Suppression of quarkonia in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

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Abstract.
We study different processes responsible for the modification of quarkonia yields in the medium produced in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The quarkonia and heavy flavour cross sections are estimated using the measurements in pp collisions at LHC energies and shadowing corrections are obtained using the EPS09 parameterizations. A kinetic model is used which incorporates quarkonia suppression inside the Quark Gluon Plasma (QGP), suppression due to hadronic comovers, and regeneration from recombination of heavy quark pairs. The quarkonia dissociation cross section due to gluon collisions, including both color-electric dipole and color-magnetic dipole transitions, has been employed. The regeneration rate is obtained using the principle of detailed balance. The effect of these processes on the nuclear modification factors for both J/ψ and Υ in different ranges of transverse momentum p_T and rapidity has been studied for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The calculations are compared with the available results from LHC experiments. Both the suppression and regeneration due to a QGP are effective in the low and intermediate p_T range. The large observed suppression of J/ψ at p_T > 10 GeV/c is larger than the suppression expected due to gluon dissociation.

PACS numbers: 12.38.Mh, 24.85.+p, 25.75.-q

1. Introduction

Quantum chromodynamics (QCD) predicts that strongly interacting matter undergoes a phase transition to quark-gluon plasma (QGP), a state in which quarks and gluons move much beyond the size of hadrons. Heavy-ion collisions at relativistic energies are performed to create and quantify the properties of QGP [1, 2]. Charmonia and bottomonia, which are bound states of charm-anticharm ($c\bar{c}$) or bottom-antibottom ($b\bar{b}$) quarks, respectively, are among the most sensitive probes of the characteristics of the QGP [3]. These bound states of heavy quarks are formed early in the heavy ion collisions and their yields are expected to be suppressed in the medium as compared to their yields in pp collisions [4, 5]. There have been a large number of studies on this phenomenon both theoretically and experimentally [3, 6, 7] enriching our understanding on quarkonia as probes of QGP. The J/ψ meson was measured at the SPS, in PbPb and In-In interactions at the centre-of-mass energy per nucleon pair $\sqrt{s_{NN}}$ = 17.2 GeV [8, 9], at RHIC in AuAu interactions at $\sqrt{s_{NN}}$ = 200 GeV [10, 11, 12], and finally at the LHC, in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV [13, 14, 15, 16, 17, 18, 19, 20]. The suppression of J/ψ observed at SPS was termed as 'anomalous' J/ψ suppression. It was even considered to be a hint of QGP [8, 9] formation. Early theoretical calculations predicted J/ψ suppression due to colour screening in a deconfined medium which become stronger as the QGP temperature increases [4, 21] but the RHIC measurements at $\sqrt{s_{NN}}$ = 200 GeV showed almost the same amount of suppression, contrary to expectation [3, 10]. These observations hint a scenario where, at higher collision energies, the expected larger suppression is compensated by J/ψ regeneration via recombination of two independently produced charm quarks [22, 23, 24].

The LHC collected first PbPb collision data at $\sqrt{s_{NN}}$ = 2.76 TeV at the end of 2010. The ATLAS was the first detector to measure the ratio of J/ψ meson with Z^0 boson hinting a centrality-dependent suppression of the yield of J/ψ mesons [13]. The J/ψ measurements at high transverse momentum (p_T > 6.5 GeV/c) in PbPb collisions at $\sqrt{s_{NN}}$=2.76 TeV and at $\sqrt{s_{NN}}$=5.02 TeV were carried out by the CMS experiment [14, 15, 16]. The nuclear modification factor R_{AA} of these high p_T prompt J/ψ decreases with increasing centrality. The R_{AA} shows a slow increase as a function of p_T after 15 GeV/c and then saturates between a value 0.4 and 0.5 showing that the J/ψ remains suppressed, even at very high p_T, up to $\sim$ 50 GeV/c. The ATLAS experiment also measured R_{AA} of J/ψ at $\sqrt{s_{NN}}$=5.02 TeV for J/ψ meson having transverse momentum above 9.0 GeV/c [17]. The amount of suppression of J/ψ mesons observed by ATLAS is similar to the suppression observed by CMS experiment. By comparing these measurements with the STAR results [12] at RHIC, it follows that at high p_T the suppression of J/ψ increases with collision energy.

The ALICE experiment measured the nuclear modification factor of J/ψ mesons in the forward rapidity (2.5< y <4.0) range at $\sqrt{s_{NN}}$=2.76 and $\sqrt{s_{NN}}$=5.02 TeV [18, 19] with J/ψ transverse momentum starting from 0.3 GeV/c. The ALICE results show that nuclear modification factor of J/ψ at low p_T (p_T < 12 GeV/c) has almost no collision centrality dependence except in the most peripheral region where it reaches almost unity. The R_{AA} of J/ψ mesons decreases substantially as a function of p_T in the ALICE experiment [18, 19]. The ALICE measurements also give a hint for an increase of R_{AA} between $\sqrt{s_{_{NN}}} = 2.76$ and 5.02 TeV in the intermediate p_T region, $2 < p_T < 6$ GeV/c. A comparison of the ALICE and PHENIX measurements reveal that at LHC, J/ψ mesons with low p_T are less suppressed as compared to RHIC. In general, the results at LHC experiments when compared to the RHIC measurements indicate that the data on J/ψ production support a picture where both suppression and regeneration take place in the QGP, the two mechanisms being dominant at high and low p_T, respectively [25, 26].

In addition to J/ψ mesons, the bottomonia states (Υ(nS)) are also measured at the LHC with very good statistical precision [27, 28, 29, 30]. The CMS measurements at $\sqrt{s_{_{NN}}}$ =2.76 TeV [27, 28] reveal a clear proof of sequential suppression : Υ(2S) and Υ(3S) are more suppressed relative to the ground state Υ(1S). The individual Υ states are also found to be suppressed in the PbPb collisions relative to the production in the pp collisions. The Υ nuclear modification factor, R_{AA}, shows a strong dependence on collision centrality but has weak dependence on Υ meson p_T and rapidity [30]. The forward rapidity ($2.5 \leq y^{\Upsilon} \leq 4.0$) measurement of the Υ suppression at ALICE [29] is found to be consistent with the midrapidity ($|y^{\Upsilon}| \leq 2.4$) measurement of the Υ suppression at the CMS. The CMS and ALICE collaborations have carried out the R_{AA} measurement of Υ at $\sqrt{s_{_{NN}}} = 5.02$ TeV with the Run II LHC PbPb collisions [31, 32, 33]. The CMS experiment measured slightly more amount of Υ suppression at $\sqrt{s_{_{NN}}} = 5.02$ TeV [31, 32] than the suppression at $\sqrt{s_{_{NN}}} = 2.76$ TeV [30] while the ALICE experiment observed less suppression at $\sqrt{s_{_{NN}}} = 5.02$ TeV than that at $\sqrt{s_{_{NN}}} = 2.76$ TeV in the most central PbPb collisions [29, 33].

