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Measurements of Quarkonia in pp, p-Pb and Pb-Pb collisions with ALICE at the LHC

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Quarkonia, bound states of quark-antiquark pairs, are important observables to understand the properties of QCD at extreme energy-densities. The nuclear modification factor of quarkonia, namely J/ψ, ψ(2S) and Υ(1S), are discussed in this paper as measured by ALICE at LHC energies for pp, p-Pb and Pb-Pb collisions.

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1. Introduction

The Lattice QCD calculation predicts that under very high energy-densities, the normal nuclear matter will undergo a phase transition to a deconfined medium of quarks and gluons, known as Quark Gluon Plasma (QGP) [1, 2]. Experimentally, such a state is formed at the early stage of the ultra-relativistic heavy-ion collisions. In this hot medium, the binding energy between the q and the $\bar{q}$ is screened by the colour charges [3] and hence a suppression of quarkonium production has been observed in heavy-ion collisions when compared with the production in pp interactions scaled by the number of nucleon-nucleon collisions in the nucleus-nucleus collision [4]. However, the charmonium states can also be produced from the thermalized medium by statistical production at the phase boundary [5, 6], or through coalescence of charm quarks in the plasma [7]. The transport models [8, 9] which assume the partial regeneration of charm quarks from deconfined medium are also able to explain the quarkonium measurements in heavy-ion collisions. Since the suppression of quarkonium states can also be due to cold nuclear matter (CNM) effects such as nuclear shadowing, energy loss [10, 11, 12, 13, 14], these effects are taken into the calculation of quarkonium suppression in heavy-ion collision. Therefore, medium effects on the quarkonium production can be understood as the interplay of hot and cold medium effects. The color screening and the (re)generation of quarkonia in nucleus-nucleus (A-A) collisions are considered as hot medium effects, whereas the CNM effects are observed in proton-nucleus (p-A) collisions.

The nuclear modification factor as defined below is used to measure the medium effects in A-A and p-A collisions. In the case of nucleus-nucleus collisions it is defined as,

$$R_{\mathrm{AA}} = \frac{Y_{\mathrm{AA}}}{\langle T_{\mathrm{AA}} \rangle \, \sigma_{\mathrm{pp}}} \tag{1.1}$$

where Y_{AA} is the inclusive quarkonium yield in A-A collisions, $\langle T_{\mathrm{AA}} \rangle$ is the nuclear overlap function calculated using the Glauber model and σ_{pp} is the quarkonium production cross section in pp collisions [15].

In p-A collisions the definition is the following:

$$R_{\mathrm{pA}} = \frac{Y_{\mathrm{pA}}}{\langle T_{\mathrm{pA}} \rangle \, \sigma_{\mathrm{pp}}} \tag{1.2}$$

where the notations represent the same observables as of Eq. 1.1, but for p-A collisions.

ALICE has performed measurements in pp collisions which are used as baseline results for the Pb-Pb study. The pp results have been also used to check the consistency with theoretical predictions.

2. Results

In the present paper, the midrapidity ($-0.8 < \eta_{\mathrm{lab}} < 0.8$) results are discussed for charmonium (J/ψ) in the dielectron channel, whereas for forward rapidity ($-4.0 < \eta_{\mathrm{lab}} < -2.5$) charmonium (J/$\psi$, ψ(2S)) and bottomonium (Υ(1S)) results are obtained in the dimuon channel. ALICE is capable to measure quarkonia down to $p_{\mathrm{T}} = 0$ GeV/c for both rapidity ranges.

The inclusive measurement of J/ψ at midrapidity uses the Inner Tracking System and the Time Projection Chamber as described in Ref. [16]. The Muon Spectrometer (MS) measures the inclusive yield of J/ψ, ψ(2S) and Υ(1S) resonances at forward rapidity [16]. Additionally, the VZERO hodoscopes are used as minimum-bias trigger detector and for the centrality calculation.

