Quarkonia suppression in PbPb collisions at $\sqrt{s}_{NN} =$ 2.76 TeV

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Abstract

We estimate the modification of quarkonia yields due to different processes in the medium produced in PbPb collisions at LHC energy. The quarkonia and heavy flavour cross sections calculated upto NLO are used in the study and shadowing corrections are obtained by EPS09 parameterization. A kinetic model is employed which incorporates quarkonia suppression inside QGP, suppression due to hadronic comovers and regeneration from charm pairs. Quarkonia dissociation cross section due to gluon collisions has been considered and the regeneration rate has been obtained using the principle of detailed balance. The modification in quakonia yields due to collisions with hadronic comovers has been estimated assuming it to be caused by pion. The menifestations of these effects in different kinematic regions in the nuclear modification factors for both J/ψ and Υ has been demonstrated for PbPb collisions at $\sqrt{s}_{NN} = 2.76$ TeV in comparison with the measurements. Both the suppression and regeneration due to deconfined medium strongly affect low intermediate p_T range. The large observed suppression of J/ψ at p_T above 10 GeV/c exceeds the estimates of suppression by deconfined medium.

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I. INTRODUCTION

Heavy ion collisions at relativistic energies are performed to create and characterize Quark Gluon plasma (QGP), a phase of strongly interacting matter at high energy density where quarks and gluons are no longer bound within hadrons. Quarkonia state (J/ψ and Υ) have been one of the most popular tools since their suppression was proposed as a signal of QGP [1]. The understanding of these probes has evolved substantially via measurements through three generations of experiments: SPS (at CERN), RHIC (at BNL) and the LHC (at CERN) and by voluminous theoretical activities [For recent reviews see Refs. [2–4]]. Quarkonia are produced early in the heavy ion collisions and if they evolve through deconfined medium their yields should be suppressed in comparison with those in pp. The first such measurement was the 'anomalous' J/ψ suppression discovered at the SPS which was considered as a hint of QGP formation. The RHIC measurements showed almost the same suppression at a much higher energy contrary to the expectation [4, 5]. Such an observation was consistent with the scenarios that at higher collision energy the expected more suppression is compensated by regeneration of J/ψ by recombination of two independently produced charm quarks [6]. After the LHC started PbPb collisions at $\sqrt{s}_{NN}$ = 2.76 TeV, a wealth of results have become available on quarkonia production [7, 8]. The CMS experiment carries out J/ψ measurement at high transverse momentum ($p_T > 6.5$ GeV/c). The nuclear modification factor R_{AA} of these high p_T prompt J/ψ decreases with increasing centrality [9, 10] showing moderate suppression even in the most peripheral collisions. Moreover R_{AA} is found to be nearly independent of p_T (above 6.5 GeV/c) showing that J/ψ remain suppressed even at very high p_T upto 16 GeV/c. On comparing with the STAR results [11] at RHIC it follows that the suppression of (high p_T) J/ψ has increased with collision energy. The ALICE results [12] of J/ψ covers low p_T range which have little or no centrality dependence. The ALICE J/ψ suppression decrease substantially with decreasing p_T and at very low p_T the suppression is small. When compared with PHENIX forward rapidity measurement at RHIC [5], it suggests that low p_T J/ψ are less suppressed at LHC. These observations suggest regeneration of J/ψ at low p_T by recombination of independently produced charm pairs. The CMS measurements [13, 14] reveal that the higher Υ states are more suppressed relative to the ground state, a phenomenon known as sequential suppression. The ALICE measurements in forward rapidity ($2.5 \leq y^{\Upsilon} \leq 4.0$) are consistent with CMS measurements in mid rapidity region ($|y^{\Upsilon}| \leq 2.4$).

Many theoertical frameworks have been developed in pre-LHC years for the modification of quarkonia due to different processes. The suppression of quarkonia in QGP are understood in terms of colour screening models e.g. Ref. [1, 15]and alternatively in terms of dissociation of quarkonia by gluon collision process [16, 17]. The statistical models [6, 18] offer estimates of the regeneration of quarkonia from charm quark pairs. The inverse of gluon dissociation process is also used to estimate regeneration [19]. The quarkonia yields in heavy ion collisions are also modified due to non-QGP effects such as shadowing, an effect due to change of the parton distribution functions inside the nucleus, and dissociation due to hadronic or comover interaction [20]. There have been many recent calculations to explain the LHC results on quarkonia using a combination of above theoretical frameworks and models [21, 22].

