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Studies of beauty-quark production, hadronisation and cold nuclear matter effects via measurements of non-prompt charm hadrons in pp and p–Pb collisions with ALICE

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Measurements of beauty-hadron production in pp collisions provide a fundamental tool for testing perturbative QCD calculations. Studies in p–Pb collisions allow us to shed light on the role of cold nuclear matter effects on beauty production and their impact on beauty-quark hadronisation. In this contribution, the final results on the production of charm mesons and baryons from beauty-hadron decays (non-prompt) in pp collisions at $\sqrt{s}$ = 13 TeV are shown. They are compared to pQCD predictions and to models with modified hadronisation mechanisms with respect to in-vacuum fragmentation. The final results of non-prompt charm-hadron production and nuclear modification factor in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV are also discussed. Lastly, the first studies of non-prompt/prompt production yield ratios of charm hadrons in pp collisions at $\sqrt{s}$ = 13.6 TeV from the LHC Run 3 data taking are reported.

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1. Introduction

Measurements of heavy-flavor hadron production in hadronic collisions provide crucial tests for calculations based on quantum chromodynamics (QCD). Given their large masses with respect to the QCD energy scale, heavy quarks (i.e. charm and beauty) are primarily produced at the early stages of the collisions through hard-scattering processes with large momentum transfer, allowing to calculate their production cross sections via perturbative QCD (pQCD). These calculations are based on a factorisation approach where the p_{T}-differential production cross sections of charm or beauty hadrons are calculated as a convolution of three terms: (i) the parton distribution functions (PDFs) of the incoming nucleons, which describe the Bjorken-x distributions of quarks and gluons inside the nucleons, (ii) the partonic scattering cross section, calculated as a perturbative series in powers of the strong coupling constant α_{S}, and (iii) the fragmentation function, which characterises the non-perturbative evolution of a heavy quark into given heavy-flavour hadron species. The fragmentation functions are usually determined from measurements in $\mathrm{e}^{+}\mathrm{e}^{-}$ collisions [1], under the assumption that the heavy-quark hadronisation processes are "universal", i.e. independent of the collision energy and system. Measurements of heavy-flavor hadron production in pp collisions serve as an important reference to the studies in larger collision systems and provide crucial tests for calculations based on QCD. Heavy-flavour hadron production in p–Pb collisions is of great interest to study the influence of cold nuclear matter (CNM) effects, which are induced by the presence of nuclei in the initial state. To isolate the effects of hadronisation, heavy-flavour hadron-to-hadron production yield ratios are particularly effective, since the PDFs and the partonic interaction cross sections are common to all charm or beauty hadron species and their effects mostly cancel out in the yield ratios when using the factorisation approach.

2. The ALICE experiment and experimental results

A Large Ion Collider Experiment (ALICE) is optimised to study the physics of strong interacting matter at the highest energy densities reached by far. The ALICE apparatus [2] comprises a central barrel covering the pseudorapidity interval $|\eta| < 0.9$. During the LHC Run 2 data-taking period, the reconstruction of heavy-flavour hadrons from their hadronic decay products at midrapidity relied on the Inner Tracking System (ITS) [3], the Time Projection Chamber (TPC) [4], and the Time-Of-Flight detector (TOF) [5] for tracking, primary and decay vertex reconstruction, and charged-particle identification (PID). The V0 detector arrays [6] are used for triggering and event selection. In Run 3, the ITS was upgraded to a seven-layer silicon pixel detector fully made of CMOS MAPS [3], contributing to a fast readout and to a significant improvement on the pointing resolution and related quantities. The upgraded TPC readout with Gas Electron Multipliers [7] achieves continuous readout ability, allowing for sustaining a significantly increased interaction rate. A new Fast Interaction Trigger (FIT) [8] was introduced for triggering, multiplicity and luminosity estimation.

