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Production of open charm and beauty states in pPb collisions with LHCb

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Abstract. A rich set of open heavy flavour states is observed by LHCb in pPb collisions data collected at 5 and 8.16 TeV nucleon-nucleon centre-of-mass energy. Results include new measurements of production of beauty hadrons in pA collisions through cleanly reconstructed exclusive decays. Open charm states, including the Λ_c^+ baryon, were also observed in pA collisions for the first time by LHCb.

1. Introduction

A hot and dense medium of deconfined quarks and gluons, called quark-gluon plasma (QGP), is known to be created in ultra-relativistic heavy-ion collisions at RHIC and LHC. Heavy quarks are particularly suitable probes to study the properties of QGP. They are produced in pairs ($c\bar{c}$, $b\bar{b}$) in the earliest stages of the collision and with a time scale that is shorter than that of the QGP formation. While propagating through the medium they interact with the medium constituents and lose energy through radiative gluonic emissions. Studying these processes is of utmost importance for the understanding of the properties and the space-time evolution of the QGP. In ultra-relativistic heavy-ions collisions these energy-loss and rescattering mechanisms are conveniently studied by means of the *nuclear modification factor* R_{AA}, defined as the ratio between the measured yield in nucleus-nucleus collisions and the proton-proton differential cross section scaled by the average nuclear overlap function $\langle T_{AA}\rangle$. Results of R_{PbPb} for prompt D^0 production at mid-rapidity, recently reported by ALICE and CMS [1, 2] as a function of the D^0 mesons transverse momentum p_T, show a strong attenuation, with R_{PbPb} of the order of 0.2 for high-centrality collisions. A correct interpretation of these phenomena in terms of QGP formation requires a full understanding of the *cold nuclear-matter effects*, which can be studied in processes where the QGP formation is traditionally not expected, such as in pPb collisions. These effects include energy-loss due to soft collisions, final-state hadronic rescattering and absorption, and modification of the nucleon PDFs (nuclear PDFs, nPDFs). The latter effect is typically studied in terms of ratios between the PDF for a nucleon N inside a nucleus A and the corresponding one for a free nucleon: $R_i^A(x, Q^2) = f_i^{N/A}(x, Q^2)/f_i^N(x, Q^2)$. Results based on global analyses [3, 4, 5, 6] have been reported as a function of the Bjorken x variable. In all cases the ratios R_i^A significantly deviate from unity and exhibit the characteristic (although still not completely understood) nuclear-matter effects: *shadowing* at small x, *anti-shadowing* at intermediate x, and the so-called *EMC effect* at very large x. Measurements of prompt open-charm production in pPb collisions at the LHC allow to constrain the nuclear PDFs at very small

x ($\sim 10^{-5} - 10^{-6}$), where the cold nuclear-matter effects are expected to be large. In particular, the LHCb experiment can play a crucial role in these studies thanks to its high performances in heavy-flavour measurements and to the possibility to measure prompt heavy flavours at low p_T and forward rapidity.

2. The LHCb detector and the pPb datasets

The LHCb detector [7, 8] is a single-arm spectrometer covering the pseudorapidity range $2.0 < \eta < 5.0$, and designed for the study of particles containing heavy-quarks. Due to the different beam energies per nucleon for the p and Pb beams, the detector covers two different rapidity regions in the nucleon-nucleon rest frame: $1.5 < y^* < 4.0$, corresponding to the "forward" configuration, and $-5.0 < y^* < -2.5$, corresponding to the "backward" configuration, where the centre-of-mass rapidity y^* is defined with respect to the direction of the proton beam. Two sets of data have been collected at LHCb with pPb collisions: the first (2013) at $\sqrt{s_{NN}} = 5.02$ TeV, with integrated luminosities of 1.06 ± 0.02 nb^{-1} and 0.52 ± 0.01 nb^{-1} for the forward and the backward configurations, respectively; the second (2016) at $\sqrt{s_{NN}} = 8.16$ TeV with an overall integrated luminosity a factor of 20 higher than that of the 5 TeV dataset. The results presented here have been obtained with the 5 TeV dataset. The 8 TeV data are currently being analysed and the new high-statistics results will also include prompt open-beauty measurements.