In this paper, we calculate the quarkonia (both J/ψ and Υ) production and suppression in a kinetic model which includes dissociation due to thermal gluons, modification of yield due to change in parton distribution functions inside nucleus and due to collisions with comover hadrons. Regeneration by thermal heavy quark pairs is also take into account. Our goal is obtain the nuclear modification factor of quarkonia as a function of transverse momentum and centrality of collision to be compared with experimental data from CMS and ALICE.

II. THE PRODUCTION RATES AND SHADOWING

The production cross sections for heavy quark pairs are calculated to NLO in pQCD using the CTEQ6M parton densities [23, 24]. The central EPS09 parameter set [25] is used to calculate the modifications of the parton densities in PbPb collisions. We use the same set of parameters as that of Ref. [26] with the NLO calculation of Ref. [27] to obtain the exclusive $Q\overline{Q}$ pair rates. The production cross sections for heavy flavor and quarkonia at $\sqrt{s_{_{NN}}} = 2.76$ TeV [28] are given in Table I. The number of $Q\overline{Q}$ pairs in a minimum bias PbPb event is obtained from the per nucleon cross section, $\sigma_{\rm PbPb}$, by

$$N_{Q\overline{Q}} = \frac{A^2 \sigma^{Q\overline{Q}}_{\rm PbPb}}{\sigma^{\rm tot}_{\rm PbPb}} \ . \quad (1)$$

At 2.76 TeV, the total PbPb cross section, $\sigma^{\rm tot}_{\rm PbPb}$, is 7.65 b [29].

TABLE I. Heavy quark and quarkonia production cross sections at $\sqrt{s_{_{NN}}} = 2.76$ TeV. The cross sections are given per nucleon pair while $N^{\rm PbPb}$ (including shadowing) gives the number of heavy quark pair/quarkonia per PbPb event.

	$c\bar{c}$	J/ψ	$b\bar{b}$	Υ
$\sigma_{\rm PbPb}$	$1.76^{+2.32}_{-1.29}$ mb	31.4 μb	$89.3^{+42.7}_{-27.2}\mu$b	0.38 μb
$N^{\rm PbPb}$	$9.95^{+13.10}_{-7.30}$	0.177	$0.50^{+0.25}_{-0.15}$	0.01
N^{pp}		0.177/0.93		0.01/0.95

III. MODIFICATION OF QUARKONIA IN THE PRESENCE OF QGP

In the kinetic approach [19], the proper time (τ) evolution of the quarkonia population N_{QO} is given by the rate equation

$$\frac{dN_{QO}}{d\tau} = -\lambda_D \rho_g N_{QO} + \lambda_F \frac{N_{Q\bar{Q}}^2}{V(\tau)}, \tag{2}$$

where $V(\tau)$ is the volume of the deconfined spatial region and $N_{Q\bar{Q}}$ is the number of initial heavy quark pairs produced per event depending on the centrality ($N_{\rm part}$). The λ_D is the dissociation rate obtained by the dissociation cross-section averaged over the momentum distribution of gluons and λ_F is the formation rate obtained by the formation cross-section averaged over the momentum distribution of Q and $\bar{Q}$. ρ_g is the density of thermal gluons. The number of quarkonia at freeze-out time τ_f is given by solution of Eq. (2) as

$$N_{QO}(p_T) = S(p_T)\, N_{QO}^{\rm PbPb}(p_T) + N_{QO}^F(p_T). \tag{3}$$

Here $N_{QO}^0(p_T)$ is the number of initially produced quarkonia (including shadowing) as a function of p_T and $S(p_T)$ is their survival probability from gluon collisions at freeze-out time τ_f and is written as

$$S(\tau_f, p_T) = \exp\left(-\int_{\tau_0}^{\tau_f} f(\tau)\lambda_{\rm D}(T, p_T)\, \rho_g(T)\, d\tau\right). \tag{4}$$

