NEW RESULTS ON INITIAL STATE AND QUARKONIA WITH ALICE

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ABSTRACT

The study of quarkonia in heavy-ion collisions has been the subject of intense experimental and theoretical effort, ever since their production was predicted to be sensitive to the formation of a deconfined state of strongly-interacting matter, known as the Quark–Gluon Plasma (QGP). In p–Pb collisions, Cold Nuclear Matter (CNM) effects, such as nuclear shadowing or partonic energy loss, are expected to influence quarkonium production. The study of such system is therefore crucial to shed light on the mechanisms taking place at the initial-state of quarkonium production, and to disentangle the cold and hot nuclear effects envisioned in Pb–Pb collisions. The ALICE experiment at the LHC, is capable of reconstructing J/ψ, ψ(2S) and Υ states at forward rapidity through their μ⁺μ⁻ decay channel, as well as J/ψ at central rapidity through their e⁺e⁻ decay channel, down to zero transverse momentum. A review of the main ALICE findings from the measurements of the inclusive quarkonium yields in p–Pb collisions at √s_{NN} = 5.02 TeV, collected during the LHC Run I period, as well as more recent results from J/ψ measurements in p–Pb at √s_{NN} = 8.16 TeV, from LHC Run II period, will be presented in this paper.

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1 Introduction

The production of quarkonia – bound states of heavy charm or beauty quark and anti-quark pairs – represents a challenging and not yet fully understood subject in the field of High-Energy Physics, which invokes aspects of both the perturbative and non-perturbative regimes of Quantum Chromodynamics (QCD). As of today, quarkonium formation in elementary hadronic systems is described by QCD-based models as a two-step process which involves the perturbative creation of the $q\bar{q}$ pair via hard scattering, and its subsequent non-perturbative evolution towards a specific bound final state. In heavy-ion systems, quarkonia play a further important role as they have long been proposed as ideal probes of the hot and dense strongly-interacting matter produced in such collisions. A suppression of charmonium production was indeed predicted as a signature of the phase transition of hadronic matter to a Quark–Gluon Plasma at sufficiently high energy densities [1].

Several effects due to the presence of Cold Nuclear Matter, and not related to the formation of QGP, can however contribute to modify the observed quarkonium yields with respect to elementary nucleon–nucleon collisions. During the initial stage of their formation, quarkonium production cross sections can be either suppressed (shadowing) or enhanced (anti-shadowing), as a result of the modification of the kinematical distributions of partons experienced in nuclei [2]. Furthermore, if the production process is dominated by low-momentum gluons, as it is expected at LHC energies, the gluons may behave as a coherent and dense partonic system, which can be described in the framework of Color–Glass Condensate effective theory, providing predictions when combined with a specific quarkonium production model [3, 4]. In addition, both the incoming partons and the outgoing $q\bar{q}$ pair propagating through the nucleus may lose energy by gluon radiation at various stages of the formation process, including the occurrence of coherent energy loss processes [5]. The evolving $q\bar{q}$ pair or even the final-state resonance may finally interact with the nucleons while traveling through the nucleus or with the other co-moving partons and hadrons produced in the collision [6], consequently losing energy or breaking up into open-flavor meson pairs. The study of p–Pb collisions at the LHC provides an ideal way to test the interplay between the different mechanisms affecting quarkonium production in a previously unexplored kinematic range, where the yield is expected to be dominated by initial-state CNM effects.

2 Quarkonium measurement with ALICE

ALICE at the CERN LHC allows the measurement of quarkonium states down to zero transverse momentum ($p_T$), in a complementary kinematic region with respect to other LHC experiments [7]. At central rapidity ($y$), the $J/\psi$ resonance is detected through its $e^+e^-$ decay channel making use of ALICE central barrel detectors, which cover the pseudorapidity range $|\eta| < 0.9$. At forward rapidity, $J/\psi$, $\psi(2S)$ and $\Upsilon$ states are reconstructed through their $\mu^+\mu^-$ decay channel by means of the ALICE muon spectrometer, covering the pseudorapidity range $-4 < \eta < -2.5$.