3. Prompt D^0 production in pPb collisions at 5 TeV

For the selection of D^0 mesons the $K^-\pi^+$ decay mode has been used[1]. The inclusive yield of D^0 candidates is extracted through an extended unbinned maximum likelihood fit to the distribution of the $K^-\pi^+$ invariant mass. The inclusive signal yield selected in this way includes both "prompt D^0" candidates, i.e. coming from the primary vertex (PV), and "non-prompt D^0" candidates, i.e. those created in the decay of b-hadrons. The two contributions are separated through a fit of the $log_{10}(\chi^2_{IP}(D^0))$ distribution, where $\chi^2_{IP}(D^0)$ is defined as the difference in vertex-fit χ^2 of a given PV computed including and not-including the D^0 candidate. This latter fit is performed for candidates with mass within ± 20 MeV/c^2 around the fitted value of the D^0 mass. The number of background candidates is constrained to the value obtained from the invariant mass fit, scaled to the selected mass range. Both fits are performed independently in each bin of p_T and y^* [9]. The double-differential cross section for production of prompt D^0 is shown in figure 1 as a function of p_T for five different bins in y^*, separately for the forward (left plot) and the backward (middle plot) beam configurations. The right plot shows the single-differential cross section (integrated over y^*) as a function of p_T. The data are compared with HELAC-Onia calculations including different nPDFs parametrizations [10, 11, 12]. The model calculations are constrained by existing LHC pp cross section measurements. The agreement with these pPb data is very good over the full kinematic range. Noteworthy, the experimental uncertainties are smaller than the theoretical ones. The fully-integrated cross sections amount to $230.6 \pm 0.5 \pm 13.0$ mb and $252.7 \pm 1.0 \pm 20.0$ mb for the forward and the backward configuration, respectively (the first uncertainties are statistical and the second systematic).

4. Prompt Λ_c^+ production in pPb collisions at 5 TeV

A similar procedure has been applied for the case of prompt Λ_c^+ baryon production [13]. In this case, the selection of the Λ_c^+ candidates is based on the $pK^-\pi^+$ decay mode. Similarly to the D^0 case, the selection of prompt Λ_c^+ is done in two steps. In a first step the inclusive yield of Λ_c^+ candidates is extracted by fitting the $pK^-\pi^+$ invariant mass distribution. The contribution of prompt Λ_c^+ is then separated from that arising from decay of b-hadrons through a fit of the

[1] Charge-conjugate modes are implicitly included throughout this document.

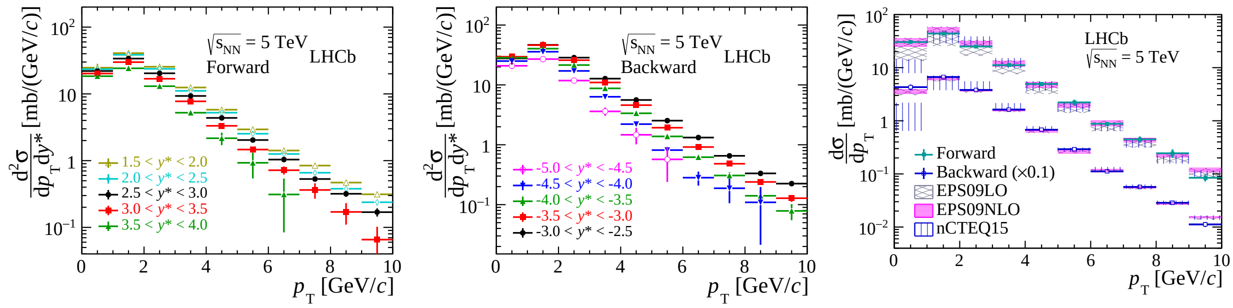

Figure 1. Double differential cross section for prompt production of D^0 mesons in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV as a function of p_T for five different bins in y^*, for the forward (left plot) and backward (middle plot) configurations. Single-differential cross section as a function of p_T (right plot) for both the forward and the backward configurations compared with HELAC-Onia predictions [10, 11, 12] including different nPDFs parametrizations. The error bars indicate the sum in quadrature of the statistical and systematic uncertainties. Colour online.

$log_{10}(\chi^2_{IP}(\Lambda_c^+))$ distribution. Similarly to the D^0 case, both fits are performed independently in each bin of p_T and y^*. The double-differential cross section for production of prompt Λ_c^+ is shown in figure 2 as a function of p_T for different bins in y^*, separately for the forward and the backward beam configurations. The fully-integrated cross sections amount to $32.1 \pm 1.0 \pm 4.1$ mb and $27.7 \pm 1.5 \pm 4.5$ mb, respectively, where the first uncertainties are statistical and the second systematic.