The field of quarkonia has attracted a large amount of theoretical activities since the first prediction of J/ψ suppression in heavy ion collisions [4, 5]. The color screening of $q\bar{q}$ potential inside the QGP [34, 35] was the first approach to study the suppression of quarkonia in heavy ion collisions. In a complementary way to this static approach, J/ψ suppression can also be understood as a result of dynamical interactions with the surrounding gluons [36, 37, 26]. One of the ways to calculate the regeneration is to use the principle of detailed balance [23]. There are other effects also, namely shadowing and comover interaction [38, 39]. Shadowing arises as the parton distribution functions are modified inside the nucleus. A comprehensive framework to explain the experimental data from LHC considering shadowing and comover [24, 40] and viscous hydrodynamics [41, 42] has recently been formulated.

Some of us have studied the modification of quarkonia yields due to various processes in AA collisions in a previous work [26]. In that work, the gluon dissociation cross section has been adopted from the calculations of Bhanot and Peskin [36] where the gluon dissociation rate has been estimated from operator product expansion in the Coulomb approximation. Recently, Chen and He have revisited the gluon dissociation using QCD multipole expansion for various quarkonia in QGP [37]. They reproduced the result of Bhanot and Peskin as the colour-electric dipole (E1) transition. They have also calculated the colour magnetic dipole (M1) transition and found its contribution to be significant at low energies. In this paper, we calculate J/ψ and Υ evolution in a kinetic model which includes dissociation by thermal gluons (both E1 and M1 transitions), modification of their yields due to shadowing and due to collisions with comovers. Regeneration by near thermal heavy quark pairs is also considered in the calculations. We obtain the nuclear modification factor of quarkonia as a function of the transverse momentum and centrality of the collision and compare it to the latest experimental data from LHC at $\sqrt{s_{NN}} = 5.02$ TeV.

2. Theoretical formulation

The theoretical formulation towards the formation and dissociation of quarkonia have already been discussed in Ref. [26]. We use the same formulation here and hence discuss only some important points.

2.1. Formation and Dissociation

In the kinetic approach [23], the evolution of the quarkonia population N_Q with the proper time, τ, is given by the kinetic equation

$$\frac{dN_Q}{d\tau} = -\lambda_D \rho_g N_Q + \lambda_F \frac{N_{q\bar{q}}^2}{V(\tau)} \tag{1}$$

In the above equation $V(\tau)$ is the spatial volume of the QGP and $N_{q\bar{q}}$ is the number of initial heavy quark pairs produced in a event as a function of the centrality defined by the number of participants N_{part}. The λ_D is the dissociation rate and the λ_F is the formation rate. Here ρ_g is the density of thermal gluons.

The gluon dissociation cross section of quarkonia was calculated by Bhanot and Peskin using operator product expansion method in the color dipole approximation [36]. Recently, Chen and He have revisited the gluon dissociation using QCD multipole expansion method [37]. They reproduced the result of Ref. [36] as the color-electric dipole (E1) transition and also calculated the color magnetic dipole (CMD-M1) transition. The E1 transition cross-section of gluon dissociation as a function of gluon energy, q^0, in the quarkonium rest frame is [36]

$$\sigma_D^{E1}(q^0) = \frac{8\pi}{3} \frac{16^2}{3^2} \frac{a_0}{m_q} \frac{(q^0/\epsilon_0 - 1)^{3/2}}{(q^0/\epsilon_0)^5} \tag{2}$$

where ϵ_0 is the quarkonia binding energy and m_q is the charm/bottom quark mass and $a_0 = 1/\sqrt{m_q \epsilon_0}$. Using the same procedure, the M1 transition cross-section of gluon dissociation can be calculated as [37]

$$\sigma_D^{M1}(q^0) = \frac{8\pi}{3} \frac{16}{3} \frac{a_0}{m_q^2} \frac{\epsilon_0 (q^0/\epsilon_0 - 1)^{3/2}}{(q^0/\epsilon_0)^3} \tag{3}$$

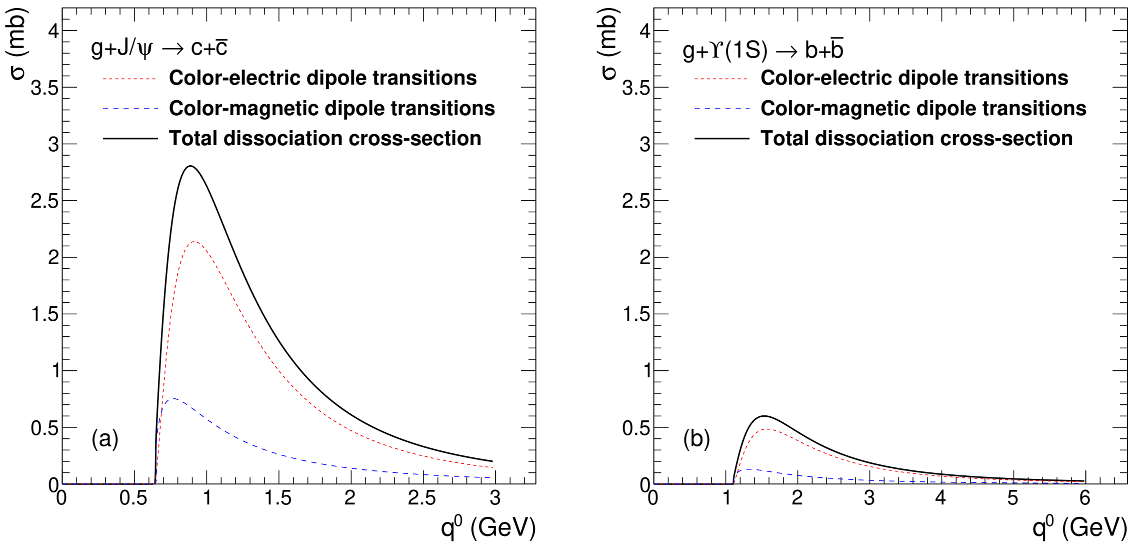

Figure 1: (Color online) Gluon dissociation cross section of J/ψ (a) and Υ(1S) (b) as a function of gluon energy (q^0) in quarkonia rest frame. The total dissociation cross-section is sum of both color-electric and chromo-magnetic dipole transitions.

The total dissociation cross section is given as

$$\sigma_D(q^0) = \sigma_D^{E1}(q^0) + \sigma_D^{M1}(q^0). \tag{4}$$

The values of ϵ_0 are taken as 0.64 GeV and 1.10 GeV for the ground states, J/ψ and Υ(1S), respectively [34]. For the excited states of bottomonia, the dissociation cross sections are used from Ref. [37, 43].