The p_{T}-differential production cross sections of non-prompt D^0 mesons and Λ_{c}^{+} baryons in pp collisions at $\sqrt{s} = 13$ TeV [30] are shown in Fig. 1. The data points are compared with theoretical models based on the B-meson cross section predicted by FONLL [9, 10] calculations, and to the TAMU statistical hadronisation model [11]. In the FONLL calculations, the beauty-quark fragmentation fraction to B mesons was taken from e^+e^- collisions [12]. The fragmentation fraction of beauty quarks to Λ_b^0 was calculated from LHCb measurements [13]. In order to obtain the non-prompt D^0 and Λ_c^+ cross sections, the resulting beauty-hadron cross sections of both models were then combined with the PYTHIA 8 decayer [14] to describe the $H_b \rightarrow H_c + X$ decay kinematics. Both predictions agree with the non-prompt D^0 cross section over the whole p_T range, while they underestimate the non-prompt Λ_c^+ baryon production cross sectioin for $2 < p_T < 4$ GeV/c.

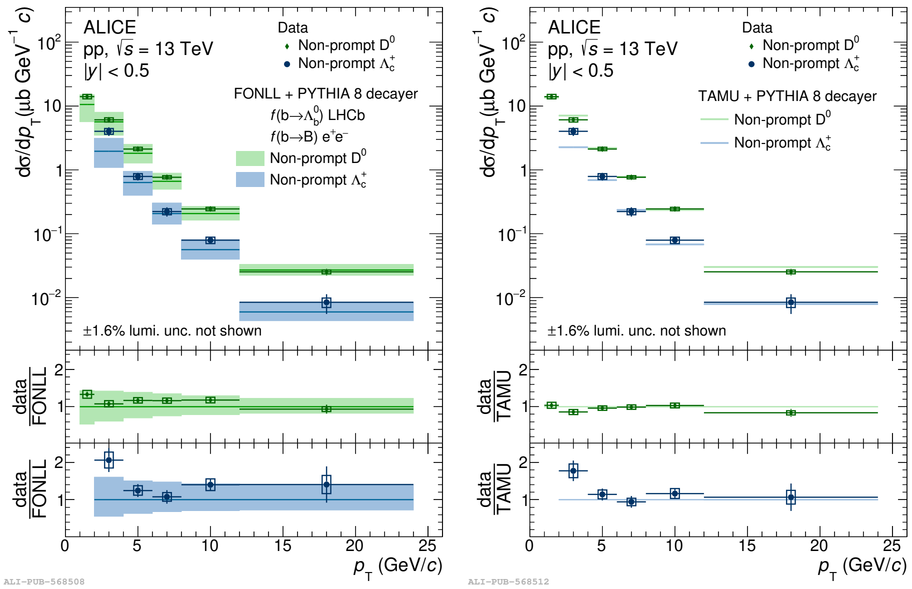

Figure 1: p_T-differential production cross sections of non-prompt D^0 and Λ_c^+ in pp collisions at $\sqrt{s}$ = 13 TeV [30], compared with model predictions obtained with FONLL calculations [9, 10] adopting $f(b \rightarrow B)$ and $f(b \rightarrow \Lambda_b^0)$ fragmentation fractions measured in e^+e^- collisions [12] and from LHCb Collaboration [13], respectively (left panel), and the TAMU model [11] (right panel), combined with PYTHIA 8 decayer [14, 15].

The p_T-differential non-prompt Λ_c^+/D^0 production yield ratio measured at midrapidity in pp collsions at $\sqrt{s}$ = 13 TeV [30] is shown in Fig.2. The data is compared with the measurements of prompt Λ_c^+/D^0 [16], Λ/K_S^0 [17], and p/π^+ [17]. The measurements for beauty and charm are compatible within the uncertainties. The experimental values are compared with model predictions obtained with PYTHIA 8 simulations using Monash 2013 tune [15] in the left panel, and CR-BLC Mode 2 setting [18] in the right panel. A good agreement for charm and strange hadrons is obtained with the CR-BLC Mode 2 setting, while the measurements of beauty hadrons are slightly overestimated for p_T < 10 GeV/c.