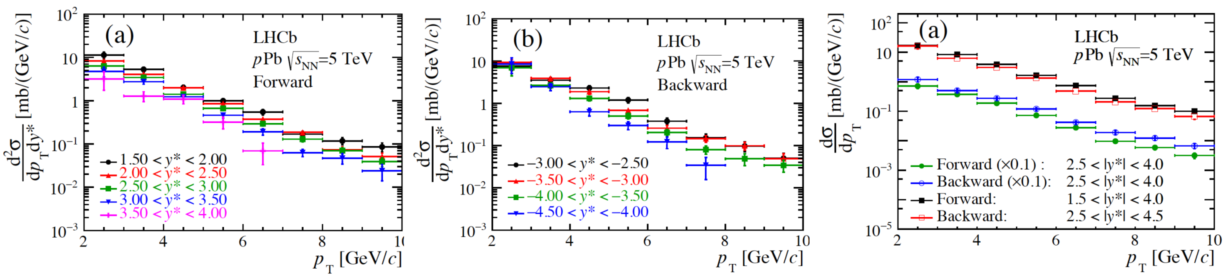

Figure 2. Double differential cross section for prompt production of Λ_c^+ baryons in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV as a function of p_T for different bins in y^*, for the forward (left plot) and backward (middle plot) configurations. Single-differential cross section as a function of p_T (right plot) for both the forward and the backward configurations. The error bars represent the quadratic sum of the statistical and the systematic uncertainties. Colour online.

5. Selected physical observables in prompt D^0 and Λ_c^+ production at 5 TeV

The nuclear modification factor, here defined as

$$R_{pPb}(p_T, y^*) = \frac{1}{A}\frac{d^2\sigma_{pPb}(p_T, y^*)/dp_T dy^*}{d^2\sigma_{pp}(p_T, y^*)/dp_T dy^*}\ , \qquad (A = 208) \tag{1}$$

has been extracted for the case of prompt D^0 production in pPb collisions [9]. The results are presented in figure 3 as a function of p_T (integrated over y^*), separately for the forward and the backward configurations, and as a function of y^* (integrated over p_T), and compared with HELAC-Onia predictions [10, 11, 12] as well as with a Colour-Glass-Condensate model [14].

The ratio $R_{pPb}(p_T, y^*)$ is significantly suppressed at forward rapidity (though slightly increasing with p_T), whereas it is consistent with unity in the backward rapidity region. The measurements are consistent with all models, with the experimental uncertainties smaller than the theoretical ones.

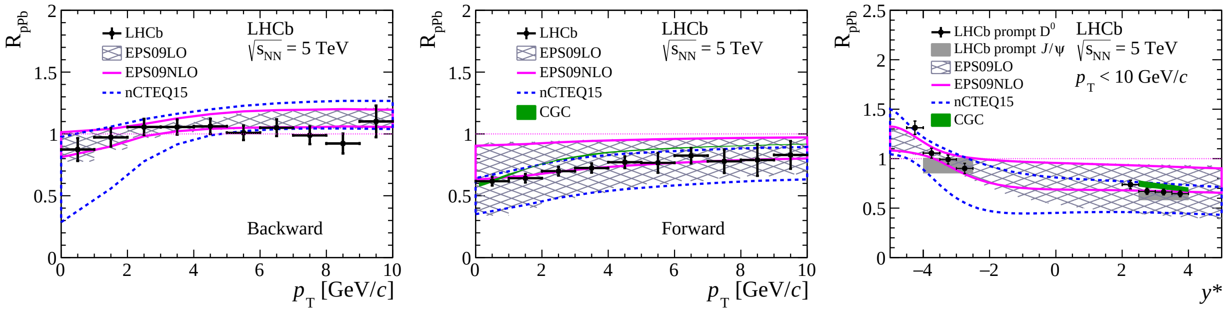

Figure 3. Nuclear Modification Factor for prompt production of D^0 mesons in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV as a function of p_T for the backward (left plot) and forward (middle plot) configurations, and as a function of y^* (right plot). Data are compared with HELAC-Onia predictions [10, 11, 12], including different nPDFs parametrizations, and a Color-Glass-Condensate model [14]. The error bars represent the quadratic sum of the statistical and the systematic uncertainties. Colour online.

Another very interesting observable, which also constitutes an excellent probe to constrain the nPDFs uncertainties, is the *forward-backward production ratio*, defined as:

$$R_{FB}(p_T, y^*) = \frac{d^2\sigma_{pPb}(p_T, +|y^*|)/dp_T dy^*}{d^2\sigma_{pPb}(p_T, -|y^*|)/dp_T dy^*} \,. \tag{2}$$

It is shown in figure 4 as a function of p_T (in the common rapidity region: $2.5 < |y^*| < 4.0$) for prompt D^0 and Λ_c^+ production. In both cases $R_{FB}(p_T, y^*)$ is significantly smaller than unity, indicating a larger production rate in the backward region compared to the forward region. The results are compared with HELAC-Onia calculations (including different LO and NLO nPDFs parametrizations) [10, 11, 12]. Data are consistent with the theory predictions in the full kinematic range for both D^0 and Λ_c^+ productions.