Figure 1 shows the gluon dissociation cross sections of J/ψ and Υ(1S) as a function of gluon energy for both color-electric and color-magnetic dipole transitions. The color-magnetic dipole transition cross-section has similar shape as that of electric cross-section and gives significant contribution in low and intermediate gluon energies. Total dissociation cross section increases with gluon energy and reaches a maximum around 0.9 GeV for J/ψ and around 1.5 GeV for Υ(1S). At higher gluon energies, the interaction probability decreases. The dissociation rate is calculated as a function of quarkonium momentum by integrating the dissociation cross section over thermal gluon momentum distribution $f_g(p_g)$ as

$$\begin{aligned} \lambda_D \rho_g = \langle \sigma v_{\rm rel} \rangle \, \rho_g &= \frac{g_g}{(2\pi)^3} \int d^3p_g \, f_g(p_g) \, \sigma_D(s) v_{\rm rel}(s) \\ &= \frac{g_g}{(2\pi)^3} \int dp_g 2\pi p_g^2 f_g(p_g) \int d\cos\theta \, \sigma_D(s) \, v_{\rm rel}(s), \end{aligned} \tag{5}$$

where $\sigma_D(s) = \sigma_D(q^0(s))$ in terms of the square of the center of mass energy s of the quarkonium-gluon system given by $s = M_Q^2 + 2p_g \sqrt{M_Q^2 + p^2} - 2p_g \, p \cos\theta$. Here M_Q is the mass and p is the momentum of quarkonium and θ is the angle between the quarkonium and the gluon. The variables q^0 and s are related by $q^0 = (s - M_Q^2)/(2\,M_Q)$. $v_{\rm rel}$ is

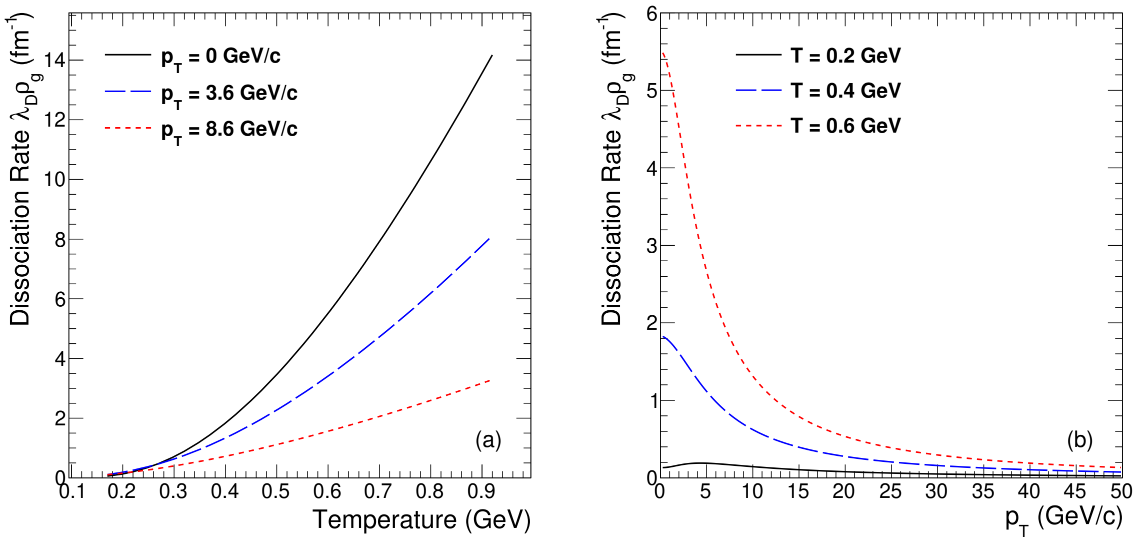

Figure 2: (Color online) Gluon dissociation rate of J/ψ as a function of (a) temperature and (b) J/ψ transverse momentum.

the relative velocity between the quarkonium and the gluon [26]. The formula in Eq. 5 is assumed for the most central collisions. We multiplied by a system size dependent factor ($\sqrt{N_{\rm part}/2A}$) to get the dissociation rate for other centralities. The J/ψ gluon dissociation rates as a function of temperature T are shown in Fig. 2(a) and as a function of p_T in Fig. 2(b). The dissociation rate increases with temperature as the gluon density increases. Also, it is maximum when the quarkonium is at rest and then decreases with p_T.

We can calculate the formation cross section from the dissociation cross section using principle of detailed balance [23, 44] as follows

$$\sigma_F = \frac{48}{36}\,\sigma_D(q^0)\frac{(s-M_Q^2)^2}{s(s-4m_q^2)}. \tag{6}$$

The formation rate of quarkonium at momentum $\mathbf{p}$ can be written as

$$\frac{d\lambda_F}{d\mathbf{p}} = \int d^3p_1\, d^3p_2\, \sigma_F(s)\, v_{\rm rel}(s)\, f_q(p_1)\, f_{\bar{q}}(p_2)\, \delta(\mathbf{p}-(\mathbf{p_1}+\mathbf{p_2})). \tag{7}$$

The variable s is the square of center of mass energy between the two heavy quarks with energy-momenta $(E_1,\, \mathbf{p_1})$ and $(E_2,\, \mathbf{p_2})$ with $v_{\rm rel}$ as their relative velocity.

The functions $f_{q/\bar{q}}(p)$ are taken as normalized near-thermal distribution functions of $q/\bar{q}$. These distributions can be described by the Tsallis function as follows

$$f_q(p,T) = A_n\left(1+\frac{\sqrt{p^2+m_q^2}}{n\,T}\right)^{-n}. \tag{8}$$

Here A_n is the normalization factor and $n = 12$ is obtained by fitting the transverse momentum spectra of D mesons measured by CMS experiment [45]. Figure 3 shows the

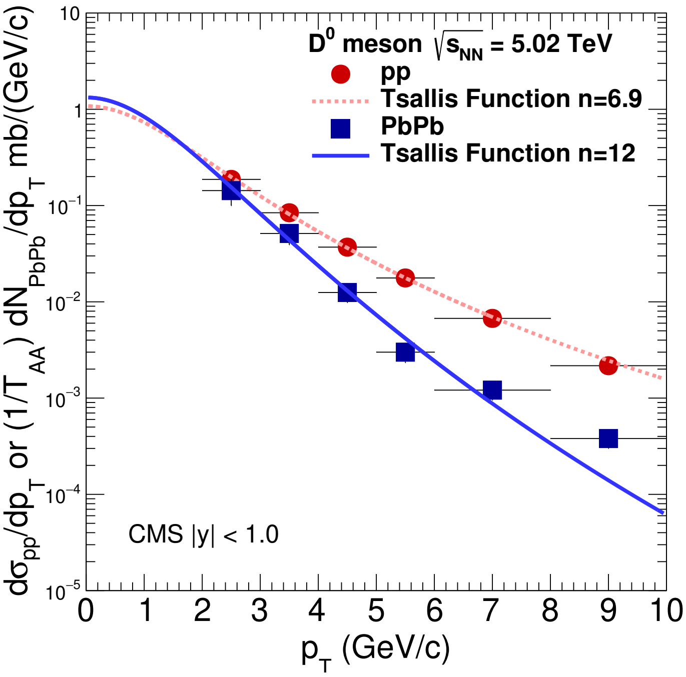

Figure 3: The transverse momentum spectra of D mesons in pp and PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV measured by CMS experiment [45]. The spectra are fitted by Tsallis function with $n = 6.9$ for pp and $n = 12$ for PbPb collisions.

