EPJ Web of Conferences **80**, 00031 (2014)
DOI: 10.1051/epjconf/20148000031

Quarkonium production in pp, p-Pb and Pb-Pb collisions with ALICE at LHC

Indranil Das (for the ALICE collaboration)[1,a]

[1] *Institut de Physique Nucléaire d'Orsay*
15 Rue Georges Clemenceau, 91406 Orsay, France

Abstract. The hadroproduction of heavy quarkonium states plays a key role to understand the properties of matter created in high energy nucleus-nucleus collisions. In this paper, the nuclear modification factors for J/ψ, $\psi(2S)$ and $\Upsilon(1S)$ measured with ALICE at LHC energies are discussed.

1 Introduction

Quarkonia, bound states of heavy quark pairs, are produced in high-energy collisions and serve as important observables to study Quantum Chromodynamics (QCD) at extreme energy-densities. One of the most interesting phenomena of QCD at high energy-densities, predicted by lattice QCD calculations, is that the hadronic matter can undergo a phase transition to a deconfined state, the so-called Quark-Gluon Plasma (QGP) [1, 2]. Experimentally, such state is formed at the early stage of ultra-relativistic heavy-ion collisions when the fireball reaches thermalization. Quarkonium states are produced before the beginning of the thermalization and are expected to partly dissociate into quark-antiquark pairs, as a consequence of the screening of the strong interaction in the high colour-charge density medium [3]. This will result in a suppression of quarkonium production 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 suppression of quarkonium states of charm and bottom quarks can be also due to cold nuclear matter (CNM) effects such as nuclear shadowing, energy loss [5–9]. Owing to the large yield of charm-anticharm pairs produced in heavy-ion collisions at high energies, charmonium states can also be produced from the thermalized medium by statistical production at the phase boundary [10, 11], or through coalescence of charm quarks in the plasma [12]. Later, two transport models have been proposed which suggest partial regeneration [13, 14] from deconfined charm quarks in the medium. Thus, medium effects on the quarkonium production can be understood as the interplay of hot medium effects and cold medium effects. The hot medium effects include suppression and the (re)generation of quarkonia in nucleus-nucleus (A-A) collisions, while the CNM effects incorporate nuclear shadowing, saturation, energy loss and quark-antiquark break-up as observed in proton-nucleus (p-A) collisions.

[a] e-mail: indranil.das@cern.ch

The medium effects are measured in A-A and p-A collisions in terms of the nuclear modification factor. In the case of nucleus-nucleus collisions it is defined as,

$$R_{\mathrm{AA}} = \frac{Y_{\mathrm{AA}}}{\langle T_{\mathrm{AA}} \rangle \, \sigma_{\mathrm{pp}}} \tag{1}$$

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:

$$R_{\mathrm{pA}} = \frac{Y_{\mathrm{pA}}}{\left\langle T_{\mathrm{pA}} \right\rangle \sigma_{\mathrm{pp}}} \tag{2}$$

where the notations represent the same observables as of Eq. 1, but for p-A collisions.

2 Results

ALICE is a general-purpose detector which focusses on the strong interaction part of QCD by measuring hadrons, electrons, photons and muons at LHC energies [16]. In the present article, 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 measures quarkonia down to zero p_{T} for both rapidity ranges.

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

ALICE has taken data in pp collisions at $\sqrt{s}$ = 2.76 TeV (integrated luminosity, $\mathscr{L}_{\mathrm{int}} \approx 1.1$ nb^{-1} and 19.9 nb^{-1} in the electron and muon channels, respectively), Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV ($\mathscr{L}_{\mathrm{int}} \approx 23$ μb^{-1} and 70 μb^{-1} have been used for electron and muon analysis, respectively) and p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. Two beam configurations have been delivered by LHC in p-Pb collisions which are,

- p-Pb : proton going towards the MS with $\mathscr{L}_{\mathrm{int}} \approx 52\,\mu$b^{-1} for electron channel ($-1.37 < y_{\mathrm{cms}} < 0.43$) and with $\mathscr{L}_{\mathrm{int}} \approx 5.03$ nb^{-1} in muon channel ($2.03 < y_{\mathrm{cms}} < 3.53$).
- Pb-p : Pb going towards the MS with $\mathscr{L}_{\mathrm{int}} \approx 5.81$ nb^{-1} for muon analysis ($-4.46 < y_{\mathrm{cms}} < -2.96$) .

In the case of p-Pb/Pb-p collisions, the positive rapidities refer to the direction of the proton beam.

