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Nuclear modification of prompt and non-prompt J/ψ production in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV with ALICE

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Abstract. Various Cold Nuclear Matter (CNM) effects, such as nuclear shadowing or partonic energy loss, can modify the production of J/ψ in heavy-ion collisions with respect to what is measured in elementary colliding systems. The study of p–Pb collisions at the Large Hadron Collider (LHC) energy scale represents a crucial tool to assess the influence of Cold Nuclear Matter on J/ψ production in order to achieve a more correct interpretation of Pb–Pb collision results. The ALICE detector at the LHC is capable of reconstructing J/ψ mesons at central rapidity through their e^+e^- decay channel down to zero transverse momentum ($p_{\rm T}$), and has measured the fraction of J/ψ produced from the decay of beauty-flavoured hadrons (non-prompt J/ψ) in p–Pb collisions down to $p_{\rm T}$ = 1.3 GeV/c. In this paper, the results obtained by ALICE from the measurement of the prompt and non-prompt J/ψ yields at mid-rapidity in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV will be discussed in comparison to different theoretical predictions including CNM effects.

1 Introduction

Quarkonia and open heavy-flavoured hadrons have long been the subject of an intense theoretical and experimental effort. Their production represents a challenging testing ground for models based on quantum chromodynamics (QCD), and several initial- or final-state effects can contribute to modify the yields measured over different colliding systems. While heavy-quarks are considered as excellent tools for probing the transition of hadronic matter to a Quark–Gluon Plasma (QGP) phase in ultra-relativistic heavy-ion collisions, several mechanisms not related to the formation of QGP, and referred as Cold Nuclear Matter (CNM) effects, can contribute to modify the observed yields with respect to elementary nucleon-nucleon (NN) collisions. For heavy quarks produced at the LHC, the most relevant are the parton-density shadowing and gluon saturation effects, which can be described using modified nuclear parton distribution functions (nPDFs) [1] or in the framework of the Color-Glass Condensate (CGC) effective theory [2]. Other effects account for the energy loss or momentum broadening of partons [3, 4], which can occur in the early stages of the collision.

The measurement of heavy-flavoured hadrons produced in proton-nucleus (p–A) collisions and its comparison to pp results provides a crucial tool to constrain these mechanisms and

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disentangle the hot and cold nuclear effects envisioned in nucleus-nucleus (A–A) collisions. The inclusive production of J/ψ mesons at the LHC in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV was studied by ALICE at backward, mid- and forward rapidity down to zero transverse momentum ($p_{\rm T}$) [5]. Besides prompt J/ψ directly produced in the p-Pb collision or via the decay of heavier charmonium states (such as $\chi_{\rm c}$ and ψ(2S)), a significant contribution comes from non-prompt J/ψ which are produced after the weak decay of beauty-hadrons. ALICE has recently reported the measurement of such component [6], allowing an assessment of CNM effects on beauty quark production as well as a more direct comparison with models describing prompt charmonium production in heavy-ion collisions.

2 Data sample and analysis

The analysis for the measurement of the prompt and non-prompt J/ψ yields was carried out on the Minimum Bias (MB) data sample collected during the LHC p–Pb run in 2013, consisting of about 10^8 events and corresponding to an integrated luminosity $L_{\rm int}$ = 51.4 ± 1.9 μb^{-1}. In order to detect J/ψ at central rapidity ($-0.43 < y_{\rm cms} < 1.37$), the resonance was reconstructed through its e^+e^- decay channel exploiting ALICE central barrel detectors, which cover the pseudorapidity range $|\eta| < 0.9$ [7]. The main detectors used are the Time Projection Chamber (TPC), which allows tracking and charged particle identification via specific ionisation energy loss (dE/dx) measurements, and the Inner Tracking System (ITS), which provides track and vertex reconstruction close to the interaction point. Other detectors, such as the V0 and T0 scintillators, are involved in the triggering of minimum bias events and in the rejection of beam-induced background.

The reconstruction of J/ψ candidates in the e^+e^- channel was performed by combining opposite-charge tracks reconstructed in the TPC and ITS and fulfilling dedicated selection criteria. In particular, the dE/dx signal in TPC was required to be compatible with that of an electron, while tracks compatible with the pion and proton assumptions were rejected. Furthermore, all tracks were required to have at least one hit in the innermost layer of the ITS in order to enhance the resolution of secondary decay vertices needed for the non-prompt signal extraction.