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Figure 4(a) shows the behaviour of the formation rate as a function of temperature at different values of J/ψ meson p_T. Figure 4(b) shows the same as a function of J/ψ meson p_T at different temperatures. It shows that the J/ψ generated from uncorrelated heavy quark pairs has softer p_T distribution than that of J/ψ's coming from the initial hard scatterings. Thus the effect of recombination will be important at low and intermediate p_T.

2.2. Nuclear modification

The nuclear modification factor (R_{AA}) as a function of p_T can be obtained as

$$R_{AA}(p_T) = \frac{\Sigma_{\rm Centrality}\, N_Q(p_T, N_{\rm part})}{\Sigma_{\rm Centrality}\, N_{\rm coll}\, N_Q^{pp}(p_T)}. \tag{9}$$

The sum over the events is performed over the measured centrality range in the experiment and $\rm N_{coll}$ is the number of binary collisions for the centrality bins used

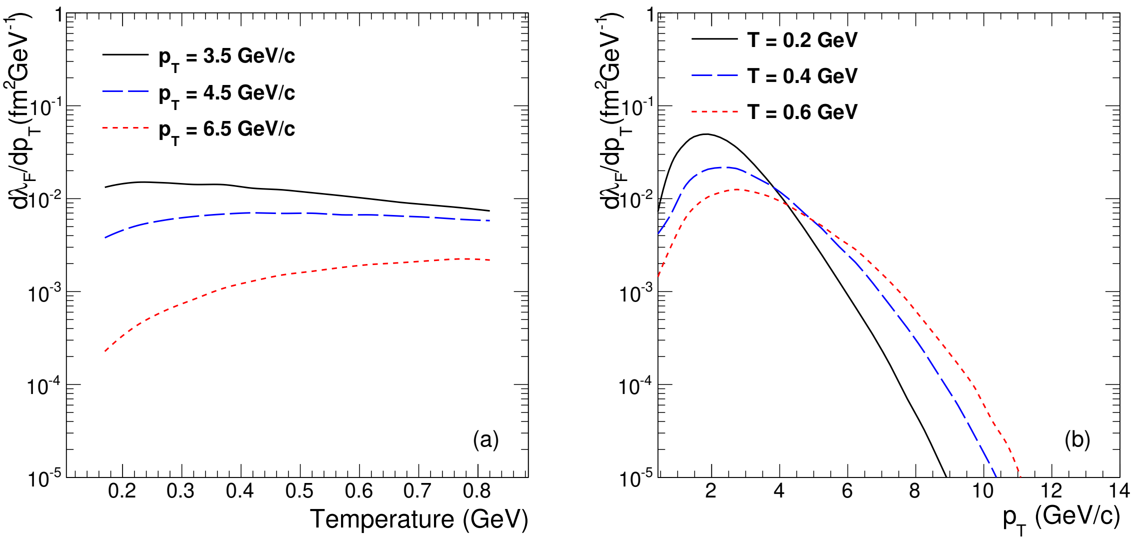

Figure 4: (Color online) Formation rate of J/ψ as a function of (a) temperature and (b) J/ψ transverse momentum.

in experiments. The R_{AA} as a function of collision centrality is obtained as

$$R_{AA}(N_{\rm part}) = \frac{\int_{p_{T\,\rm cut}} N_Q(p_T, N_{\rm part})\, p_T dp_T}{\int_{p_{T\,\rm cut}} N_{\rm coll}\ N_Q^{\rm pp}(p_T)\, p_T dp_T} \tag{10}$$

Here $p_{T\ \rm cut}$ defines the p_T range for acceptance of the experiment. The shape of quarkonia p_T distribution in pp collisions is obtained from PYTHIA 6.424 [46]. The PYTHIA generator gives good description of quarkonia data at LHC energy [47]. The number of $Q\bar{Q}$ pairs in different centrality classes are obtained by the $N_{\rm coll}$ scaling. The $N_{\rm coll}$ values in different centrality classes are calculated using the Glauber model [48].

The evolution of the system for each centrality range is governed by an isentropic cylindrical expansion ($s(T)\,V(\tau) = s(T_0)\,V(\tau_0)$) with prescription given in Ref. [26]. The equation of state (EOS) obtained by Lattice QCD and by hadronic resonances is used [49]. The radius R for a given centrality with number of participant $N_{\rm part}$ is obtained as $R(N_{\rm part}) = R_A\sqrt{N_{\rm part}/2A}$, where R_A is radius of the nucleus. The initial entropy density, $s(\tau_0)|_{0-5\%}$, for 0-5% centrality is

$$s(\tau_0)|_{0-5\%} = \frac{a_m}{V(\tau_0)|_{0-5\%}} \left(\frac{dN}{d\eta}\right)_{0-5\%}. \tag{11}$$

Here a_m ($= 5$) is a constant connecting the total entropy to the final hadron multiplicity $dN/d\eta$ obtained from hydrodynamic calculations [50]. The initial temperature, T_0, in the 0-5% most central collisions is estimated from the total multiplicity in the given rapidity, assuming that the initial time is $\tau_0 = 0.3$ fm/c. The total multiplicity in a given rapidity window is 1.5 times the measured charged particle multiplicity in PbPb collisions at 5.02 TeV. With the lattice EOS, at midrapidity, with $(dN_{\rm ch}/d\eta)_{0-5\%} = 1943$ [51], we find $T_0 = 0.516$ GeV. Likewise, at forward rapidity [52]; T_0 is 0.487 GeV. The freeze out temperature is taken to be $T_f = 0.140$ GeV.

2.3. Hadronic comovers

The suppression of quarkonia caused due to comoving pions is obtained by folding the quarkonium-pion dissociation cross section $\sigma_{\pi Q}$ over thermal pion distributions [53]. The cross section of pion-quarkonia is calculated by convoluting the gluon-quarkonia cross section σ_D over the gluon distribution obtained inside the pion [54],

$$\sigma_{\pi Q}(p_\pi) = \frac{p_+^2}{2(p_\pi^2 - m_\pi^2)} \int_0^1 dx\, G(x)\, \sigma_D(xp_+/\sqrt{2}), \tag{12}$$

where $p_+ = (p_\pi + \sqrt{p_\pi^2 - m_\pi^2})/\sqrt{2}$. The term $G(x)$ is the gluon distribution inside a pion which can be given by the GRV parameterization [55]. The comover cross section is expected to be small at LHC energies [56].

2.4. Experimental data to fit

The total charm and total bottom production cross-sections are measured by different experiments at LHC [57, 58, 59]. Table 1 and Table 2 show the values of total $c\bar{c}$ and $b\bar{b}$ production cross-section measured in pp collisions at LHC. We use these values to estimate the total heavy quark production cross section at $\sqrt{s_{NN}} = 5.02$ TeV. The quarkonium production cross sections are calculated from the measured heavy quark production cross-section using the energy independent factors (0.00526 for J/ψ and 0.002 for Υ) obtained from the color evaporation model [26, 60, 61]. The cold nuclear matter (CNM) effects i.e. the modifications of the parton distribution functions (nPDF) in PbPb collisions is calculated using the central EPS09 NLO parameter set [62]. The uncertainty in cold matter effects is obtained by adding the EPS09 NLO uncertainties in quadrature.