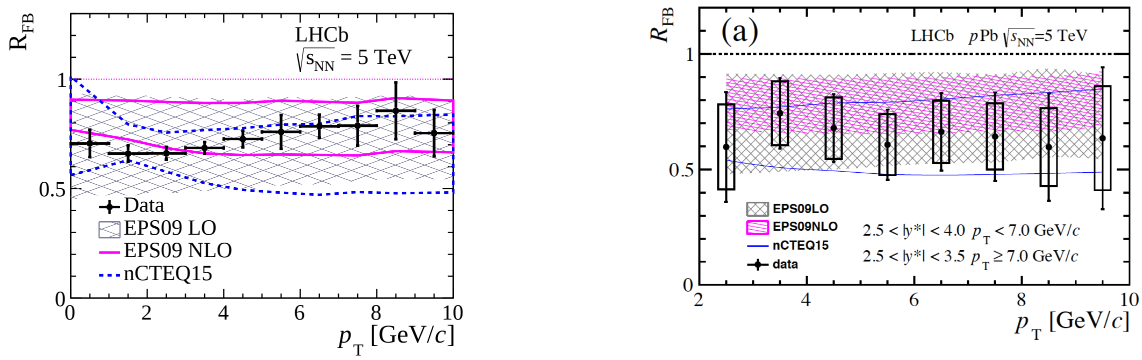

Figure 4. Forward-backward production ratios for prompt D^0 mesons (left) and prompt Λ_c^+ baryons (right) as a function of p_T compared with HELAC-Onia predictions [10, 11, 12]. Colour online.

Finally, the charmed *baryon-to-meson ratio* was also measured. This observable provides information on the hadronization mechanisms in the charm sector and is sensitive to the ratio of the fragmentation functions of a c-quark into Λ_c^+ and D^0 hadrons. It is defined as:

$$R_{\Lambda_c^+/D^0}(p_T, y^*) = \sigma_{\Lambda_c^+}(p_T, y^*)/\sigma_{D^0}(p_T, y^*) \ . \tag{3}$$

From the theoretical point of view, it constitutes an ideal observable since most of the nPDFs uncertainties cancel in the ratio. The results are shown in figure 5 as a function of p_T, separately for the backward and the forward regions, and as a function of y^*. The theoretical predictions [10, 11, 12], tuned to pp data, indicate a slight increase of $R_{\Lambda_c^+/D^0}$ with p_T and are consistent with data within the experimental uncertainties, except for the forward configuration in the high-p_T region, where they overestimate the data.

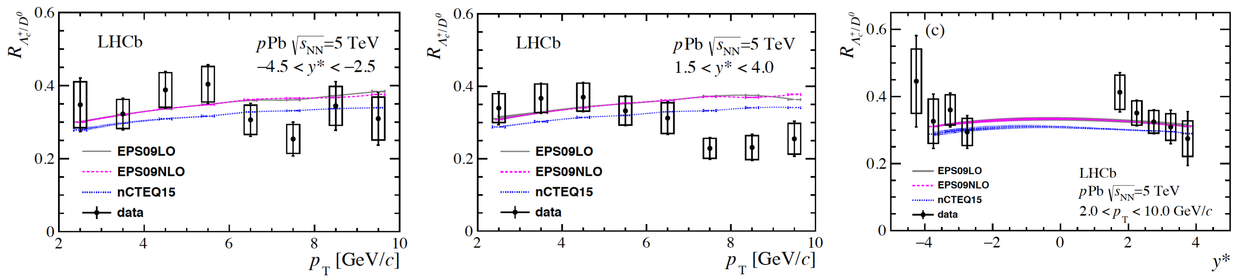

Figure 5. Λ_c^+/D^0 production ratios as a function of p_T for the backward (left plot) and forward (middle plot) configurations, and as a function of y^* (right plot) compared with HELAC-Onia predictions [10, 11, 12]. Colour online.

6. Conclusions

LHCb provided first measurements of prompt D^0 and Λ_c^+ production in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV. Several physical observables (nuclear modification factor, forward-backward ratio, charmed baryon-to-meson ratio) have been measured and compared with model predictions. These observables are sensitive to cold-nuclear-matter effects and, under the assumption that nuclear PDFs modification is the dominant effect, they allow to constrain the nPDFs parametrizations and to reduce their uncertainties. High statistics data, obtained from pPb collisions at $\sqrt{s} = 8$ TeV, will soon be released, providing new high-precision results on both the charm and the beauty sectors.

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