Charmonium production in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV with ALICE

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Abstract.
The production of charmonium states, J/ψ and ψ(2S), in heavy-ion collisions, is an important probe to investigate the formation of a plasma of quarks and gluons. In such a hot and deconfined medium, quarkonium production is, indeed, expected to be significantly modified, with respect to the pp yields, due to the interplay of color screening and charm-quark recombination mechanisms. The ALICE Collaboration at the LHC has measured charmonium production in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The nuclear modification factor of inclusive J/ψ, evaluated at forward ($2.5 < y < 4$) rapidity, is measured as a function of the event centrality and of the J/ψ kinematic variables such as transverse momentum and rapidity. In this article, we report on the new J/ψ results, obtained at forward rapidity, at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. These new results are compared to that obtained at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and to the available theoretical predictions.

1. Introduction

The suppression of quarkonia (bound states of a heavy quark and its anti-quark) in ultra-relativistic heavy-ion collisions is one of the most prominent probes used to investigate and quantify the properties of the Quark-Gluon Plasma (QGP). The in-medium dissociation probability of the different quarkonium states could provide an estimate of the temperature of the fireball since the dissociation is expected to take place at different temperatures depending on the binding energies of the quarkonium states when the medium reaches or exceeds the critical temperature of the phase transition (T_{c}). For charmonium (c$\bar{\mathrm{c}}$) states, the J/ψ is likely to survive significantly above T_{c} ($1.5 - 2\ T_{\mathrm{c}}$) whereas χ_c and ψ(2S) melt near T_{c} ($1.1 - 1.2\ T_{\mathrm{c}}$) [1,2]. At LHC energies, due to the large increase of the c$\bar{\mathrm{c}}$ production cross-section with the collision energy, there is a possibility of J/ψ production via recombination of deconfined c and $\bar{\mathrm{c}}$. Thus, the observation of J/ψ production in nucleus-nucleus collisions via recombination also constitutes an evidence of QGP formation. The two effects act in opposite directions and the comparison of the J/ψ production at the different collision energies can provide insights to the evolution of the relative contributions of the two processes.

The ALICE experiment has studied inclusive J/ψ production in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and 5.02 TeV through its dimuon decay channel. Muons are identified and tracked in the Muon Spectrometer, which covers the pseudorapidity range $-4 < \eta < -2.5$ [3]. The pixel layers of the Inner Tracking System allow the vertex determination, while forward VZERO scintillators are used for triggering purposes. The VZERO is also used to determine the centrality of the collisions. In order to improve the purity of the muon tracks the following

selection criteria were applied: (1) both muon tracks with $p_T > 1$ GeV/c and matched with trigger, (2) both muon tracks in the pseudo-rapidity range $-4 < \eta < -2.5$, (3) transverse radius coordinate of the tracks at the end of the hadron absorber (the longitudinal position of the absorber from the interation point (IP) is $-5.0 < z < -0.9$ m) in the range $17.6 < R_{abs} < 89.5$ cm and (4) dimuon rapidity in the range $2.5 < y < 4$. These cuts eliminate mainly tracks hitting the edges of the spectrometers or crossing the thicker part of the beam shield. The data samples used in this analysis correspond to an integrated luminosity $L_{int}^{Pb-Pb} \approx 225$ μb^{-1} for Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV and $L_{int}^{pp} \approx 106$ nb^{-1} for pp collisions at $\sqrt{s} = 5.02$ TeV. The analysis techniques are described in detail in [4].

2. Results

The in-medium modification of the J/ψ production is quantified through the nuclear modification factor (R_{AA}), defined as the ratio of the J/ψ yield measured in Pb–Pb collisions to the expected yield obtained by scaling the J/ψ production cross section in pp collisions with the number of binary nucleon-nucleon collisions. The R_{AA} of the inclusive J/ψ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, integrated over the centrality, rapidity and transverse momentum (p_T) ranges (0–90%, $2.5 < y < 4$ and $p_T < 12$ GeV/c) is $R_{AA} = 0.65 \pm 0.01(\text{stat}) \pm 0.05(\text{syst})$ [4]. This shows that there is a suppression of the J/ψ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with respect to pp collisions at the same energy.
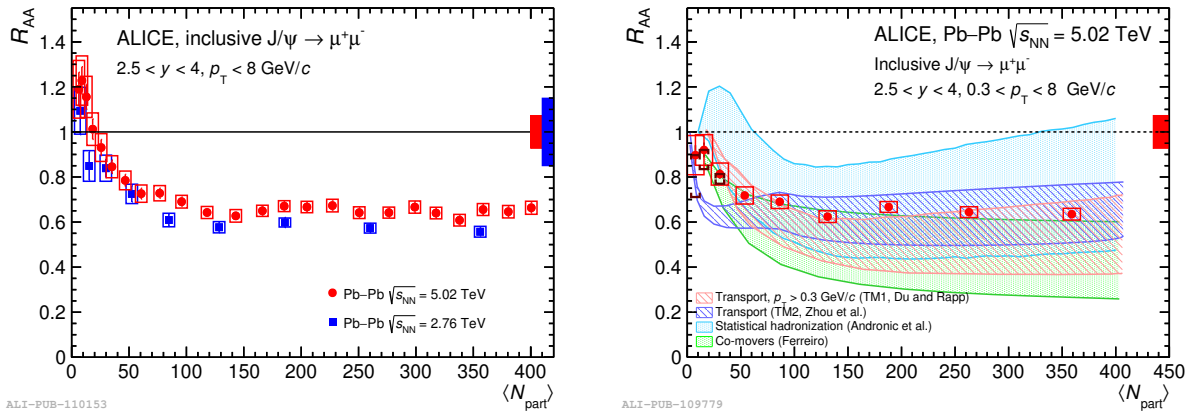