The production cross sections for heavy flavor and quarkonia at $\sqrt{s_{NN}} = 5.02$ TeV are given in Table 3. The yields in a minimum bias PbPb event is obtained from the per nucleon cross section, $\sigma_{\rm PbPb}$ as

$$N = \frac{A^2 \sigma_{\rm PbPb}}{\sigma_{\rm PbPb}^{\rm tot}} . \tag{13}$$

At 5.02 TeV, the total PbPb cross section, $\sigma_{\rm PbPb}^{\rm tot}$, is 7.7 b [48].

Table 1: Total $c\bar{c}$ production cross-section measured by ALICE experiment in pp collisions at LHC.

$\sqrt{s}$(TeV)	$\sigma^{c\bar{c}} \pm$ stat. $\pm$ syst.(mb)	Experiment	Ref.
2.76 TeV	$4.8 \pm 0.8^{+1.0}_{-1.3}$	ALICE	[57]
7 TeV	$8.5 \pm 0.5^{+1.0}_{-2.4}$	ALICE	[57]

Table 2: Total $b\bar{b}$ production cross-section measured by ALICE experiment in pp collisions at LHC.

$\sqrt{s}$(TeV)	$\sigma^{b\bar{b}} \pm$ stat. $\pm$ syst.(μb)	Experiment	Ref.
2.76 TeV	$130 \pm 15.1^{+42.1}_{-49.8}$	ALICE	[58]
7 TeV	$282 \pm 74^{+58}_{-68}$	ALICE	[59]

Table 3: Heavy quark and quarkonia production cross sections per nucleon pair at $\sqrt{s_{_{NN}}}$ = 5.02 TeV. The quantity N^{PbPb} gives the initial number of heavy quark pair/quarkonia in one PbPb event.

	$c\bar{c}$	J/ψ	$b\bar{b}$	Υ
σ_{pp}	$6.754^{+1.195}_{-2.015}$ mb	$35.32^{+6.247}_{-10.537}$ μb	$210.30^{+70.769}_{-77.640}$ μb	$0.4206^{+0.142}_{-0.155}$ μb
σ_{PbPb}	$4.669^{+0.826}_{-1.393}$ mb	$24.56^{+4.344}_{-7.327}$ μb	$179.30^{+60.337}_{-66.195}$ μb	$0.3586^{+0.121}_{-0.132}$ μb
N^{PbPb}	$26.23^{+4.639}_{-7.825}$	$0.1381^{+0.024}_{-0.041}$	$1.007^{+0.339}_{-0.372}$	$0.0020^{+0.0007}_{-0.0007}$

3. Results and discussions

Figure 5(a) and (b) show the estimations of different contributions to the nuclear modification factor, R_{AA}, for the J/ψ meson as a function of p_T along with the mid rapidity and high p_T measurements from CMS [16] and ATLAS [17] experiments respectively. Figure 5(c) shows the same for the low p_T and forward rapidity compared with the measurement by ALICE experiment [19]. At low p_T, regeneration of J/ψ gives dominant contribution which overcomes the strong suppression by gluon dissociation. This looks to be the reason for the increase of the R_{AA} of J/ψ around $p_T \approx 2$ GeV/c. The suppression due to gluon dissociation is substantial at low p_T and reduces as we move to higher p_T. At low and intermediate p_T, both regeneration and dissociation, due to the presence of QGP are effective. The high p_T suppression ($p_T > 10$ GeV/c) of J/ψ measured by CMS is greater than the suppression caused by gluon dissociation in the QGP. The suppression measured by CMS and ATLAS is at high p_T values greater than the heavy quark mass, and thus here the energy loss from initial partonic scatterings might play a crucial role as it does for open heavy flavour. The feed-down contributions for the J/ψ are not very large. At the LHC energies, around 80% J/ψ are from the directly produced hard scattering [63]. Moreover, the gluon dissociation cross section for the excited charmonia states are not reliable. Thus we chose not to consider the feed-down from the higher states for the J/ψ. The band around the total R_{AA} includes all the uncertainties in the dissociation and regeneration processes as discussed in the next paragraph. The band around CNM effects is shown separately and is not included in the total uncertainty band for a better display. The values of gluon-quarkonia cross section (σ_D) and the initial temperature T_0 can have uncertainties and will affect the results.