ALICE has collected data in pp collisions at $\sqrt{s}$ = 2.76 TeV (integrated luminosity, $\mathscr{L}_{\rm int} \approx$ 1.1 nb^{-1} and 19.9 nb^{-1} in the electron and muon channels, respectively), Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV ($\mathscr{L}_{\rm int} \approx 23\ \mu$b^{-1} and 70 μb^{-1} have been used for electron and muon analysis, respectively) and p-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. In the case of p-Pb collisions data was taken in two configurations by inverting the direction of the LHC beams, which allow to measure quarkonia in the following rapidity ranges: $-1.37 < y_{\rm cms} < 0.43$ in the dielectron channel and $2.03 < y_{\rm cms} < 3.53$ and $-4.46 < y_{\rm cms} < -2.96$ in the dimuon channel, with integrated luminosities $\mathscr{L}_{\rm int}$ of 52 μb^{-1}, 5.03 nb^{-1}, 5.81 nb^{-1}, respectively. Positive rapidities are defined by the direction of the proton beam.

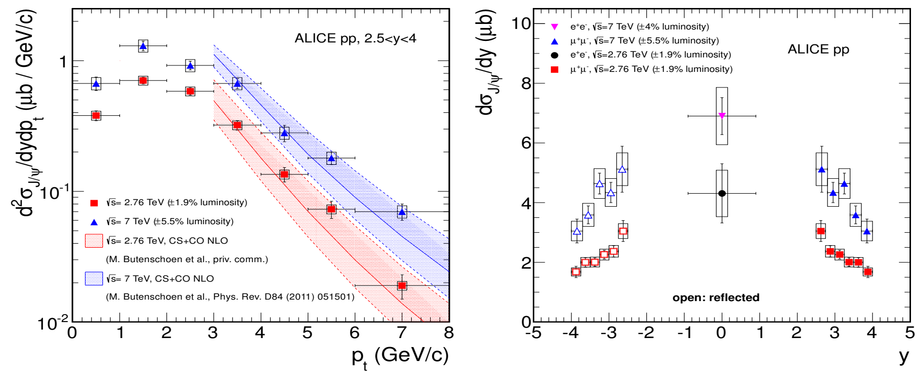

Figure 1: The inclusive J/ψ production as a function $p_{\rm T}$ (left panel) and rapidity (right panel) for pp collisions at $\sqrt{s}$ = 2.76 TeV and $\sqrt{s}$ = 7 TeV [17].

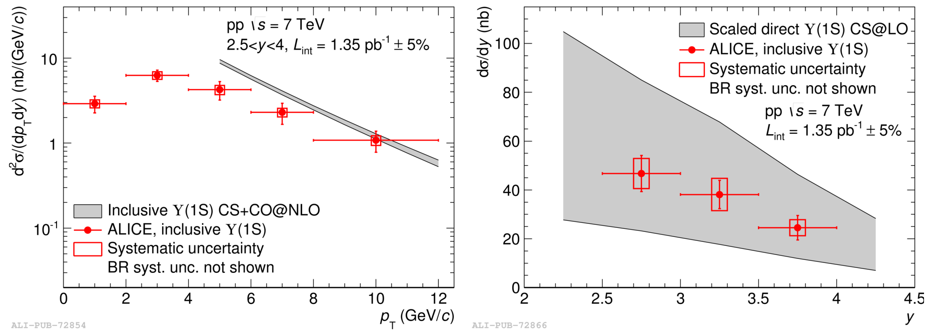

Figure 2: The $p_{\rm T}$ (left panel) and rapidity (right panel) distribution of inclusive Υ(1S) production for pp collisions at $\sqrt{s}$ = 7 TeV.

ALICE measurements of inclusive J/ψ production is shown as a function of $p_{\rm T}$ and rapidity in Fig. 1 for pp collisions at $\sqrt{s}$ = 2.76 TeV [17] and $\sqrt{s}$ = 7 TeV ($\mathscr{L}_{\rm int} \approx$ 5.6 nb^{-1} in e^+e^- channel and 15.6 nb^{-1} in $\mu^+\mu^-$ channel) [18]. The NLO NRQCD (Non-relativistic QCD) models are in agreement with the results as shown in the $p_{\rm T}$ differential plot of J/ψ in Fig. 1. ALICE has measured Υ(1S) production with higher $\mathscr{L}_{\rm int} \approx$ 1.35 pb^{-1} data in dimuon channel and the theoretical calculations based on NLO NRQCD models and Color Singlet (CS) model agrees with the results [19].