The temperature $T(\tau)$ and the QGP fraction $f(\tau)$ evolve from initial time τ_0 to freeze-out time τ_f due to expansion of QGP. The initial temperatures and thus the evolution is dependent on $N_{\rm part}$. $N_{QO}^F(p_T)$ is the number of regenerated quarkonia per event and is given by

$$N_{QO}^F(p_T) = S(\tau_f, p_T) N_{Q\bar{Q}}^2 \int_{\tau_0}^{\tau_f} \frac{\lambda_{\rm F}(T, p_T)}{V(\tau)\, S(\tau, p_T)} d\tau \tag{5}$$

The nuclear modification factor (R_{AA}) can be written as

$$R_{AA}(p_T) = S(p_T)\, R(p_T) + \frac{N^F_{QO}(p_T)}{N^{pp}_{QO}(p_T)}. \tag{6}$$

Here $R(p_T)$ is the shadowing factor. R_{AA} as a function of collision centrality, including the regeneration will be

$$R_{AA}(N_{\rm part}) = \frac{\int_{p_T\,{\rm Cut}} N^{pp}_{QO}(p_T) S(p_T)\, R(p_T) dp_T}{\int_{p_T\,{\rm Cut}} N^{pp}_{QO}(p_T) dp_T} + \frac{\int_{p_T\,{\rm Cut}} N^{F}_{QO}(p_T) dp_T}{\int_{p_T\,{\rm Cut}} N^{pp}_{QO}(p_T) dp_T} \tag{7}$$

Here $p_{\rm Cut}$ defines the p_T range as per the experimental measurements. $N^{pp}_{QO}(p_T)$ is the unmodified p_T distribution of quarkonia obtained by NLO calculations which is scaled to a particular centrality of PbPb collisions.

The evolution of the system for each centrality of collision is governed by an isentropical cylindrical expansion with volume element

$$V(\tau) = \tau\, \pi\, (R + \frac{1}{2} a\, \tau^2)^2, \tag{8}$$

where a_T=0.1c^2 fm^{-1} is the transverse acceleration [21]. The initial transverse size, R as a function of centrality is obtained as

$$R(N_{\rm part}) = R_{0-5\%} \sqrt{\frac{N_{\rm part}}{(N_{\rm part})_{0-5\%}}}, \tag{9}$$

where $R_{0-5\%} = 0.92\, R_{\rm Pb}$; $R_{\rm Pb}$ being the radius of the Pb nucleus.

The evolution of entropy density for each centrality is obtained by entropy conservation condition $s(T)\, V(\tau) = s(T_0)\, V(\tau_0)$. The equation of state obtained by Lattice QCD along with hadronic resonance gas [30] is used for $s(T)$ to obtain the temperature as a function of proper time τ. The initial entropy density for each centrality is calculated using

$$s(\tau_0) = s(\tau_0)|_{0-5\%} \left(\frac{dN/d\eta}{N_{\rm part}/2}\right) / \left(\frac{dN/d\eta}{N_{\rm part}/2}\right)_{0-5\%}. \tag{10}$$

Measured values of $\left(\frac{dN/d\eta}{N_{\rm part}/2}\right)$ as a function of $N_{\rm part}$ [31] are used in the calculations. The initial entropy density $s(\tau_0)|_{0-5\%}$ for 0-5% centrality is obtained as

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

Here $a_m = 5$ relating the total entropy with the mutliplicity is obtained from hydrodynamic calculations [32].