The left panel of Fig.3 shows the average R_{pPb} of non-prompt D^0 and D^+ mesons [35], and the average R_{pPb} of prompt D^0, D^+, and D^{*+} mesons [19] measured in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [35]. Within the statistical and systematic uncertainties, the R_{pPb} of prompt and non-prompt D mesons are compatible with each other and with unity over the entire p_T interval. The p_T-integrated R_{pPb} for non-prompt D^0 and D^+ mesons in $-0.96 < y_{cms} < 0.04$ were calculated from the production cross sections of non-prompt D^0 and D^+ mesons in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV extraplolated down to p_T = 0, and from those measured in pp collisions at $\sqrt{s}$ = 5.02 TeV [20]. The values are shown in the right panel of Fig.3, compared with the R_{pPb} of non-prompt J/ψ measured at midrapidity by the ALICE Collaboration [21] and the R_{pPb} of B^+ and non-prompt

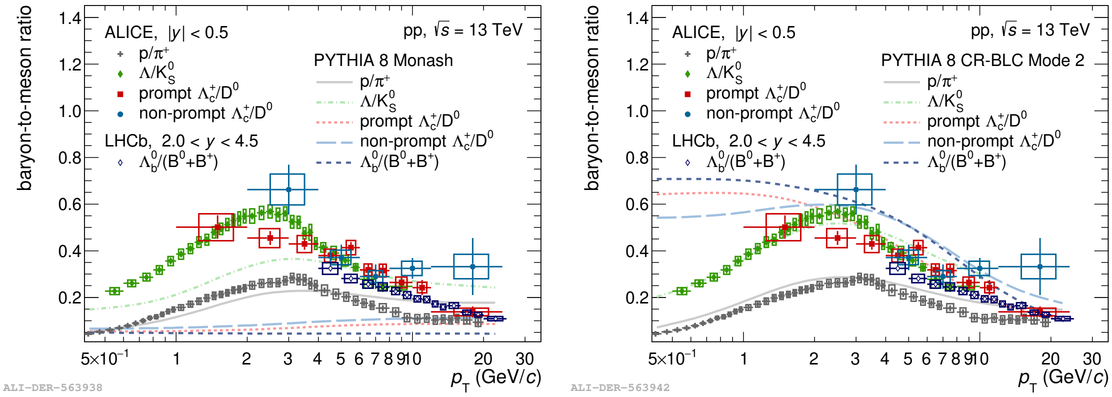

Figure 2: Non-prompt Λ_c^+/D^0 [30], prompt Λ_c^+/D^0 [16], Λ/K_S^0 [17], and p/π^+ [17] yield ratios measured at midrapidity in pp collisions at $\sqrt{s}$ = 13 TeV compared with the $\Lambda_b^0/(B^0 + B^+)$ ratio measured by the LHCb Collaboration at forward rapidity ($2.5 < y < 4$) [13] and with model predictions obtained with the PYTHIA 8 using Monash 2013 tune [15] and the CLR-BLC Mode 2 [18].

J/ψ at forward ($2.5 < y_{cms} < 3.5$, $1.5 < y_{cms} < 4$) and backward ($-3.5 < y_{cms} < -2.5$, $-5 < y_{cms} < -2.5$) rapidity by the LHCb Collaboration [22, 23]. The experimental results of the p_T-integrated R_{pPb} are compared with model predictions for the B^+ meson in p–Pb/Pb–p collisions at $\sqrt{s_{NN}}$ = 8.16 TeV using the HELAC-onia generator [24–26] with three different sets of nPDFs, i.e. EPPS16 [27], nCTEQ15 [28], and EPPS16* [29]. The values of non-prompt D mesons at midrapidity agree with unity and with the model predictions within the uncertainties, suggesting that the overall CNM effects in the charm and beauty sector are not significant and, if any, have a similar strength for charm and beauty.

The ratio of the p_T-differential production cross sections of non-prompt Λ_c^+ and D^0 hadrons measured in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [35] is shown in the left panel of Fig.4. The result is compared to the analogous ratio measured in pp collisions at $\sqrt{s}$ = 13 TeV [30], and with the Λ_b^0/B^0 ratio measured by the LHCb Collaboration at forward rapidity ($2 < y_{cms} < 4.5$) in pp collisions at $\sqrt{s}$ = 13 TeV [31]. An increasing trend is observed with decreasing p_T for both pp and p–Pb collisions. At low p_T, the baryon enhancement suggested by data is qualitatively similar to that in pp collisions, which can be explained by different hadronisation mechamisms from models beyond pure in-vacuum fragmentation being in play in hadronic collisions.