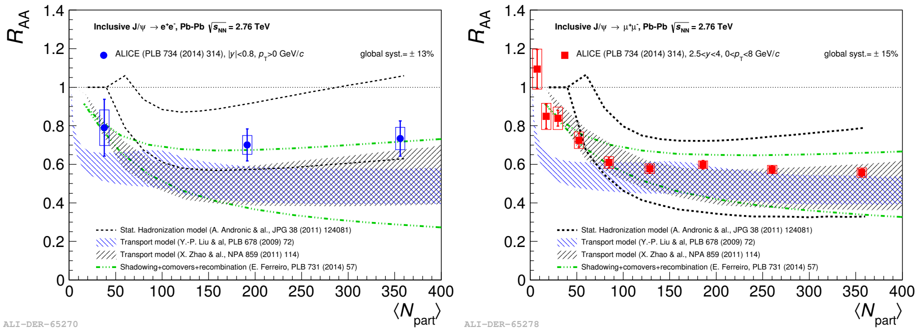

Figure 3: The J/ψ R_{AA} as a function of number of participating nucleons at midrapidity (left panel) and forward rapidity (right panel).

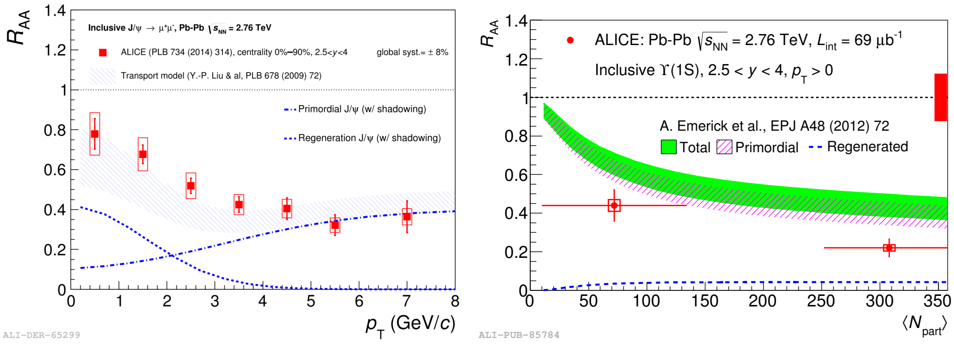

Figure 4: The R_{AA} of inclusive J/ψ as a function of p_{T} at forward rapidity (left panel). The $\Upsilon(1\mathrm{S})$ R_{AA} as a function of number of participating nucleons at forward rapidity (right panel). The filled box around 1 shows the global systematic uncertainties (also applicable to the following plots).

The nuclear modification factor of inclusive J/ψ production have been measured by ALICE in Pb-Pb collision at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV. The centrality integrated result in the case of the e^+e^- decay channel is $R_{\mathrm{AA}}^{0\%-90\%} = 0.72 \pm 0.06(\mathrm{stat.}) \pm 0.10(\mathrm{syst.})$, while for the $\mu^+\mu^-$ channel it is $R_{\mathrm{AA}}^{0\%-90\%} = 0.58 \pm 0.01(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})$ [20]. The measured J/ψ R_{AA} in the dielectron decay channel at midrapidity (left panel of Fig. 3), does not exhibit any significant dependence with the number of participant nucleons ($\langle N_{\mathrm{part}} \rangle$). Similarly, the R_{AA} at forward rapidity also shows no centrality dependence for $\langle N_{\mathrm{part}} \rangle$ larger than 70 (right panel of Fig. 3). However, in case of the $\Upsilon(1\mathrm{S})$ the R_{AA} decreases with increasing $\langle N_{\mathrm{part}} \rangle$ (right panel of Fig. 4) and the centrality integrated value is, $R_{\mathrm{AA}}^{0\%-90\%} = 0.30 \pm 0.05(\mathrm{stat.}) \pm 0.04(\mathrm{syst.})$ [21]. The models which combine the contibution of primordial J/ψ suppression due to color screening and J/ψ enhancement due to full or partial regeneration of charm quarks well reproduce the J/ψ R_{AA} as function of p_{T} . The $\Upsilon(1\mathrm{S})$ R_{AA} suppression is underestimated by transport model calculations, similar to those used for the J/ψ, including a small $\Upsilon(1\mathrm{S})$ regeneration component. According to transport models, the regenerated J/ψ's are preferentially produced in the low-p_{T} region (<3 GeV/c) and the contribution of primordial J/ψ is dominant in the high-p_{T} region. These models explain fairly well the p_{T} dependence of the J/ψ R_{AA} at forward rapidity (left panel of Fig. 4). The R_{AA} of J/ψ and $\Upsilon(1\mathrm{S})$ are shown as function of rapidity in the left and right panel of Fig. 5, respectively. Models based only on shadowing effects cannot reproduce the measured rapidity dependence of the J/ψ R_{AA}. The low value of the $\Upsilon(1S)$ R_{AA} at forward rapidity is not described by the available model calculations [21].