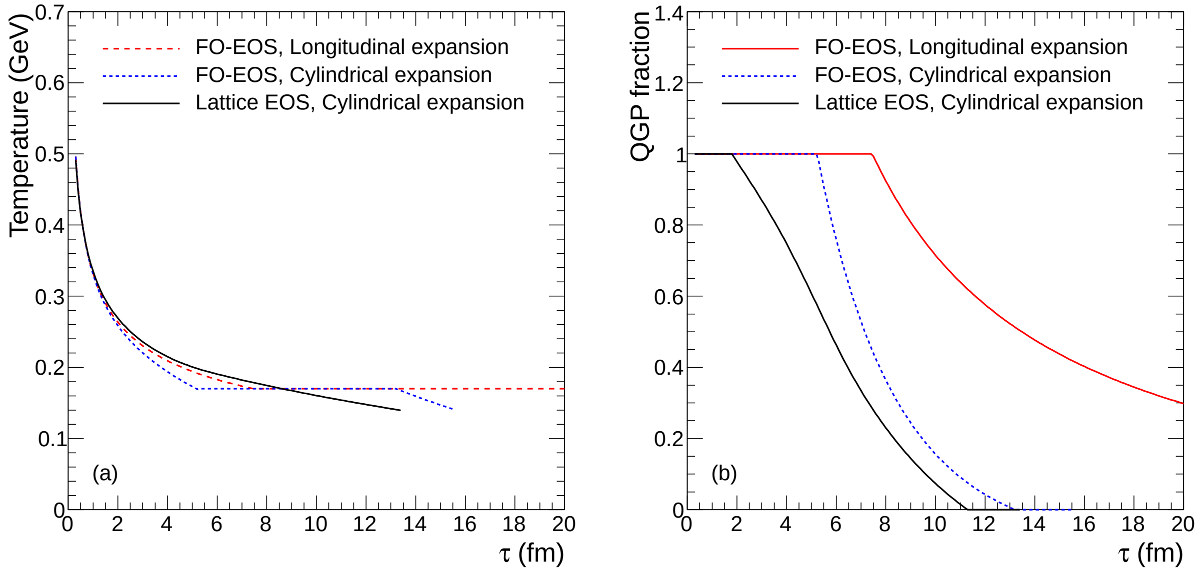

FIG. 1. (Color online) (a) Temperature and (b) QGP fraction in the system as a function of proper time τ in case of the most central (0-5%) collisions for longitudinal and cylindrical expansions using first order and lattice equation of state .

Using $(dN/d\eta)_{0-5\%}$=1.5×1600 obtained from the charge particle multiplicity measured in PbPb collisions at 2.76 TeV and with lattice equation of state we obtain the initial temperature for the most central collisions as 0.492 GeV at time τ_0 = 0.3 fm/c.

The (proper)time evolution of temperature is shown in Fig. 1(a) and QGP fraction in Fig. 1(b) in case of most central (0-5%) collisions for both longitudinal and cylindrical expansions using first order and lattice Equation of state (EOS). For the first order EOS, T_C = 0.170 GeV and the QGP fraction goes from 1 to 0 at this temperature assuming a mixed phase of QGP and hadrons. The QGP fraction in case of lattice EOS governs number of degrees of freedom decided by entropy density. It is fixed to 1 above an entropy density corresponding to a 2-flavour QGP and fixed to zero below entropy density for a hot rasonance gas. The freeze out temperature in all cases is T_f = 0.140 GeV.

A. Dissociation Rate

In colour dipole approximation the gluon dissociation cross section as function of gluon energy q^0 in the quarkonium rest frame is given by [16]

$$\sigma_D(q^0) = \frac{8\pi}{3}\frac{16^2}{3^2}\frac{a_0}{m_Q}\frac{(q^0/\epsilon_0 - 1)^{3/2}}{q^0/\epsilon_0^5}, \tag{12}$$

where ϵ_0 is the quarkonia binding energy and m_Q is the charm/bottom quark mass and $a_0 = 1/\sqrt{m_Q\epsilon_0}$. The values of ϵ_0 are taken as 0.64 and 1.10 GeV for ground states J/ψ and $\Upsilon(1S)$, respectively [33]. For excited states of bottommonia we use dissociation cross section from Ref. [34].

Figure 2 shows the gluon dissociation cross section of J/ψ and $\Upsilon(1S)$ as a function of gluon energy. The dissociation cross section is zero when gluon energy is less than the binding energy of the quarkonia. It increases with gluon energy and reaches maximum at 1.2 (1.5) GeV for $J/\psi\,(\Upsilon)$. At higher gluon energy, the interaction probability decreases. q^0 is related to the centre of mass energy square s, of quakonium-gluon system as

$$q^0 = \frac{s - M_{QO}^2}{2\,M_{QO}}. \tag{13}$$

Using this relation, $\sigma_D(q^0(s))$ can be obtained which we write as $\sigma_D(s)$. The s can be obtained as $s = M_{QO}^2 + 2p_g\sqrt{M_{QO}^2 + p^2}(1-\cos\theta)$, where M_{QO} and p are mass and momentum of quarkonium and θ is its angle with gluon.

