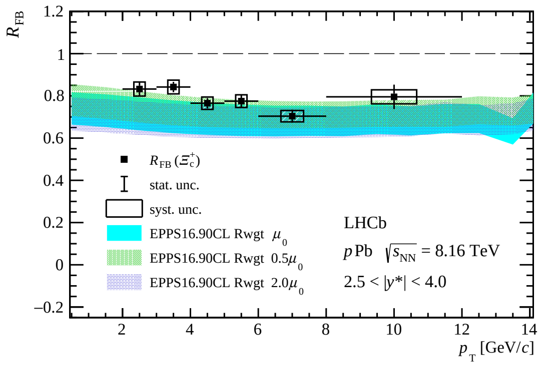


Figure 3: Forward-backward ratio of Ξ_c^+ production as a function of p_{T}. The error bars represent the statistical uncertainties, while the boxes indicate the systematic uncertainty.

The nuclear modification factor, $R_{p\mathrm{Pb}}$ of the D^0 meson as a function of p_{T} is shown on Fig. 4, where 10 panels report the results in different y^* subintervals. The results are compared with several theoretical calculations: reweighted EPPS16 [8] and nCTEQ15 [9] nPDF sets calculated with HELAC-Onia approach [6, 7], two calculations based on the CGC effective field theory [10–12] and a calculation estimates D^0 suppression caused by medium-induced fully coherent energy loss (FCEL) [13]. Results are also compared with the LHCb D^0 measurement at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [14]. In general, HELAC-Onia predictions give best description of data. At forward rapidity, the calculations are in general agreement with the data, while at backward rapidity and high p_{T} the data are significantly lower than the calculations, indicating a weaker antishadowing effect or possible final-state effects.

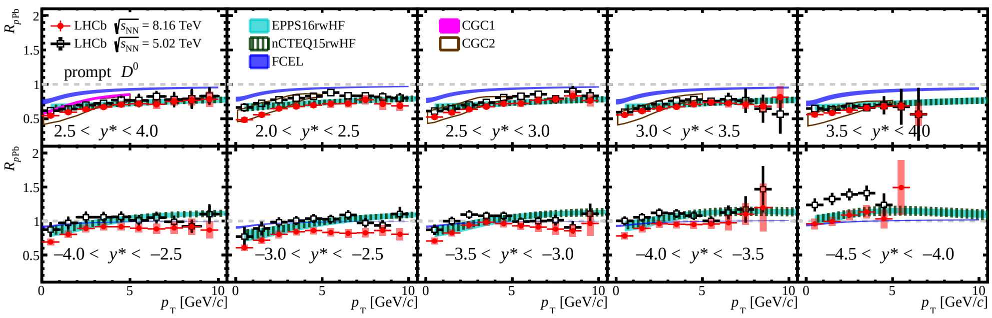


Figure 4: Nuclear modification factor as a function of p_{T} and y^* intervals for prompt D^0 meson in the (top) pPb and (bottom) pPb collisions. The error bars show the statistical uncertainties and the boxes show the systematic uncertainties. The LHCb results at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [14] and theoretical calculations at $\sqrt{s_{\mathrm{NN}}} =$ 8.16 TeV from Refs. [8–13] are also shown.

Fig. 5 shows $R_{p\mathrm{Pb}}$ as a function of experimental proxies bjorken-x in different momentum transfer Q^2 intervals. x_{exp} and Q^2_{exp} are defined as

$$x_{\mathrm{exp}} \equiv 2\frac{\sqrt{{p_{\mathrm{T}}}^2(D^0) + M^2(D^0)}}{\sqrt{s_{\mathrm{NN}}}}e^{-y^*} \quad \text{and} \quad Q^2_{\mathrm{exp}} \equiv {p_{\mathrm{T}}}^2(D^0) + M^2(D^0), \tag{1}$$

where $p_T(D^0)$ and $M(D^0)$ denotes p_T and mass of D^0 mesons respectively. The result is compared with data from LHCb and ALICE [15] at $\sqrt{s_{NN}}$ = 5.02 TeV. Data from LHCb at the two energies are in good agreement with each other at common x_{exp} and data from ALICE is compatible with the overall trend withing uncertainties. The data is also compared with HELAC-Onia predictions, which are in general agreement with the data. The data hint at a stronger shadowing effect, or other possible effects such as FCEL at small x_{exp} and Q^2_{exp} and the values from the model are larger at big x_{exp} and Q^2_{exp}, indicating smaller antishadowing effects in the data or suggesting additional suppression mechanisms.

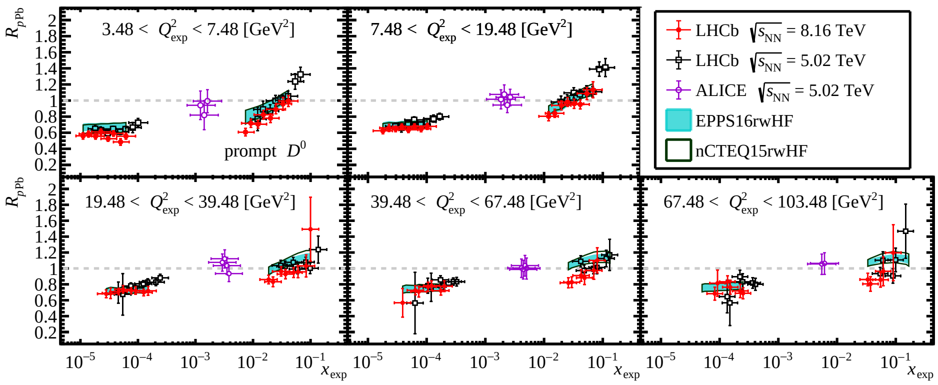


Figure 5: Nuclear modification factor as a function of x_{exp} in different Q^2_{exp} intervals for prompt D^0 mesons for LHCb result at $\sqrt{s_{NN}}$ = 8.16 TeV and $\sqrt{s_{NN}}$ = 5.02 TeV [14] and the ALICE result at $\sqrt{s_{NN}}$ = 5.02 TeV [15]. Theoretical calculations at $\sqrt{s_{NN}}$ = 8.16 TeV [8, 9] are also shown. The horizontal error bars account for the maximum and minimum x_{exp} values for a given (p_T, y^*) interval and the vertical error bars show the quadric sum of statistical and systematic uncertainties.

4. Conclusion

The latest measurements of prompt Ξ_c^+ and D^0 production in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV are performed with the LHCb detector. The production ratio of Ξ_c^+ to Λ_c^+ and D^0 in agreement with theoretical calculations within uncertainties. These results imply potential for the understanding of hadronisation mechanisms in hadronic collisions. The forward-backward ratio of prompt Ξ_c^+ is well described by nuclear shadowing calculations. Whereas measurement of nuclear modification factor of prompt D^0 showed strong cold nuclear matter effects. A stronger suppression than the predictions of nPDF calculations is observed for the lowest transverse momentum region in backward rapidity, hinting at a weaker antishadowing or additional effects. This result provides the most precise measurement of the prompt D^0 production in pPb collisions to date providing unique constraints to improve nPDF parameterisation down to $x \sim 10^{-5}$.

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