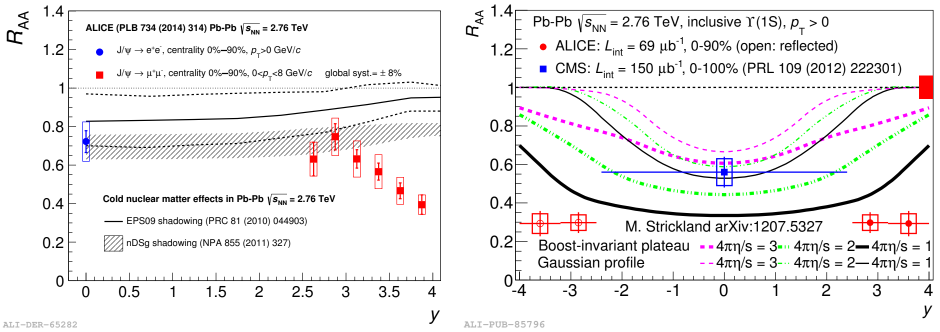

Figure 5: The rapidity dependence of the J/ψ R_{AA} as measured in ALICE (left panel) and of the $\Upsilon(1S)$ measured in ALICE and CMS (right panel).

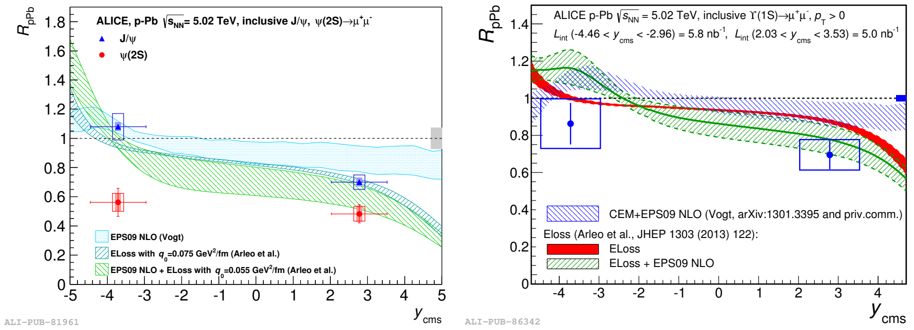

Figure 6: The R_{pPb} of inclusive J/ψ and $\psi(2S)$ as measured in backward and forward rapidity (left panel). The $\Upsilon(1S)$ R_{pPb} as measured in forward and backward rapidity (right panel).