Figure 1. (Left) The inclusive J/ψ R_{AA} as a function of centrality at $\sqrt{s_{NN}} = 5.02$ TeV compared to published results at $\sqrt{s_{NN}} = 2.76$ TeV [5]. The statistical uncertainties are represented by the error bars. The boxes around the points represent the uncorrelated systematic uncertainties, while correlated global uncertainties are shown as filled boxes around $R_{AA} = 1$. (Right) The inclusive J/ψ R_{AA} for $0.3 < p_T < 8$ GeV/c compared to the theoretical models [6–11].

The centrality dependence of the inclusive J/ψ R_{AA} at $\sqrt{s_{NN}} = 5.02$ TeV and the comparison to that obtained at $\sqrt{s_{NN}} = 2.76$ TeV [5] are shown in Fig. 1. The large statistics collected at $\sqrt{s_{NN}} = 5.02$ TeV allows to carry out the measurement in much narrower centrality bins w.r.t. 2.76 TeV. The figure shows that there is an increasing suppression with centrality up to $N_{part} \sim 100$ followed by a roughly constant R_{AA} value at both energies. A systematic increase by about 15% is visible when comparing the two sets of results, although such an increase is within the overall uncertainty of the measurements. The R_{AA} of prompt J/ψ would be about 10% higher if $R_{AA}^{non-prompt} = 0$ (J/ψ's produced from b-hadron decays are called non-prompt J/ψ) and about 5% (1%) smaller if $R_{AA}^{non-prompt} = 1$ for central (peripheral) collisions.

An excess of J/ψ production at very-low p_T, which might originate from photo-production, was observed in peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [12]. According to the

prediction from STARLIGHT MC simulation [13] a p_T cut at 0.3 GeV/c removes ∼80% of the photo-produced J/ψ. The hadronic J/ψ R_{AA}, for $0 < p_T < 8$ GeV/c, is estimated to be about 34%, 17% and 9% smaller than the measured values in the 80–90%, 70–80% and 60–70% centrality classes, respectively [14]. The variation decreases to about 9%, 4% and 2%, respectively, when considering the R_{AA} for J/ψ with $0.3 < p_T < 8$ GeV/c, due to the remaining small contribution from photo-produced J/ψ. After such a selection, a less pronounced increase of R_{AA} for peripheral events can indeed be seen by comparing the left and right plots in Fig. 1. The brackets shown in the right figure for the three most peripheral centrality intervals represent the range of variation for the hadronic J/ψ R_{AA} under extreme hypothesis [14] on the photo-production contamination.

The results have been compared to the theoretical calculations based on a statistical model approach [6], a transport model (TM1) [9,10], which is based on a thermal rate equation, a second transport model (TM2) [11], which implements a hydrodynamic description of the medium evolution and finally a 'co-mover' model [7,8], where the J/ψ are dissociated via interactions with the partons/hadrons produced in the same rapidity range. The large uncertainties in the models are due to the choice of the corresponding input parameters and in particular of $d\sigma_{c\bar{c}}/dy$. Except for the statistical hadronization model, a better description is found when considering their upper limits. But for transport models this corresponds to the absence of nuclear shadowing, which can be clearly considered as an extreme assumption for J/ψ [15,16].
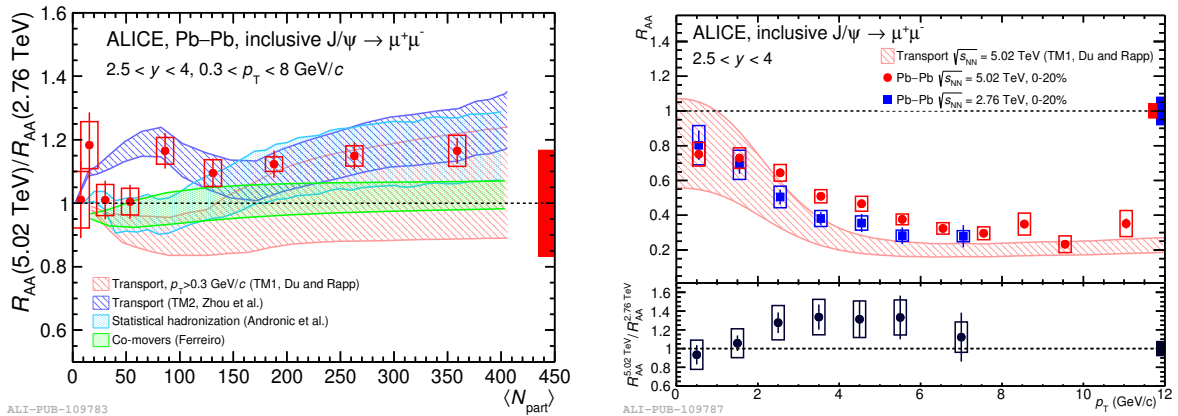