We can calculate dissociation rate as a function of quarkonium momentum by integrating the dissociation cross-section on thermal gluon momentum distribution $f_g(p_g)$ as

$$\begin{aligned}\lambda_D\rho_g = \langle\sigma v_{\rm rel}\rangle\,\rho_g &= \frac{g_g}{(2\pi)^3}\int d^3p_g\, f_g(p_g)\,\sigma_D(s)v_{\rm rel}(s)\\ &= \frac{g_g}{(2\pi)^3}\int 2\pi p_g^2 dp_g f_g(p_g)\int \sigma_D(s)v_{\rm rel}(s)d(\cos\theta)\end{aligned} \tag{14}$$

The relative velocity $v_{\rm rel}$ between the quarkonium and the gluon is given by

$$v_{\rm rel} = \frac{s - M_{QO}^2}{2p_g\, p_g\sqrt{M_{QO}^2 + p^2}} \tag{15}$$

The gluon dissociation rates of J/ψ as a function of temperature are shown in Fig. 3(a) and as a function of transverse momentum are shown in Fig. 3(b). The dissociation rate increases with temperature due to increase in gluon density. Dissociation rate of quarkonium is maximum when it is at rest and decreases with its (transverse) momentum.

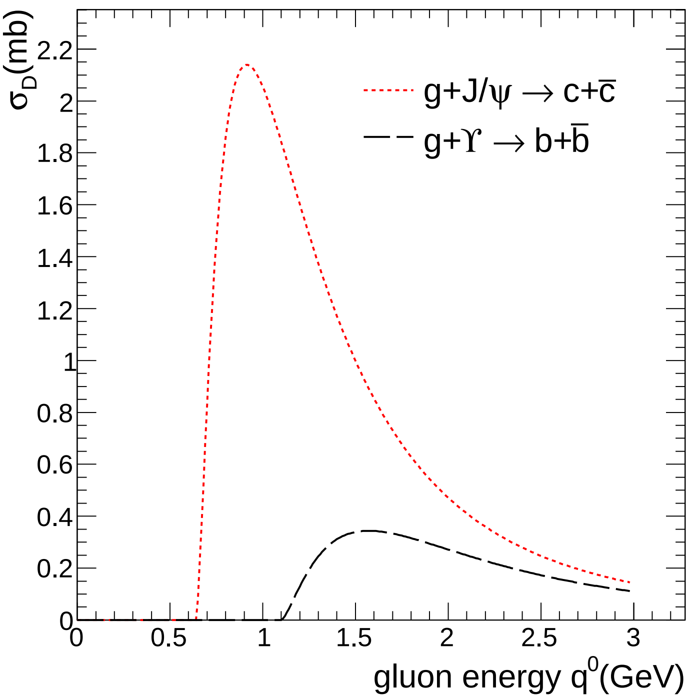

FIG. 2. Gluon dissociation cross-section of quarkonia as a function of gluon energy (q^0) in quarkonia rest frame.