The measurement of the fraction $f_{\rm b}$ of the J/ψ yield originated from beauty-hadron decays was performed on a statistical basis, following the same approach used in previous analyses for the pp and Pb–Pb colliding systems [8, 9]. Such approach relies on the discrimination of J/ψ produced far from the primary p-Pb collision vertex by means of the pseudo-proper decay length (x) variable, defined as

$$x = \frac{\vec{L} \cdot \vec{p}_{\rm T}^{\,{\rm J}/\psi}}{p_{\rm T}^{{\rm J}/\psi}} \cdot \frac{c \cdot m^{{\rm J}/\psi}}{p_{\rm T}^{{\rm J}/\psi}} ,$$

with $\vec{L}$ being the vector from the primary vertex to the J/ψ decay vertex and $m^{{\rm J}/\psi}$ being the J/ψ pole mass value. An un-binned maximum likelihood fit to the two-dimensional distribution of invariant mass $m_{e^+e^-}$ and x of the candidate di-electron pairs is then performed to extract $f_{\rm B}$. As shown in Figure 1, prompt and non-prompt J/ψ exhibit well-distinguished x distributions, allowing their statistical separation down to $p_{\rm T}$ as low as $\sim$ 1.3 GeV/c. The main systematic uncertainties affecting the determination of $f_{\rm B}$ arise from the estimation of the x resolution function and from the assumptions on the x and $m_{e^+e^-}$ probability density functions employed in the likelihood fit for the description of the background, prompt and non-prompt components. Figure 2 shows the values of the fraction of non-prompt J/ψ measured by ALICE as a function of transverse momenta compared to the results of ATLAS [10] covering the high $p_{\rm T}$

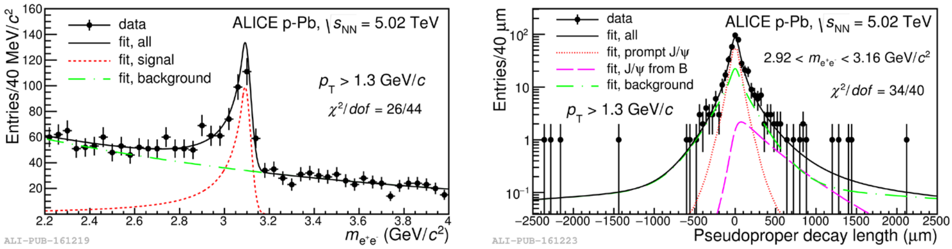

Figure 1. e^+e^- invariant mass (left panel) and pseudo-proper decay length (right panel) distributions of J/ψ candidates, with $p_{\mathrm{T}} > 1.3$ GeV/c. The projections of the prompt, non-prompt and background components resulting from the likelihood fit are shown superimposed.

region ($p_{\mathrm{T}} > 8$ GeV/c) in a similar rapidity range. Similar measurements performed in NN collisions are also shown.

3 Results

The modifications affecting J/ψ production due to the presence of the nuclear medium were quantified by means of the nuclear modification factor R_{pPb}. For a given y and p_{T} of the J/ψ, it is defined as the ratio of the differential production cross section in p–Pb collisions to that in pp collisions, scaled by the Pb atomic mass number A_{Pb}:

$$R_{\mathrm{pPb}}(y, p_{\mathrm{T}}) = \frac{\mathrm{d}^2\sigma^{\mathrm{J}/\psi}_{\mathrm{pPb}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}{A_{\mathrm{Pb}} \cdot \mathrm{d}^2\sigma^{\mathrm{J}/\psi}_{\mathrm{pp}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}.$$

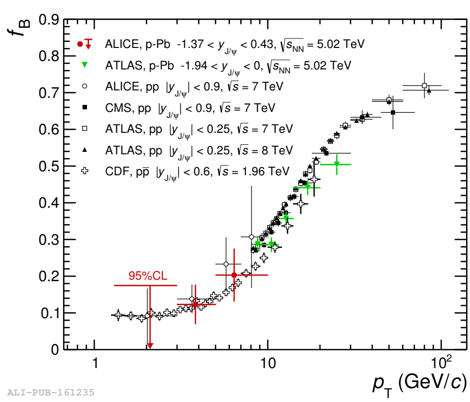

Figure 2. Fraction of J/ψ from the decay of b-hadrons at mid-rapidity as a function of the p_{T} of the J/ψ in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV compared with results from ATLAS [10] and with previous measurements performed in NN collisions at different energies. Vertical error bars represent the quadratic sum of the statistical and systematic errors. For the interval $1.3 < p_{\mathrm{T}} < 3$ GeV/c, the upper limit at the 95% confidence level on the ALICE data point is shown.