ALICE has measured the nuclear modification factor of inclusive J/ψ production in Pb-Pb collision at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV. In the case of the e^+e^- decay channel, the centrality integrated result 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 $R_{\mathrm{AA}}^{0\%-90\%} = 0.58 \pm 0.01(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})$ [17, 18]. At midrapidity, in the dielectron decay channel (left panel of Fig. 1), the J/ψ R_{AA} does not exhibit any significant dependence with the number of participant nucleons ($\langle N_{\mathrm{part}} \rangle$). Also the R_{AA} at forward rapidity shows no centrality dependence for $\langle N_{\mathrm{part}} \rangle$ larger than 70 (right panel of Fig. 1). Similar measurements have been also performed for Υ(1S). The Υ(1S) R_{AA} decreases with increasing $\langle N_{\mathrm{part}} \rangle$ (right panel of Fig. 2) and the centrality integrated value is, $R_{\mathrm{AA}}^{0\%-90\%} = 0.30 \pm 0.05(\mathrm{stat.}) \pm 0.04(\mathrm{syst.})$ [19]. The measured J/ψ R_{AA} is well reproduced by

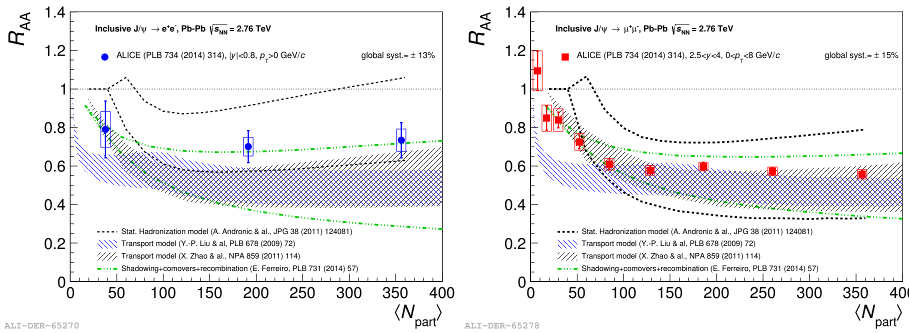

Figure 1. The R_{AA} of inclusive J/ψ as a functions of number of participating nucleons at midrapidity (left panel) and forward rapidity (right panel).

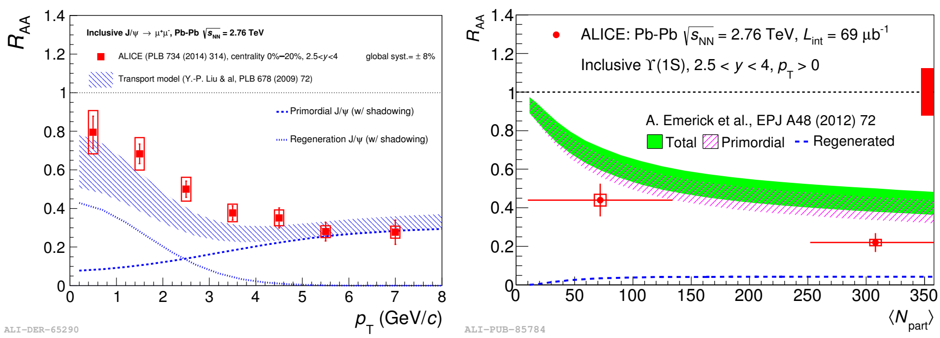

Figure 2. J/ψ R_{AA} as a function of p_T at forward rapidity for the most central collisions (left panel). The R_{AA} measurement of inclusive Υ(1S) as a functions of number of participating nucleons at forward rapidity (right panel). The filled box around 1 shows the global systematic uncertainties (also applicable to the following plots).

models including full or partial regeneration from charm quarks. The Υ(1S) R_{AA} is overestimated by transport model calculations, similar to those used for the J/ψ, including a small Υ(1S) regeneration component. According to transport models, the regenerated J/ψ's are preferentially created 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 describe fairly well the p_T dependence of J/ψ R_{AA} in most central collisions at forward rapidity (left panel of Fig. 2). The R_{AA} of J/ψ and Υ(1S) are shown as function of rapidity in the left and right panel of Fig. 3, respectively. Models implementing only shadowing effects cannot reproduce the J/ψ R_{AA} for $y > 3$. However, these models fairly reproduce the measurements for $|y| < 3$; it is worth to stress once more that suppression and regeneration effects are both at play. The strong decrease of the Υ(1S) R_{AA} at forward rapidity is not reproduced by the available model calculations [19].

