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 $\Lambda_c^+$ 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 (∼ 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 < η < 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. The two sets of data have been collected at LHCb with pPb collisions: the first (2013) at √sNN = 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 √sNN = 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^−π^+ decay mode has been used. The inclusive yield of D^0 candidates is extracted through an extended unbinned maximum likelihood fit to the distribution of the K^−π^+ invariant mass. The inclusive signal yield selected in this way includes both “prompt D^0νν” candidates, i.e. coming from the primary vertex (PV), and “non-prompt D^0νν” candidates, i.e. those created in the decay of b-hadrons. The two contributions are separated through a fit of the log_{10}(χ^2_F(D^0)) distribution, where χ^2_F(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*. 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 ± 0.5 ± 13.0 mb and 252.7 ± 1.0 ± 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^−π^+ 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^−π^+ 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.
The nuclear modification factor, here defined as \( R_{pPb}(p_T, y^*) \), 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.

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

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

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 \( \Lambda^+_c \) 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 \( \Lambda^+_c \) productions.
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 $\Lambda_c^+$ and $D^0$ hadrons. It is defined as:

$$R_{\Lambda_c^+/D^0}(p_T, y^*) = \frac{\sigma_{\Lambda_c^+}(p_T, y^*)}{\sigma_{D^0}(p_T, y^*)}.$$  \hfill (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. $\Lambda_c^+/D^0$ 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.](image)