The right panel of Fig.4 shows the first measurement of the non-prompt D^0 fraction in pp collisions at $\sqrt{s}$ = 13.6 TeV collected during the LHC Run 3. A good agreement between Run 2 and Run 3 measurements is obtained. For the new measurement, the p_T range is extended down to 0, with an increased granularity with respect to Run 2 results at $\sqrt{s}$ = 13 TeV [32], which represents a better input for constraining modeling of charm and beauty production and hadronisation.

In summary, the assumption of universal fragmentation fractions across collision systems is violated for heavy quarks. The hadronisation mechanisms of beauty quarks are similar in pp and p–Pb collisions. In the beauty and charm sectors, mild and similar CNM effects are suggested by the measurements. Exploiting the Run 3 pp data sample, a precise measurement of the non-prompt D^0 fraction has been performed with extended p_T coverage down to 0. With the major upgrade of the ALICE detector for Run 3, larger data samples, and the foreseen upgrades for Run 4, further new and important results are expected from ALICE in this field.

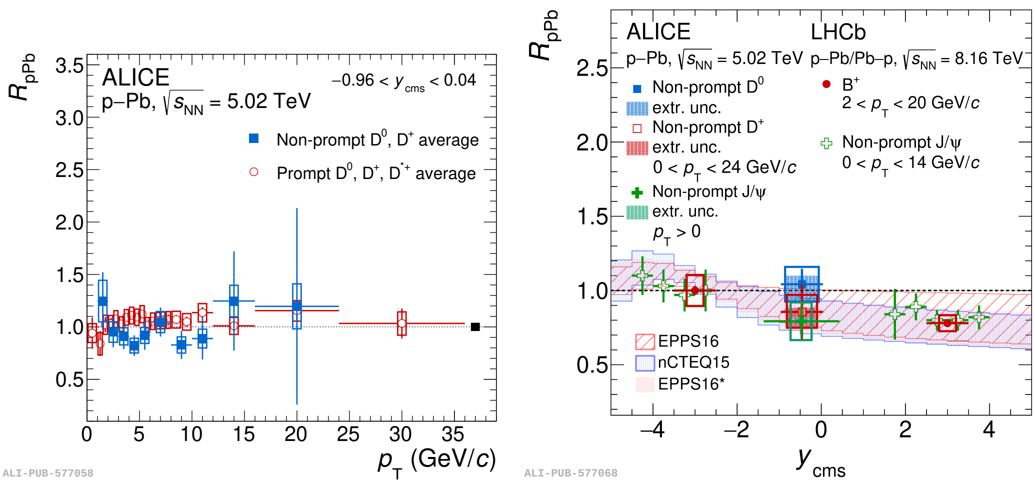

Figure 3: Average p_T-differential R_{pPb} of prompt D^0, D$^+$, and D* [19], and non-prompt D^0 and D$^+$ mesons [35] (left panel). Nuclear modification factors of non-prompt D^0 and D$^+$ mesons measured in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [35] compared with the R_{pPb} measurement of non-prompt J/ψ at midrapidity [21], and the R_{pPb} measurements of non-prompt J/ψ and B$^+$ mesons at forward and backward rapidity [22, 23]. The results are also compared with B-meson R_{pPb} calculations using different nPDF sets [27–29].