The quarkonium measurements in p-Pb collisions help to understand the role of CNM effects in heavy-ion collisions. ALICE has measured the inclusive J/ψ, ψ(2S) and Υ(1S) production in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [20, 21]. Since the pp production cross sections are not available at $\sqrt{s}$ = 5.02 TeV, the extrapolated results from lower energy measurement at $\sqrt{s}$ = 2.76 TeV and from high energy $\sqrt{s}$ =7 TeV have been used for the calculation of R_{pA} as described in [20, 21]. A comparison of the nuclear modification factor of J/ψ and ψ(2S) are shown along with model predictions in the

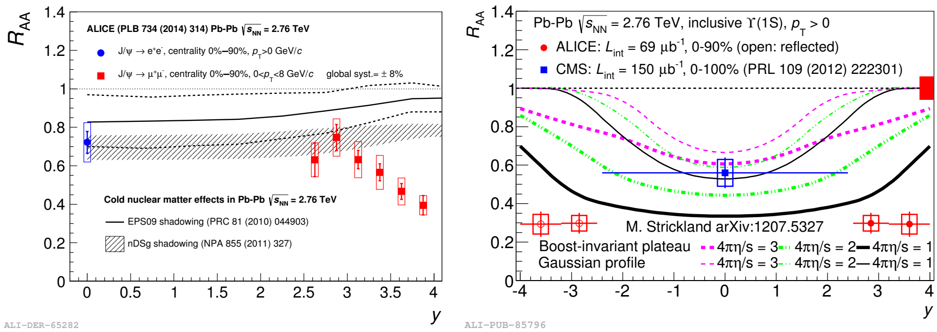

Figure 3. The rapidity dependence of the R_{AA} of J/ψ as measured in ALICE (left panel) and of the Υ(1S) measured in ALICE and CMS (right panel).

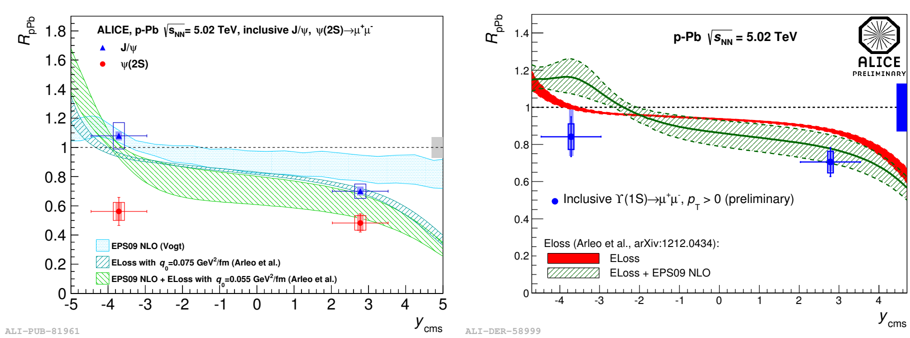

Figure 4. The R_{pPb} of inclusive J/ψ and ψ(2S) as measured in forward and backward rapidity (left panel).The R_{pPb} of inclusive Υ(1S) as measured in forward and backward rapidity (right panel).

left panel of Fig. 4. The models based on shadowing and coherent parton energy loss with or without shadowing can explain the J/ψ R_{pA} [8, 9]. The model predictions for ψ(2S) are expected to be identical to the J/ψ ones, since no dependence on the quantum number of the resonances is considered. Theoretical predictions cannot thus explain simultaneously the J/ψ and the ψ(2S) behavior, in particular at backward rapidity ($-4.46 < y_{\mathrm{cms}} < -2.96$). While model calculations are in fair agreement with the J/ψ, they strongly overestimate the ψ(2S) suppression. The coherent energy loss model calculation including shadowing reproduces the Υ(1S) R_{pPb} at forward rapidity but tends to overestimate it at backward rapidity. The opposite trend is found for the coherent energy loss calculation only(right panel of Fig. 4)

At LHC energies, the dominant mechanism of heavy quark production is via the gluon-gluon fusion process [22]. Since the typical momentum fraction of the interacting gluons is in the same range both in Pb-Pb at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV and p-Pb at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV collisions, the contribution of CNM effects in Pb-Pb can be estimated as $R_{\mathrm{AA}} = R_{\mathrm{pPb}} \times R_{\mathrm{Pbp}}$, if one assumes that shadowing effect is the only contributor to CNM effects. The p_{T} dependence of J/ψ R_{AA} is shown together with the extrapolated CNM effects for midrapidity and forward rapidity in the left and the right panel of Fig. 5, respectively. At both forward and midrapidity, the suppression due 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 the hot medium effects. In case of low-p_T there is a hint of an excess of J/ψ above CNM likely due to regeneration.

