Charmonium production in pp, p–Pb and Pb–Pb collisions at forward rapidity with ALICE at the LHC

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Abstract. This contribution presents recent ALICE measurements on charmonium production at forward rapidity in pp collisions at $\sqrt{s} = 7$ TeV, p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV and Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV. The charmonium production cross sections in pp collisions are in good agreement with calculations within the NRQCD approach. The comparison between J/ψ and $\psi(2S)$ yields in p–Pb collisions indicates the presence of Cold Nuclear Matter effects on charmonium production in the final state. In Pb–Pb collisions the measured J/ψ suppression is in agreement with models that introduce J/ψ regeneration mechanisms through the recombination of $c\bar{c}$ pairs produced in the medium.
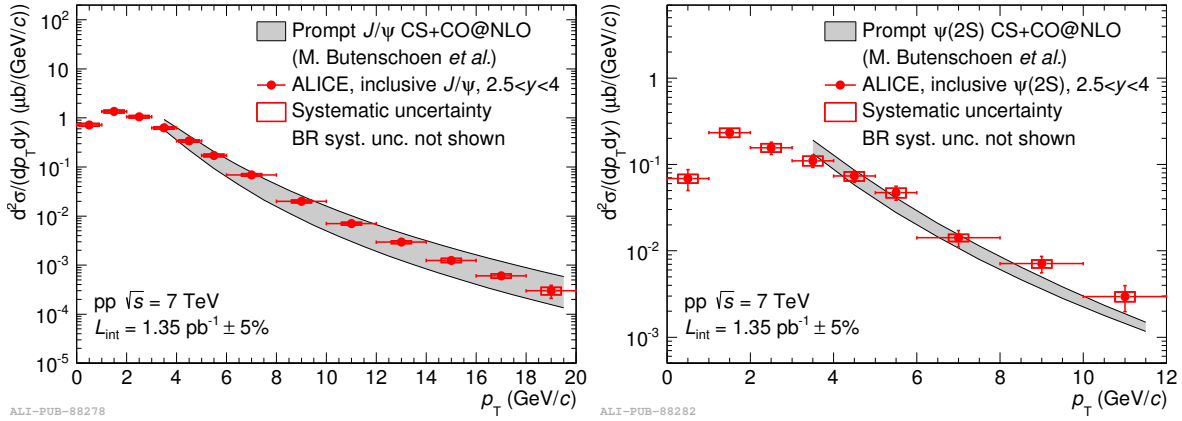
1. Introduction

Charmonia have been an intense subject of study since their discovery 40 years ago [1, 2]. Their production involves different energy scales allowing to test different regimes of quantum chromodynamics (QCD). Experimental and theoretical efforts have since then addressed the question of charmonium production mechanisms in nucleon–nucleon collisions [3]. Also interesting, charmonium states have been proposed as a probe of the Quark–Gluon Plasma (QGP) formation in high-energy heavy-ion collisions [4]. In the presence of the hot medium their yields are expected to be modified with respect to those in nucleon–nucleon collisions due to color screening effects on the $c\bar{c}$ binding potential. Charmonium suppression in nucleus–nucleus collisions was observed by a number of experiments at SPS, RHIC and LHC [5–8]. At LHC energies, however, a smaller suppression compared to that measured at RHIC has been observed at low transverse momentum, $p_{\rm T}$, suggesting the presence of regeneration mechanisms in the medium [9–11]. Those effects are usually quantified by measuring the nuclear modification factor $R_{\rm AA}$, defined as the ratio of charmonium production yields in nucleus–nucleus and nucleon–nucleon collisions scaled by the average number of binary collisions. Furthermore, Cold Nuclear Matter (CNM) effects like the modification of the nucleon Parton Distribution Functions in the nucleus (nPDF), multiple scattering of partons in the nucleus, nuclear absorption or dissociation by comoving particles can also affect charmonium production yields. Charmonium suppression in nucleon–nucleus collisions was reported as well by experiments at SPS, RHIC and LHC [12–15]. The ALICE Collaboration studied J/ψ and $\psi(2S)$ production in pp, p–Pb and Pb–Pb collisions. The data were collected during LHC Run 1 at mid- and forward rapidity. At forward rapidity the study is performed in the dimuon decay channel with muon tracks reconstructed in the forward muon spectrometer. Details about the ALICE detector and the analysis procedures can be found in any of the cited ALICE publications (e.g. [11, 14, 16]).