Figure 2. (Left) The ratio of the inclusive J/ψ R_{AA} for $0.3 < p_T < 8$ GeV/c between $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV vs. centrality compared to theoretical models [6–11]. (Right) The inclusive J/ψ R_{AA} as a function of p_T at $\sqrt{s_{NN}} = 5.02$ TeV in the centrality interval 0–20% compared to the corresponding result at $\sqrt{s_{NN}} = 2.76$ TeV [5] and to the prediction of a transport model (TM1) [9,10]. The p_T dependence of the ratio of R_{AA} between the two energies is also shown.

The ratio of the inclusive J/ψ R_{AA} between the two energies as a function of centrality compared with the theoretical models is shown in the left panel of Fig. 2. Many theoretical uncertainties cancel out due to the correlation between the parameters at the two energies. The uncertainties on the average nuclear overlap function ($\langle T_{AA} \rangle$) cancel out in data. This ratio for the prompt J/ψ would be about 2% (1–2%) higher if beauty hadrons were fully (not) suppressed by the medium. The prediction from the transport model of Ref. [9,10] (TM1) shows a decrease of this ratio with the increase of centrality due to the larger suppression effects at higher energy followed by an increase which is due to the regeneration that acts in the opposite direction and becomes dominant for central collisions. The other transport model (TM2) [11] also exhibits an increase for central collisions while for peripheral collisions the behaviour is different. No visible structure as a function of centrality is observed in the co-mover model [7,8] and the calculation favours this ratio to be slightly below unity which implies that in this model the

increase of the suppression effects with energy may be dominant over the regeneration effects for all centralities. Finally, the statistical model [6] predicts a continuous increase of this ratio with centrality dominated by the increase in the $c\bar{c}$ cross section with energy. The uncertainty bands in the theoretical models shown in left panel of Fig. 2 correspond to $\sim$5% variations of the $c\bar{c}$ cross section at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Within the uncertainties the data show no clear centrality dependence and are compatible with the theoretical models. This ratio for central collisions and for $0.3 < p_{\mathrm{T}} < 8$ GeV/c is $1.17 \pm 0.04(\mathrm{stat}) \pm 0.20(\mathrm{syst})$.

The R_{AA} as a function of p_{T} for the centrality interval 0–20% compared to the corresponding results obtained at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and to theoretical models is shown in the right panel of Fig. 2. The p_{T} dependence of R_{AA} has an increasing trend at low p_{T}, which is a sensitive test of the presence of the regeneration component in theoretical calculations. Since the contribution of J/ψ photo-production is negligible with respect to the hadronic one for central events [12], the region $p_{\mathrm{T}} < 0.3$ GeV/c is not excluded. The transport model of Ref. [9,10] (TM1) describes the data at low p_{T} but underestimates the data at intermediate p_{T} ($3 < p_{\mathrm{T}} < 7$ GeV/c). The ratio of R_{AA} vs. p_{T} between the two energies is also shown in the same figure. In the region $2 < p_{\mathrm{T}} < 6$ GeV/c, a hint of increase of R_{AA} with $\sqrt{s_{\mathrm{NN}}}$ is visible. The R_{AA} of prompt J/ψ is expected to be 7% larger (2% smaller) for $p_{\mathrm{T}} < 1$ GeV/c and 30% larger (55% smaller) for $10 < p_{\mathrm{T}} < 12$ GeV/c when the beauty contribution is fully (not) suppressed. The ratio of R_{AA} appears to be less sensitive to the non-prompt J/ψ contribution if we assume that $R_{\mathrm{AA}}^{\mathrm{non-prompt}}$ does not vary significantly between the two collision energies.

3. Conclusion

ALICE has measured the inclusive J/ψ production in pp and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Comparison with the previous measurement at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV shows a systematic increase in R_{AA} by about 15%, although such an effect is within the total uncertainty of the measurements. A less pronounced increase of R_{AA} for peripheral events is observed upon removing the very-low p_{T} J/ψ ($p_{\mathrm{T}} < 0.3$ GeV/c). The rejection of photo-produced J/ψ [12] is a possible explanation for this decrease. The theoretical calculations describe R_{AA} and the ratio of R_{AA} between $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 2.76 TeV closer to their upper limits. The p_{T} dependence of R_{AA} exhibits an increase at low p_{T} which is ascribed to the contribution of regenerated J/ψ. In the region $2 < p_{\mathrm{T}} < 6$ GeV/c, a hint of an increase of R_{AA} between $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV is observed. The results on J/ψ production support a picture where a combination of suppression and regeneration takes place in the QGP, with the two mechanisms being dominant at high and low p_{T}, respectively.

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