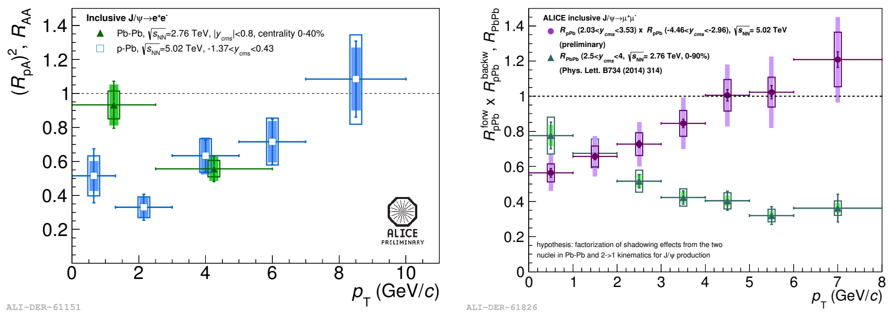

Figure 5. The R_{AA} measurement of inclusive J/ψ as a functions of p_T and the estimated effect of shadowing in Pb-Pb collisions using the R_{pPb} results in midrapidity (left panel) and forward rapidity (right panel).

3 Conclusions

ALICE has measured the charmonium and bottomonium production in pp, p-Pb and Pb-Pb collisions. The results suggest the presence of regenerated J/ψ for central collisions in the low-p_T region. 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 (smaller R_{AA}). The available models do not predict a significant production of Υ(1S) via regeneration. Another interesting feature is noticed in ALICE data, when the nuclear modification factor is considered as function of charmonium states. The charmonium shows a strong variation of R_{AA} with rapidity in the range $(-4.0 < \eta_{lab} < -2.5)$ which is absent in case of Υ(1S). A notable result in p-Pb collision is the suppression of ψ(2S) at backward rapidity which is not explained by models describing fairly well the J/ψ p-Pb data. An attempt to factorize out the CNM effects measured in p-Pb from the Pb-Pb J/ψ R_{AA} measurements suggests a possible J/ψ enhancement in the low-p_T region. ALICE aim to collect 10 nb^{-1} minimum bias data in Run 2 period of LHC. This will improve the high precision study of quarkonium dissociation and regeneration pattern as probe of deconfinement.

References

[1] N. Cabibbo and G. Parisi, Phys. Lett. B **59**, 67 (1975)

[2] J. C. Collins and M. J. Perry, Phys. Rev. Lett. **34**, 1353 (1975)

[3] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986)

[4] The ALICE Collaboration, Phys. Rev. Lett. **106**, 032301 (2011)

[5] J. J. Aubert *et al.* (EMC Collaboration), Phys. Lett. B **123**, 275 (1983)

[6] K. J. Eskola, H. Paukkunena and C. A. Salgado, JHEP **04**, 065 (2009)

[7] D. Kharzeev and K. Tuchin, Nucl. Phys. A **770**, 40 (2006)

[8] F. Arleo and S. Peigné, Phys. Rev. Lett. **109**, 122301 (2012)

[9] R. Vogt, Nucl. Phys. A **700**, 539 (2002)

[10] P. Braun-Munzinger and J. Stachel, Phys. Lett. B **490**, 196 (2000)
[11] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nucl. Phys. A **789**, 334 (2007)
[12] R. L. Thews, M. Schroedter and J. Rafelski, Phys. Rev. C **63**, 054905 (2001)
[13] X. Zhao and R. Rapp, Nucl. Phys. A **859**, 114 (2011)
[14] Y. Liu, Z. Qu, N. Xu, and P. Zhuang, Phys. Lett. B **678**, 72 (2009)
[15] The ALICE Collaboration, Phys. Rev. C **88**, 044909 (2013)
[16] The ALICE Collaboration, JINST **3**, S08002 (2008)
[17] The ALICE Collaboration, Phys. Lett. **743**, 314 (2014)
[18] The ALICE Collaboration, Phys. Rev. Lett. **109**, 072301 (2012)
[19] The ALICE Collaboration, arXiv:1405.4493
[20] The ALICE Collaboration, JHEP **02**, 073 (2014)
[21] The ALICE Collaboration, arXiv:1405.3796
[22] N. Brambilla *et al.*, Eur. Phys. J. C **71**, 1534 (2011)