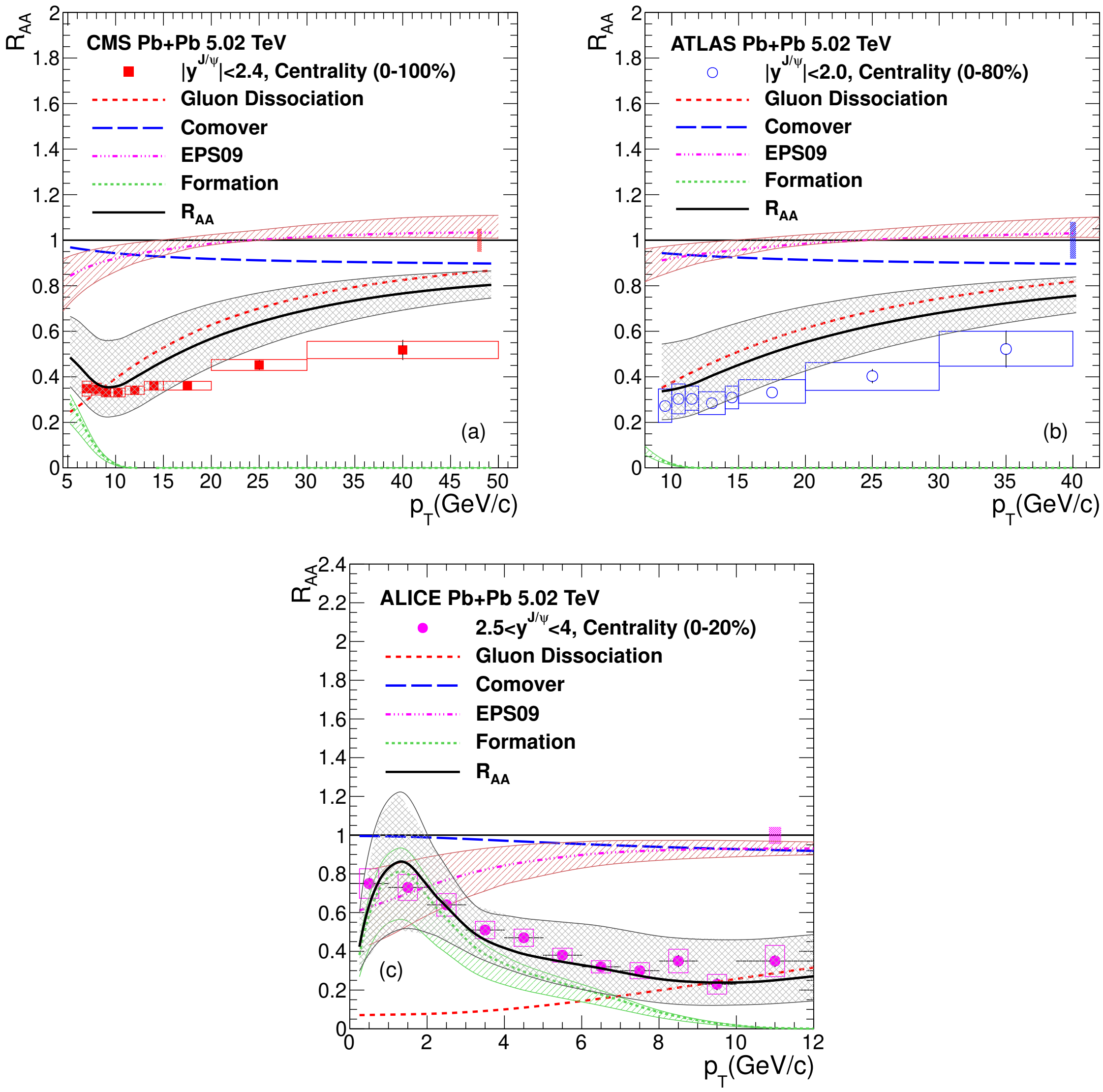

Figure 5: (Color online) Calculated nuclear modification factor (R_{AA}) as a function of J/ψ transverse momentum compared with (a) CMS, (b) ATLAS and (c) ALICE measurements [16, 17, 19]. The global uncertainty in R_{AA} is shown as a band around the line at 1.

The value of σ_D is varied by $\pm 50\%$ around the calculated value to obtain the uncertainty in R_{AA}. The initial temperature is calculated using measured charged particle density and nominal value of $\tau_0 = 0.3$ fm/c. The value of τ_0 is varied in the range $0.1 < \tau_0 < 0.6$ fm/c which corresponds to the variation in the initial temperature from +45 % to - 20 %. The uncertainty in the charm pair cross section is also considered as a source while obtaining the contribution due to regeneration. The total uncertainty is obtained by adding in quadrature all individual uncertainties.

The calculation of R_{AA} of J/ψ is also made as a function of collision centrality (system size). Figure 6 shows calculations of different contributions to the J/ψ nuclear

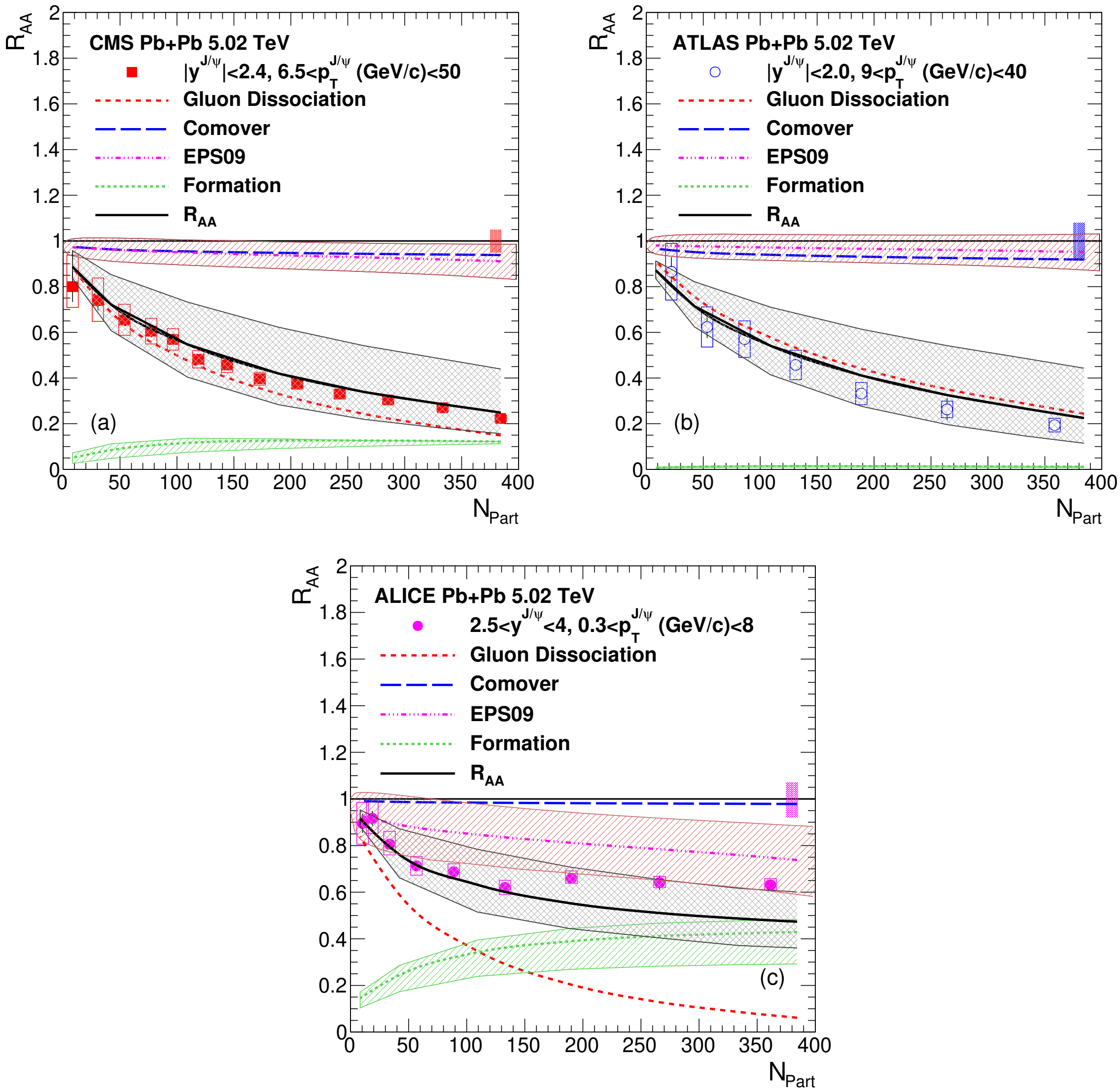

Figure 6: (Color online) Calculated nuclear modification factor (R_{AA}) of J/ψ as a function of centrality of collisions, compared with (a) CMS, (b) ATLAS and (c) ALICE measurements [16, 17, 19]. The global uncertainty in R_{AA} is shown as a band around the line at 1.

modification factor as a function of system size, along with the measurements from CMS in (a), ATLAS in (b) and ALICE in (c) [16, 17, 19]. The figure shows that the suppression of J/ψ due to QGP increases when the system size grows. The contribution from regeneration process is minimum in the high p_T range (p_T > 9 GeV/c) for ATLAS case as shown in Fig. 6(b) and maximum in the low p_T range for the ALICE case shown in Fig. 6(c). For low p_T ALICE measurement, the nuclear modification factor is almost flat from mid to central collisions because the regeneration compensates the gluon dissociation, a trend which is well-reproduced by our calculations. The CMS centrality dependence of the R_{AA} of J/ψ given in Fig. 6(a) is reasonably well described by the