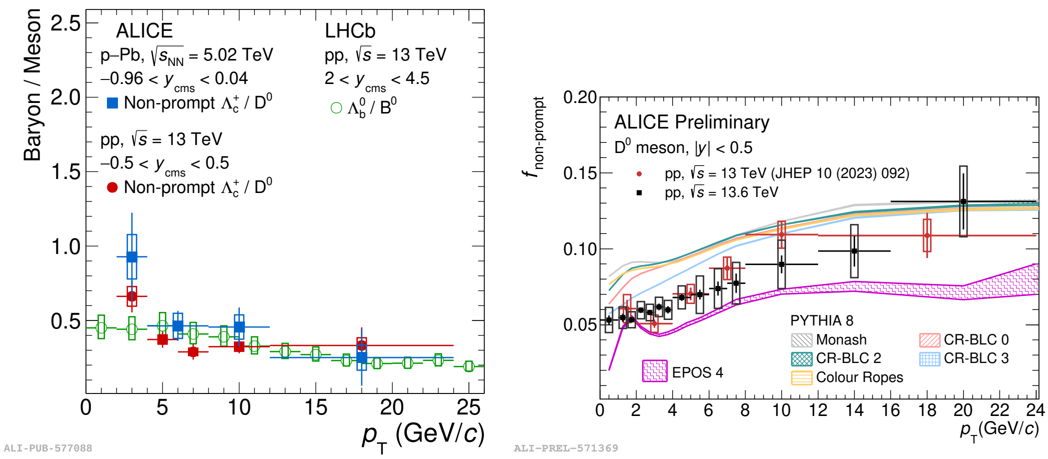

Figure 4: Non-prompt Λ_c^+/D^0 yield ratios as a function of p_T measured by ALICE in pp (red) [30] and p–Pb (blue) [35] collisions compared with the Λ_b^0/B^0 ratio (green) [31] measured by the LHCb Collaboration at forward rapidity ($2 < y_{cms} < 4.5$) in pp collisions (left panel). Non-prompt D^0 fraction measured at midrapidity at $\sqrt{s}$ = 13.6 TeV compared with the result measured at the rapidity at $\sqrt{s}$ = 13 TeV and with predictions obtained with PYTHIA 8 [18] and EPOS [33] event generators and the CGC model [34].

References

[1] L. Gladilin, Eur. Phys. J. C **75** (2015) no.1, 19

[2] ALICE Collaboration, JINST **3** (2008), S08002

[3] ALICE Collaboration, J. Phys. G **41** (2014), 087002

[4] J. Alme *et al.*, Nucl. Instrum. Meth. A **622** (2010), 316-367

[5] A. Akindinov *et al.*, Eur. Phys. J. Plus **128** (2013), 44

[6] ALICE Collaboration, JINST **8** (2013), P10016

[7] ALICE Collaboration, JINST **16** (2021) no.03, P03022

[8] ALICE Collaboration, Nucl. Instrum. Meth. A **845** (2017), 463-466

[9] M. Cacciari *et al.*, JHEP **05** (1998), 007

[10] M. Cacciari *et al.*, JHEP **10** (2012), 137

[11] M. He *et al.*, Phys. Rev. Lett. **131** (2023) no.1, 1

[12] Particle Data Group, PTEP **2022** (2022), 083C01

[13] LHCb Collaboration, Phys. Rev. D **100** (2019) no.3, 031102

[14] T. Sjöstrand *et al.*, Comput. Phys. Commun. **191** (2015), 159-177

[15] P. Skands *et al.*, Eur. Phys. J. C **74** (2014) no.8, 3024

[16] ALICE Collaboration, Phys. Rev. Lett. **128** (2022) no.1, 012001

[17] ALICE Collaboration, Eur. Phys. J. C **81** (2021) no.3, 256

[18] J. R. Christiansen and P. Z. Skands, JHEP **08** (2015), 003

[19] ALICE Collaboration, JHEP **12** (2019), 092

[20] ALICE Collaboration, JHEP **05** (2021), 220

[21] ALICE Collaboration, JHEP **06** (2022), 011

[22] LHCb Collaboration, Phys. Lett. B **774** (2017), 159-178

[23] LHCb Collaboration, Phys. Rev. D **99** (2019) no.5, 052011

[24] H. S. Shao, Comput. Phys. Commun. **184** (2013), 2562-2570

[25] H. S. Shao, Comput. Phys. Commun. **198** (2016), 238-259

[26] J. P. Lansberg and H. S. Shao, Eur. Phys. J. C **77** (2017) no.1, 1

[27] K. J. Eskola *et al.*, Eur. Phys. J. C **77** (2017) no.3, 163

[28] K. Kovarik *et al.*, Phys. Rev. D **93** (2016) no.8, 085037

[29] A. Kusina *et al.*, Phys. Rev. Lett. **121** (2018) no.5, 052004

[30] ALICE Collaboration, Phys. Rev. D **108** (2023) no.11, 112003

[31] LHCb Collaboration, Phys. Rev. Lett. **132** (2024) no.8, 081901

[32] ALICE Collaboration, JHEP **10** (2023), 092

[33] K. Werner *et al.*, Phys. Rev. C **89** (2014) no.6, 064903

[34] I. Schmidt and M. Siddikov, Phys. Rev. D **101** (2020) no.9, 094020

[35] ALICE Collaboration, arXiv:2407.10593 [nucl-ex]