The measurement of quarkonia in p-Pb collisions help to understand the role of CNM effects in heavy-ion collisions. The inclusive J/ψ, $\psi(2S)$ and $\Upsilon(1S)$ production in p-Pb collisions has been measured by ALICE at $\sqrt{s_{NN}}$ = 5.02 TeV [22, 23, 24]. Since the pp production cross sections are not measured at $\sqrt{s}$ = 5.02 TeV, an interpolation between lower energy ($\sqrt{s}$ = 2.76 TeV) and higher energy ($\sqrt{s}$ = 7 TeV) measurements has been used for the calculation of R_{pA} as described in [22, 23, 24]. The nuclear modification factor of J/ψ and $\psi(2S)$ are compared along with model predictions in the left panel of Fig. 6. The models depending on shadowing and coherent parton energy loss with or without shadowing can explain the J/ψ R_{pA} [13, 14]. The model predictions for the $\psi(2S)$ are identical to the J/ψ ones, since no dependence on the quantum number of the resonances is considered. Theoretical calculations based on shadowing and/or energy loss can not explain simultaneously the J/ψ and the $\psi(2S)$ behavior, in particular at backward rapidity ($-4.46 < y_{cms} < -2.96$). While model calculations are in good agreement with the J/ψ, they strongly underestimate the $\psi(2S)$ suppression. Therefore, additional final state CNM effects are needed to explain the lower $\psi(2S)$ R_{pA} and interaction with a hadronic medium is a possible explanation [25, 26]. The coherent energy loss model calculation including shadowing reproduces the $\Upsilon(1S)$ R_{pPb} at forward rapidity but overestimate it at backward rapidity. An opposite trend is found for the coherent energy loss calculation without shadowing (right panel of Fig. 6).

Assuming a 2 → 1 ($gg \rightarrow$J/ψ) [27] production process, the covered Bjorken-x ranges in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV and in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV are similar. If in addition one assumes a factorisation of CNM effects in Pb-Pb collisions (shadowing being the dominant effect), then the contribution of CNM effects in Pb-Pb can be estimated by $R_{\mathrm{pPb}}^{\mathrm{forw}} \times R_{\mathrm{pPb}}^{\mathrm{backw}}$. The p_{T} dependence of J/ψ R_{AA} is plotted together with the extrapolated CNM effects for midrapidity and forward rapidity in the left and the right panel of Fig. 7, respectively. At both forward and midrapidity, the suppression owing to CNM has very small contribution at high-p_{T} , therefore the suppression of the quarkonium resonances in the high-p_{T} domain is due to hot medium effects. At low-p_{T} there is a hint of an excess of J/ψ above CNM possibly due to regeneration.

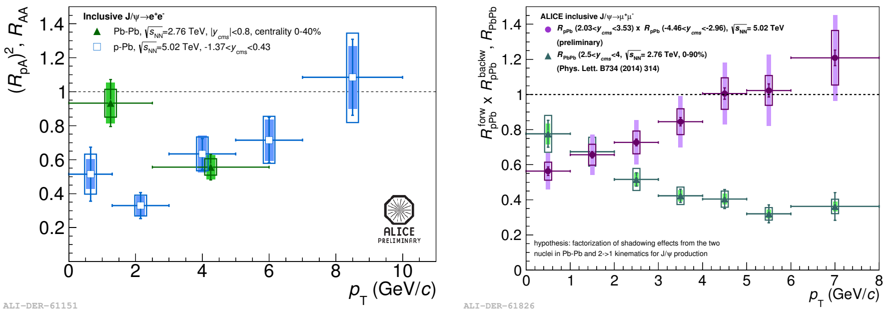

Figure 7: The J/ψ R_{AA} as a function of p_{T} and the estimated effect of shadowing in Pb-Pb collisions using the R_{pPb} results obtained at midrapidity (left panel) and forward rapidity (right panel).

3. Conclusion

The production of charmonium and bottomonium in pp, p-Pb and Pb-Pb collisions has been measured by ALICE. The results support the presence of regenerated J/ψ for central Pb-Pb collisions in the low-p_{T} region. Whereas, in the high-p_{T} region, the suppression of J/ψ is observed and can be attributed to hot medium effects. The Υ(1S) measurement shows a stronger suppression than the J/ψ. None of the available models predict significant production of Υ(1S) via regeneration. The charmonium R_{AA} shows a strong variation with rapidity in the range ($-4.0 < \eta_{\mathrm{lab}} < -2.5$) which is absent in case of Υ(1S). In p-Pb collision, a notable suppression of ψ(2S) at backward rapidity has been observed which is not explained by models describing fairly well the J/ψ p-Pb data. A final state effect of the ψ(2S) break-up due to hadronic interaction is a possible explanation of the observed suppression. ALICE plans to collect 1 nb^{-1} minimum bias data in Run 2 period of LHC. This will improve the precision of the quarkonium measurements helping to understand the quarkonium dissociation and regeneration pattern as probe of the QGP.

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