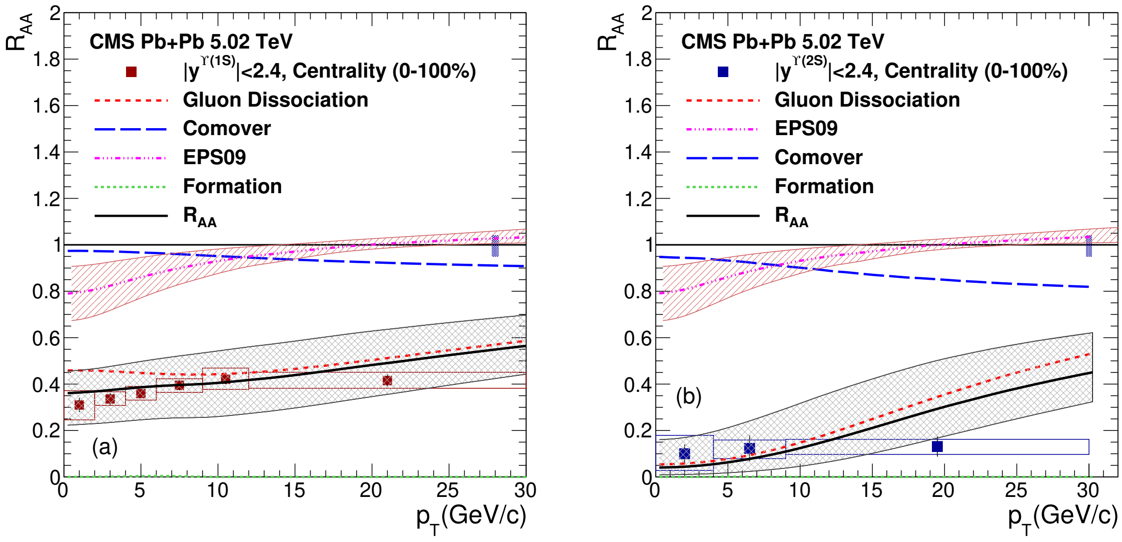

Figure 7: (Color online) Calculated nuclear modification factor (R_{AA}) of (a) Υ(1S) and (b) Υ(2S) as a function of p_T compared with CMS measurements [32]. The global uncertainty in R_{AA} is shown as a band around the line at 1.

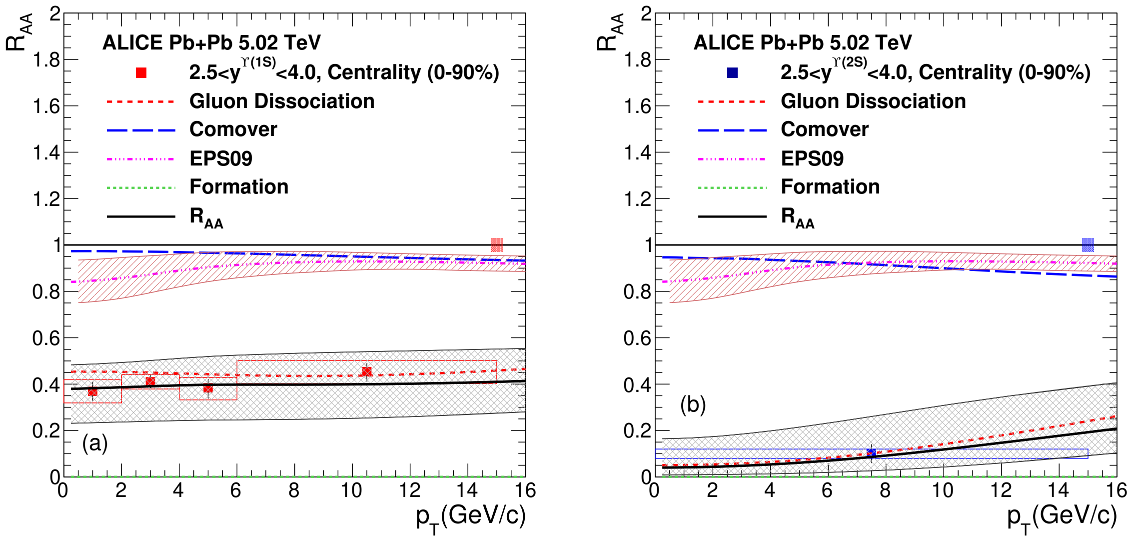

Figure 8: (Color online) Calculated nuclear modification factor (R_{AA}) of (a) Υ(1S) and (b) Υ(2S) as a function of p_T in the kinematic range of ALICE detector at LHC [33]. The global uncertainty in R_{AA} is shown as a band around the line at 1.

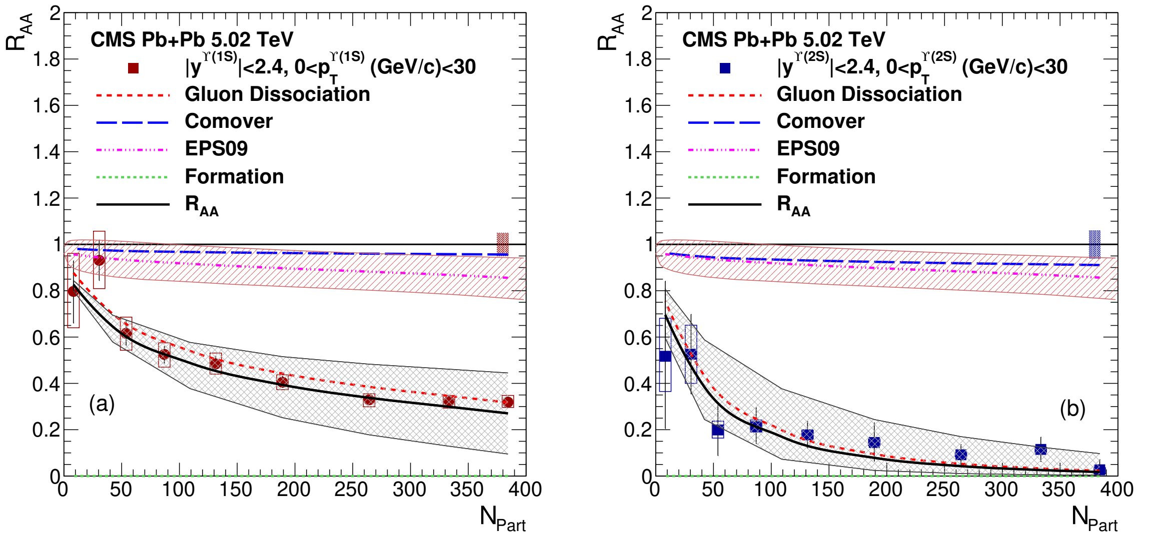

Figure 9: (Color online) Calculated nuclear modification factor (R_{AA}) of (a) Υ(1S) and (b) Υ(2S) as a function of centrality of the collisions compared with the CMS measurements [32].The global uncertainty in R_{AA} is shown as a band around the line at 1.