2. Results from pp collisions at $\sqrt{s} = 7$ TeV

The results presented in this section were obtained from the pp at $\sqrt{s} = 7$ TeV data collected during 2011 [16]. Figure 1 shows the p_T dependence of the differential production cross section for


Figure 1. Inclusive J/ψ (*left*) and $\psi(2S)$ (*right*) double differential production cross section as a function of p_T. The data are compared with NLO NRQCD calculations [17].

inclusive J/ψ (left panel) and $\psi(2S)$ (right panel) in the rapidity range $2.5 < y < 4$. The data are compared with results from theoretical predictions for prompt J/ψ and $\psi(2S)$ production in the NRQCD framework, including NLO Color Singlet (CS) and Color Octet (CO) contributions [17]. A constant scaling factor was applied to the calculations to account for the prompt-to-inclusive comparison; good agreement between the data and the theoretical calculations is observed.

3. Results from p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The measurements in this section were performed on the p–Pb data sample recorded in 2013, where two center-of-mass (cms) rapidity domains were explored: backward rapidity ($-4.46 < y_{cms} < -2.96$) in the configuration in which the lead beam goes towards the muon spectrometer and forward rapidity ($2.03 < y_{cms} < 3.53$) in the opposite case. Figure 2 (left
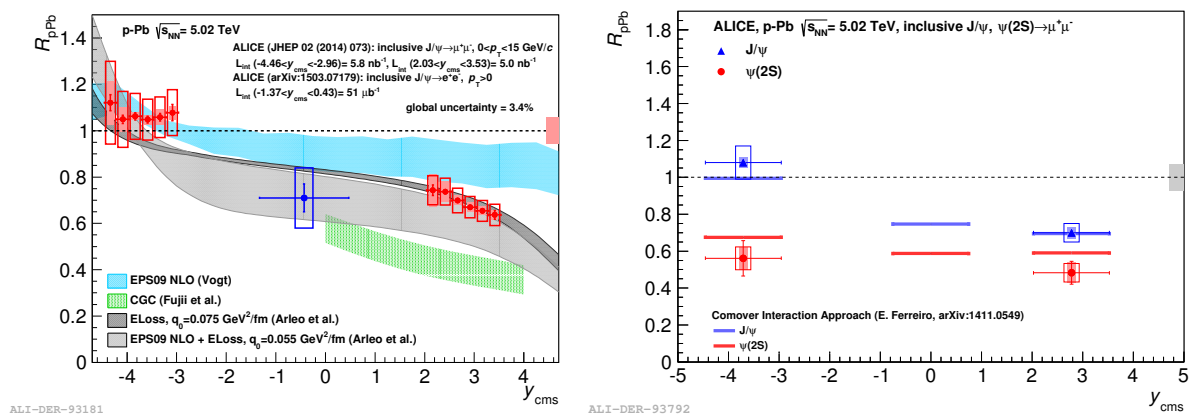
Figure 2. *Left:* inclusive J/ψ R_{pPb} as a function of rapidity. *Right:* inclusive J/ψ and $\psi(2S)$ R_{pPb} vs rapidity. The different theoretical calculations are described in the text.

panel) shows the nuclear modification factor R_{pPb} for inclusive J/ψ in the transverse momentum

interval $0 < p_{\text{T}} < 15$ GeV/c as a function of rapidity [14]. J/ψ suppression is observed at mid- and forward rapidity, while at backward rapidity R_{pPb} is compatible with unity within uncertainties. The data are compared with several models: a NLO CEM calculation that uses the EPS09 shadowing parameterization [18]; a prediction based on the Color Glass Condensate framework [19] and a calculation including coherent parton energy loss processes with and without shadowing effects [20]. Models including coherent energy loss processes in the nuclear matter are able to describe the experimental results.Figure 2 (right panel) shows the results for $\psi(2\text{S})$ and J/ψ in two rapidity bins for $p_{\text{T}} > 0$ [15]. A stronger suppression is observed in the case of $\psi(2\text{S})$ compared to J/ψ in particular in the backward rapidity region. Effects like shadowing and coherent energy loss are not expected to be sensitive to the final charmonium state, thus the theoretical predictions shown in the left panel of Figure 2 are essentially the same for both resonances. Nuclear absorption is also not expected to affect differently the J/ψ and $\psi(2\text{S})$ yields at the LHC (see for instance discussions in [15]). However, other final state mechanisms may be at place: predictions within the comover interaction approach are shown in the right panel of Figure 2 [21]. The dissociation by comovers is expected to have a stronger impact on the $\psi(2\text{S})$ yields due to its larger size compared to the J/ψ meson; additionally, the effect should be stronger in the Pb-going configuration (backward rapidity) due to the higher comover density. The inclusion of this effect results in a good qualitative agreement with the experimental measurements for both resonances.