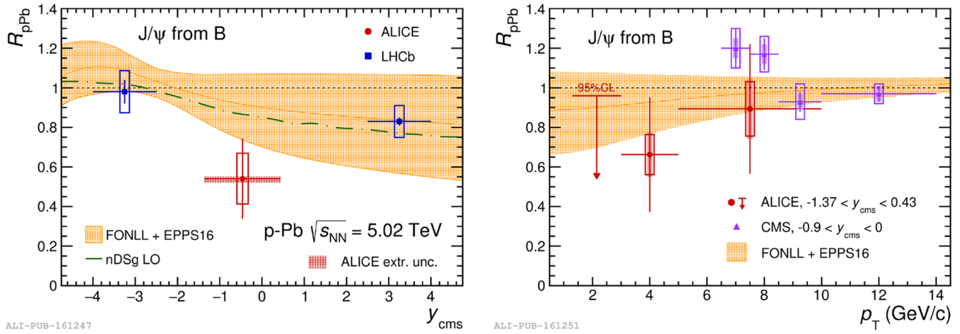

Figure 3. $R_{\rm pPb}$ of non-prompt J/ψ as a function of rapidity for $p_{\rm T} > 0$ (left panel) and as a function of $p_{\rm T}$ at mid-rapidity (right panel). Error bars and boxes indicate the statistical and systematic uncertainties, respectively. For the ALICE data points, the systematic uncertainty due to the extrapolation down to $p_{\rm T} = 0$ is depicted as a red box in the left panel, whereas the upper confidence limit at 95% confidence level for the interval $1.3 < p_{\rm T} < 3$ GeV/c is shown as an arrow in the right panel.

In the absence of nuclear effects, $R_{\rm pPb}$ is expected to equal unity, whereas $R_{\rm Pb} < 1$ ($R_{\rm Pb} > 1$) indicates a suppression (enhancement) with respect to what expected in the case of a scaling with the number of binary NN collisions.
By combining the $R_{\rm pPb}$ of inclusive J/ψ measured from the same data sample [5] with the interpolated value of $f_{\rm B}$ in pp collisions at $\sqrt{s} = 5.02$ TeV and with the measurements of $f_{\rm B}$ in p–Pb collisions, the nuclear modification factor for prompt and non-prompt J/ψ mesons at mid-rapidity was determined either $p_{\rm T}$-integrated or as a function of transverse momentum in three $p_{\rm T}$ intervals.
Figure 3 shows the $R_{\rm pPb}$ of non-prompt J/ψ as measured by ALICE for $p_{\rm T} > 0$ in comparison to LHCb measurements [11] at backward and forward rapidity, and as a function of $p_{\rm T}$ in comparison to CMS results [12]. The measurements appear to be in reasonable agreement with theoretical calculations including gluon shadowing from the nuclear modification of the parton distribution functions [13, 14]. In Figure 4, the $R_{\rm pPb}$ of prompt J/ψ is similarly reported as a function of rapidity and transverse momentum, compared to predictions from various models implementing CNM effects. In particular, data appear in fair agreement with models combining parton shadowing with energy loss mechanisms [15] or with the effects from the interaction with a nuclear medium [16], while purely energy loss calculations [17] appear disfavoured. Recent models based on different implementations of the CGC effective theory [18, 19] are also in good agreement with the measurements at forward rapidity.

4 Summary

The production of J/ψ mesons in p-Pb collisions at the LHC has been measured by ALICE at mid-rapidity and down to J/ψ $p_{\rm T}$ of 1.3 GeV/c. The nuclear modification factor has been computed for both prompt and non-prompt J/ψ in order to quantify the effects of the cold nuclear medium on charmonium and beauty production. ALICE results, covering the low $p_{\rm T}$ region at mid-rapidity, complement the data of the other LHC experiments and suggest that the reduced production observed at mid-rapidity for both prompt and non-prompt J/ψ with respect to expectations from pp collisions is a low-$p_{\rm T}$ effect. While the suppression is

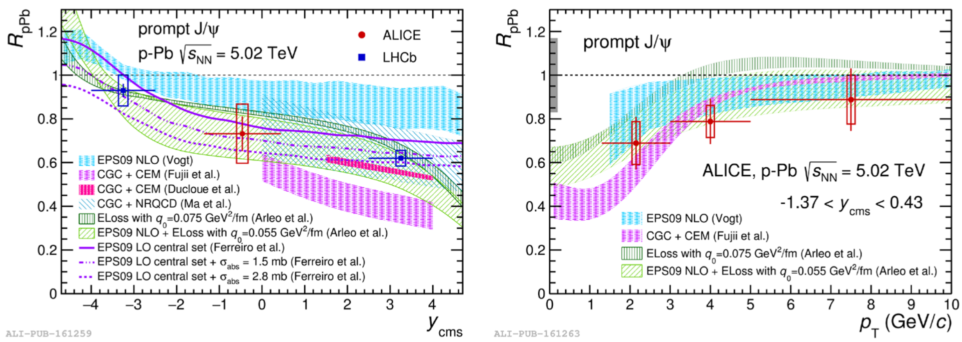

Figure 4. $R_{\rm pPb}$ of prompt J/ψ as a function of rapidity for $p_{\rm T} > 0$ (left panel) and as a function of $p_{\rm T}$ at mid-rapidity (right panel). Statistical and systematic uncertainties are shown as vertical error bars and open boxes, respectively. The size of the $p_{\rm T}$-correlated relative systematic uncertainties is shown as a grey box around $R_{\rm pPb} = 1$ in the right panel.

compatible within uncertainties to theoretical predictions employing CNM effects, present uncertainties still do not allow a precise discrimination among the different models.

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