The Time Projection Chamber (TPC) is the main tracking detector of the barrel, consisting of a large cylindrical drift chamber which allows also charged particle identification through specific energy loss ($dE/dx$) measurements. The Inner Tracking System (ITS) is a cylindrically-shaped tracker made up of six layers of silicon detectors which provide precise tracking and vertex reconstruction close to the interaction point. The muon spectrometer consists of a front absorber, used to filter out the hadrons produced in the interaction, a tracking system, made up of five Cathod Pad Chamber stations, a large 3 T·m dipole magnet, and two Resistive Plate Chamber trigger stations, shielded by a muon filter wall. The information from the Zero Degree Calorimeters (ZDC), symmetrically placed at 112.5 m from the interaction point, is used to reject de-bunched proton-lead collisions, while two scintillator hodoscopes (V0), with pseudorapidity coverage $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, are used to remove beam-induced background. A signal coincidence in the two V0 detectors provides the trigger to select Minimum Bias (MB) events on which most analyses are performed, whereas dimuon analyses rely on a dimuon trigger which requires, in addition to the MB condition, the detection of two opposite-sign tracks in the muon trigger stations. Finally, the slow neutron energy deposited by the Pb nucleus remnants in the ZDC is used to determine the event centrality. Such observable was found to be less sensitive to the dynamical bias observed in centrality estimations based
on charged-particle multiplicity, which are usually employed in Pb–Pb collisions [8]. Over the last years, ALICE collected p–Pb data in two beam configurations, corresponding to either protons or lead ions going towards the muon spectrometer, which allowed the coverage of two different intervals in the forward and backward dimuon rapidity regions and of two corresponding Bjorken-\(x\) (\(x_{Bj}\)) ranges. At the beginning of 2013, during the LHC Run I period, data samples from p–Pb collisions at the centre-of-mass energy per nucleon-nucleon collision \(\sqrt{s_{NN}} = 5.02\) TeV were collected, with corresponding integrated luminosities of 5 nb\(^{-1}\), 5.8 nb\(^{-1}\) and 51 \(\mu\)b\(^{-1}\) for the forward, backward and central rapidity intervals. The analysis of such samples provided a wide variety of physics results which helped investigating the size of CNM effects on both charmonium and bottomonium production. In 2016, p–Pb collisions at \(\sqrt{s_{NN}} = 8.16\) TeV delivered during the LHC Run II period allowed even larger data samples to be collected, with corresponding integrated luminosities of 8.7 nb\(^{-1}\) and 12.9 nb\(^{-1}\) in the forward and backward rapidity intervals, on which dimuon analyses of \(J/\psi\) production have recently been carried out.

3 Results from Quarkonium analyses in p–Pb collisions

The production of \(J/\psi\) in p–Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV has been deeply studied by ALICE, carrying out measurements of the \(J/\psi\) yield either as a function of \(y\) and \(p_T\) [9, 10], or as a function of centrality [11]. In order to quantify the size of nuclear effects on their production, the nuclear modification factor (\(R_{pPb}\)), i.e. the ratio of the yield measured in p–Pb collisions to that in pp scaled by the number of binary collisions, was employed. The first measurements showed that the \(J/\psi\) yield at forward rapidity was significantly suppressed while at backward rapidity the production was consistent with a binary scaling from pp collisions. Later, differential measurements as a function of transverse momentum, pointed out that the suppression was strongly dependent on \(p_T\), being significantly larger at forward \(y\) and low \(p_T\) while tending to vanish towards high \(p_T\) and at backward \(y\). The results were found to be in fair agreement with theoretical calculations including nuclear shadowing and/or energy loss, as well as with CGC-inspired models. Further measurements as a function of centrality, in three rapidity intervals, indicated that while data at backward \(y\) were consistent with no nuclear modifications for the most peripheral and semi-central events, a significant suppression of the \(J/\psi\) production in the full centrality range was present in the middle and forward rapidity intervals, whereas a hint for enhancement was observed in the most central collisions at backward rapidity. The recent analysis of p–Pb data at \(\sqrt{s_{NN}} = 8.16\) TeV, collected during the LHC Run II period, provided an even more detailed comparison to model predictions, thanks to the unprecedented reach in integrated luminosity. In Figure 1, ALICE measurements of the nuclear modification factor for inclusive \(J/\psi\) production in p–Pb collisions at \(\sqrt{s_{NN}} = 8.16\) TeV [12] are reported as a function of \(y\), over the rapidity intervals \(-4.46 < y < -2.96\) and \(2.03 < y < 3.53\), and as a function of transverse momentum, up to \(p_T = 20\) GeV/c.

While a significant suppression has been measured at forward rapidity, no significant nuclear effects are seen

![Figure 1: The nuclear modification factor for inclusive J/ψ production at √sNN = 8.16 TeV as a function of rapidity (Left) and as a function of transverse momentum, at backward (Middle) and forward (Right) y, compared to theory predictions. The error bars represent statistical uncertainties, the boxes around R_{pPb} = 1 represent the correlated global uncertainties.](image-url)
at backward rapidity, revealing a compatible trend to previous measurements at $\sqrt{s_{NN}} = 5.02$ TeV. Results as a function of $p_T$ show hints for an enhancement of the production at $p_T > 4$ GeV/c at backward $y$, whereas at forward $y$ the $R_{p\text{Pb}}$ tends to unity towards high-$p_T$. Data are compared with various theoretical calculations implementing different combinations of CNM effects. In particular, predictions from models including shadowing parametrizations \[13\,14\], CGC-based approaches \[3\,4\] and coherent energy loss mechanisms \[5\], in combination with different production models, are reported. Central predictions from models based on a comover approach \[6\] or including a combination of CNM effects and interactions with the produced medium \[15\] are also compared to data. All the calculations appear reasonably in agreement with the data, although it should be noted that data achieved a precision which is challenging for most model predictions.