4. Results from Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

Figure 3 shows the inclusive J/ψ nuclear modification factor R_{PbPb} as a function of p_{T} in the centrality range 0–90%. The Pb–Pb data sample used for these results was collected at the end of 2011 [11]. In the left panel, we can see the comparison with the product $R_{\text{pPb}}^{\text{forw}} \times R_{\text{pPb}}^{\text{backw}}$, which can be interpreted as an extrapolation of CNM effects to R_{PbPb} [22]. The extrapolation is valid if one assumes that shadowing is the main CNM effect involved in J/ψ production and given that the Bjorken-x ranges probed by the J/ψ production process in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV and at forward and backward rapidity in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, are approximately the same. From the comparison, it can be inferred that CNM effects cannot explain the J/ψ production yields in Pb–Pb collisions. At low-p_{T}, one would expect a stronger J/ψ suppression just as a result of nucleus related effects; R_{PbPb} being greater than $R_{\text{pPb}}^{\text{forw}} \times R_{\text{pPb}}^{\text{backw}}$ constitutes a hint of J/ψ production enhancement in Pb–Pb collisions. The results in the high-p_{T} region suggests that the strong suppression observed in Pb–Pb collisions is associated to hot nuclear matter effects. In the right panel of Figure 3 data are compared with two transport models [23, 24], primordial and regenerated J/ψ contributions are shown separately as well. The calculations of the two models differ essentially in the rate equation that controls J/ψ dissociation and regeneration. The uncertainty bands are related to the inclusion of CNM effects and the $c\bar{c}$ cross section. Both predictions show a fair agreement with the data. The J/ψ R_{AA} centrality dependence [11] and elliptic flow measurements [25], not shown here, confirms the regeneration model ansatz.

5. Conclusions

ALICE studied charmonia production at forward rapidity in all collision systems available during the LHC Run 1. A selection of results was presented here. J/ψ and $\psi(2\text{S})$ production cross sections in pp collisions at 7 TeV are in agreement with calculations including NLO CS+CO contributions within the NRQCD framework. The J/ψ nuclear modification factor in p–Pb collisions at 5.02 TeV indicates a higher impact of CNM effects at forward than at backward rapidities. The rapidity dependence can be explained by models including nPDF related effects and coherent energy loss processes. The $\psi(2\text{S})$ nuclear modification factor shows no significant dependence on rapidity, a stronger suppression compared to that of J/ψ was observed. The

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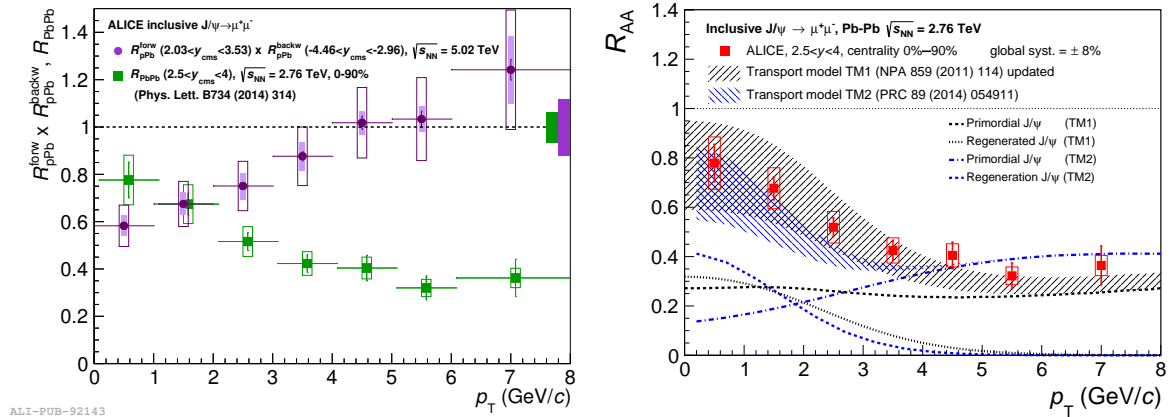
Figure 3. J/ψ R_{PbPb} as a function of p_{T} in the centrality range 0–90%. In the left panel a result from a CNM extrapolation is also shown. In the right panel the data are compared with two transport models [23, 24].

results could be interpreted in terms of a strong dissociation effect at backward rapidity due to the interaction with comovers, while the results at forward rapidity are dominated by shadowing effects. The p_{T} dependence of the J/ψ nuclear modification factor in Pb–Pb collisions at 2.76 TeV is in good agreement with transport models, thus favoring the interpretation of $c\bar{c}$ recombination mechanisms at the LHC energies.

6. Acknowledgement

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