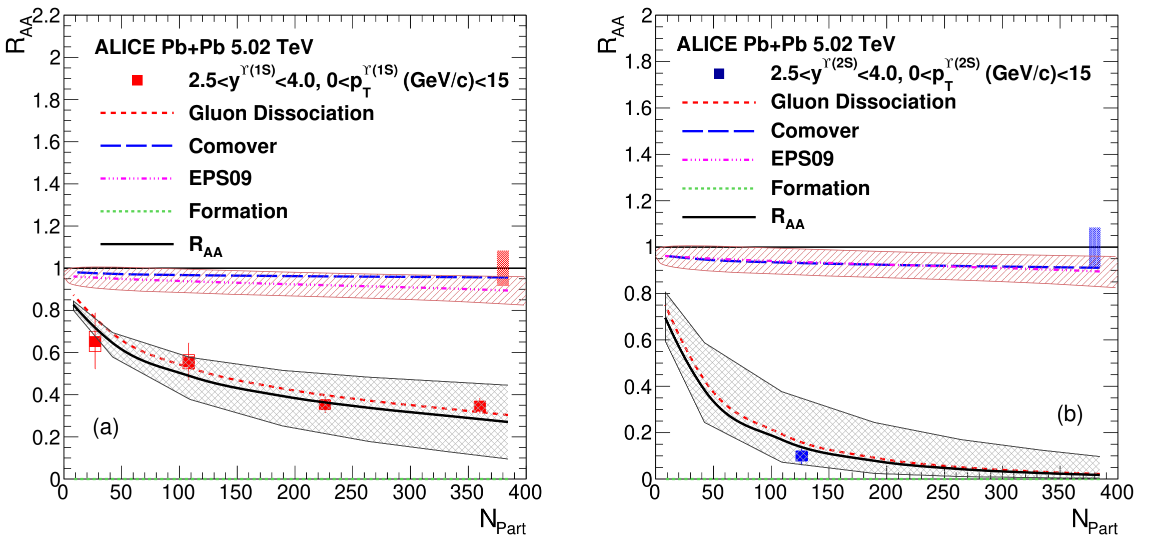

Figure 10: (Color online) Calculated nuclear modification factor (R_{AA}) of (a) Υ(1S) and (b) Υ(2S) as a function of centrality of the collisions compared with the ALICE measurement [33]. The global uncertainty in R_{AA} is shown as a band around the line at 1.

model since the contribution of the CMS data comes from J/ψ with $6.5 < p_T < 10$ GeV/c where the suppression due to gluon dissociation dominates. For the case of ATLAS data, the model reproduces the shape of centrality dependence of the R_{AA} of J/ψ observed in the data.

Figure 7(a) and (b) show the calculations of contributions to the nuclear modification factor, R_{AA}, for the Υ(1S) and Υ(2S) respectively as a function of p_T compared with the mid rapidity measurements from CMS [32]. The gluon dissociation mechanism combined with the pion dissociation and shadowing corrections gives good description of data in mid p_T range ($p_T \approx$ 5-10 GeV/c) for both Υ(1S) and Υ(2S). The contribution from the regenerated Υs is negligible even at LHC energies. Our calculations under-predict the suppression observed at the highest measured p_T for Υ(1S) and Υ(2S) which is similar for the case of J/ψ. The states Υ(1S) and Υ(2S) also have feed-down contributions from decays of higher b$\bar{\rm b}$ bound states. The nuclear modification factor, R_{AA} is obtained taking into account the feed-down corrections as follows

$$R_{AA}^{\Upsilon(3S)} = R_{AA}^{\Upsilon(3S)} \tag{14}$$

$$R_{AA}^{\Upsilon(2S)} = f_1 R_{AA}^{\Upsilon(2S)} + f_2 R_{AA}^{\Upsilon(3S)} \tag{15}$$

$$R_{AA}^{\Upsilon(1S)} = g_1 R_{AA}^{\Upsilon(1S)} + g_2 R_{AA}^{\chi_b(1P)} + g_3 R_{AA}^{\Upsilon(2S)} + g_4 R_{AA}^{\Upsilon(3S)} \tag{16}$$

The factors fs and gs are obtained from CDF measurement [64]. The values of g_1, g_2, g_3 and g_4 are 0.509, 0.27, 0.107 and 0.113 respectively. Here g_4 is assumed to be the combined fraction of Υ(3S) and χ_b(2P). The values of f_1 and f_2 are taken as 0.50 [65].

Figure 8(a) and (b) show the model prediction of the nuclear modification factor, R_{AA}, for the Υ(1S) and Υ(2S) respectively as a function of p_T in the kinematic range covered by ALICE detector. The ALICE data [33] is well described by our model.

Figure 9(a) depicts the calculated centrality dependence of the Υ(1S) nuclear modification factor, along with the midrapidity data from CMS [32]. Our calculations combined with the pion dissociation and shadowing corrections gives very good description of the measured data. Figure 9(b) shows the same for the Υ(2S) along with the midrapidity CMS measurements. The suppression of the excited Υ(2S) states is also well described by our model. As stated earlier, the effect of regeneration is negligible for Υ states.

Figure 10(a) shows the forward rapidity ALICE measurement of the Υ(1S) nuclear modification factor [33] along with our calculations. The suppression due to thermal gluon dissociation describes the measured data after including the comover and shadowing corrections. Figure 10(b) shows the calculations for the Υ(2S) nuclear modification factor in ALICE detector kinematic range. The suppression due to thermal gluon dissociation describes the ALICE measurements after including the comover and shadowing corrections.

4. Summary

We presented detailed calculations of the J/ψ and Υ production and the modifications of their yields in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. A kinetic model is employed which incorporates quarkonia suppression inside QGP, suppression due to hadronic comovers and regeneration from heavy quark pairs. The behaviour of the dissociation and formation rates are studied as a function of transverse momentum and medium temperature. The nuclear modification factors for both J/ψ and Υ are obtained as a function of system size and transverse momentum and have been compared to the measurements in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. It is found that regeneration of J/ψ is the dominant process at low p_T. As a result the J/ψ production is found to be enhanced in the ALICE low p_T data. In the same p_T range gluon dissociation is also substantial however it becomes small as we move to high p_T. Both these processes affect the yields of quarkonia in a QGP medium at low and intermediate p_T. The high p_T suppression ($p_T > 10$ GeV/c) of J/ψ measured by CMS and ATLAS is more than the suppression expected due to gluon dissociation in QGP. The energy loss from initial partonic scatterings might play a crucial role in this region as it does for open heavy flavour. As the system size grows J/ψ's are increasingly suppressed. The nuclear modification factor at low p_T (ALICE case) as a function of centrality remains flat since the increased suppression is compensated by regenerated J/ψ's as the system size grows. We could reproduce the centrality dependence of R_{AA} for high p_T J/ψ's reasonably well. The p_T and centrality dependence of suppression of Υ states are well reproduced by the model.

5. Acknowledgement

Authors thank Board of Research in Nuclear Sciences (BRNS) for support. AB thanks Alexander von Humboldt (AvH) foundation and Federal Ministry of Education and Research (Gernamy) for support through Research Group Linkage Programme.

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