Figure 2: The nuclear modification factor for inclusive $\psi(2S)$ production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of rapidity (Left) and of centrality at backward (Middle) and forward (Right) $y$. Data are compared to similar measurements for J/$\psi$, as well as to different theory predictions. The error bars represent statistical uncertainties, the boxes around the points the uncorrelated systematic uncertainties and the filled boxes around $R_{p\text{Pb}} = 1$ represent the correlated global uncertainties.

The nuclear modification factor for the $\psi(2S)$ state production was measured by ALICE in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, integrated over $p_T$, as a function of rapidity \[16\] and centrality \[11\], and is reported in Figure 2. Measurements showed a significantly stronger suppression of the $\psi(2S)$ with respect to the J/$\psi$ in the same kinematic ranges, especially at backward $y$, which increases with the centrality of the collision. Considering that, within the accessed kinematic domains, the time needed to form the final-state resonance is larger than the crossing time of the $c\bar{c}$ pair in the nucleus, such observation cannot be ascribed to a break-up by cold nuclear matter of the more weakly bound $\psi(2S)$ state. Furthermore, CNM models based on shadowing and parton energy loss, being independent on quantum numbers of the final-state, predict the same degree of suppression for both charmonium states and fail in reproducing $\psi(2S)$ experimental results. Final-state effects need to be introduced to explain the different suppression. Models including a dissociation contribution with co-moving partons and particles \[6\], or with a hot hadron resonance gas experiencing a short phase transition to a QGP phase \[17\], appear indeed capable of reproducing the size of the observed suppression.

The production of bottomonium in p–Pb systems was also studied by ALICE \[18\]. In Figure 3 the measurements of the nuclear modification factor for the $\Upsilon(1S)$ state as a function of rapidity in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are reported either differentially, in four rapidity intervals, or integrated over the backward or forward rapidity ranges. Data indicate a suppression of the inclusive $\Upsilon(1S)$ production yields at forward rapidity in p–Pb compared to pp collisions, whereas at backward rapidity the $R_{p\text{Pb}}$ is compatible with unity within uncertainties. When compared to previous J/$\psi$ measurements, the $\Upsilon(1S)$ and J/$\psi$ $R_{p\text{Pb}}$ exhibit a similar trend, with the J/$\psi$ $R_{p\text{Pb}}$ being systematically higher at negative rapidities but rather similar to the $\Upsilon(1S)$ $R_{p\text{Pb}}$ at positive rapidities within uncertainties. Results are compared to a model implementing a shadowing parametrization \[13\], and to a parton energy loss calculation \[5\], either with or without gluon shadowing. Even if the experimental uncertainties are large, the calculations tend to overestimate the measured nuclear modification factors, especially at backward rapidities, where a strong gluon anti-shadowing...
Figure 3: The nuclear modification factor for inclusive Υ(1S) production in p–Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV as a function of rapidity. Results are compared to those for J/ψ (Left) as well as to different model predictions (Right). The vertical error bars represent the statistical uncertainties and the open boxes the uncorrelated systematic uncertainties. The filled boxes around \( R_{pPb} = 1 \) show the size of the correlated uncertainties.

contribution appears disfavoured. The Υ(2S) production was also studied, and the ratio of the Υ(2S) to Υ(1S) production cross sections was measured in both rapidity ranges. Within uncertainties, compatibility with previous ALICE measurements of the same ratio in pp collisions at \( \sqrt{s} = 7 \) TeV was found, therefore suggesting no evidence of a different magnitude of CNM effects for the Υ(2S) with respect to the Υ(1S).

4 Conclusions

Quarkonium production was measured in p–Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV by ALICE as a function of \( p_T, y \) and centrality for different quarkonium states, and in p–Pb collisions at \( \sqrt{s_{NN}} = 8.16 \) TeV for the J/ψ state. A significant suppression of the J/ψ yield at forward rapidity and low \( p_T \) was observed, while the results appear compatible at the two energies. The trend of the suppression can be fairly described by models implementing different CNM effects, such as shadowing and energy loss. A significantly stronger suppression of the ψ(2S) state relative to J/ψ was measured in p–Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV. Models including final-state interactions are needed to explain the different degree of suppression. Measurements of Υ(1S) production at \( \sqrt{s_{NN}} = 5.02 \) TeV show that the yield in p–Pb collisions is suppressed with respect to expectations from pp collisions at forward \( y \), while at backward \( y \) the data are consistent with no suppression within experimental uncertainties, disfavouring models with strong gluon anti-shadowing contributions.

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