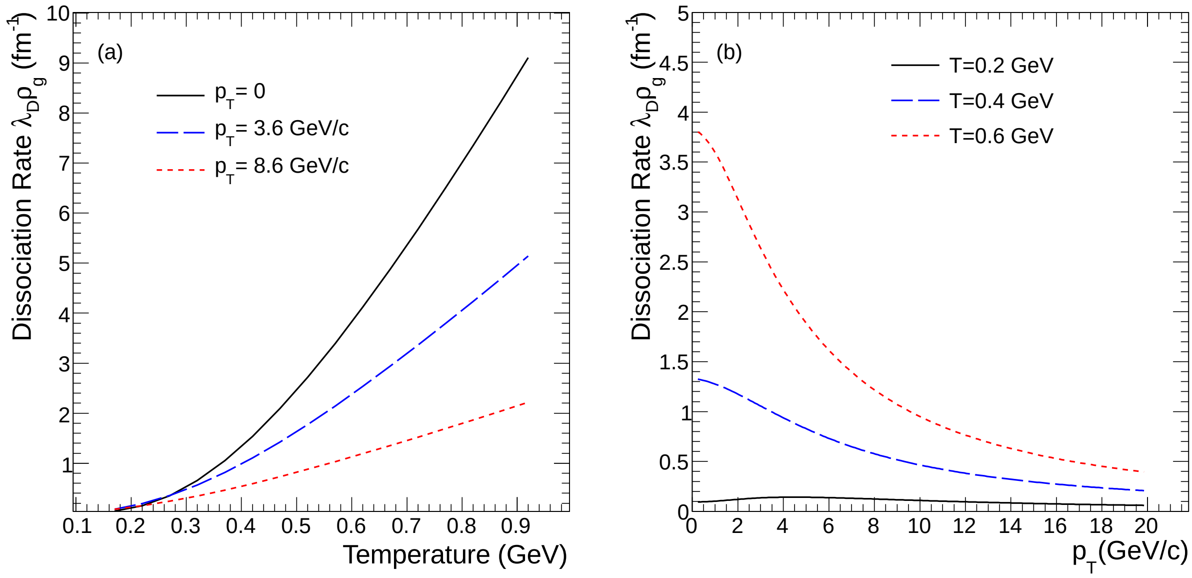

FIG. 3. (Color online) Gluon dissociation rate of J/ψ as a function of (a) temperature and (b) as a function of transverse momentum.

B. Formation Rate

We can calculate formation cross section from dissociation cross section using detailed balance relation [19, 35] as

$$\sigma_F = \frac{48}{36}\,\sigma_D(q^0)\frac{(s-M_{QO}^2)^2}{s(s-4m_Q^2)}. \tag{16}$$

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

$$d\lambda_F/d\mathbf{p} = \int \sigma_F(s)\, v_{\rm rel}(s)\, f_Q(p_1)\, f_{\bar{Q}}(p_2)\, d^3p_1\, d^3p_2\, \delta(\mathbf{p}-(\mathbf{p_1}+\mathbf{p_2})) \tag{17}$$

Here $f_{Q/\bar{Q}}(p)$ are taken as thermal distribution function of $Q/\bar{Q}$ which are normalized to one as per $\int f_Q(p)d^3p = 1$. $v_{\rm rel}$ is relative velocity between $Q\bar{Q}$ quark pair and is given by

$$v_{\rm rel} = \frac{\sqrt{(p_1.p_2)^2 - m_Q^4}}{E_1\, E_2} \tag{18}$$

Here $p_1 = (E_1, \mathbf{p_1})$, $p_2 = (E_2, \mathbf{p_2})$ are four momenta of heavy quark and anti-quarks, respectively.

Figure 4 (a) shows variation of formation rate of J/ψ as a funcion of medium temperature and Fig. 4 (b) shows as a function of transverse momentum of J/ψ. The J/ψ generated from recombination of uncorrelated heavy quark pairs will have softer p_T distributions than that of J/ψ coming from initial hard scattering and thus effect of recombination will be important only at low p_T.

IV. EFFECT OF HADRONIC COMOVERS

The suppression of quarkonia by comoving pions can be calculated by folding the quarkonium-pion dissociation cross section $\sigma_{\rm I}$ over thermal pion distributions [36]. It is expected that at LHC energies cross-section of comover suppression will be small [37]. We take 1 mb cross-section for both J/ψ and Υ states. The dissociation rate λ_{D_π} can be written as

$$\begin{aligned}\lambda_{D_\pi}\,\rho_\pi &= \frac{g_\pi}{(2\pi)^3}\int d^3p f_\pi(p)\sigma_I v_{\rm rel} \\ &= \frac{g_\pi}{(2\pi)^3}\int 2\pi p^2 dp f_\pi(p)\int \sigma_{\rm I} v_{\rm rel}(s)\Theta(s-4m_D^2)d(cos\theta)\end{aligned} \tag{19}$$

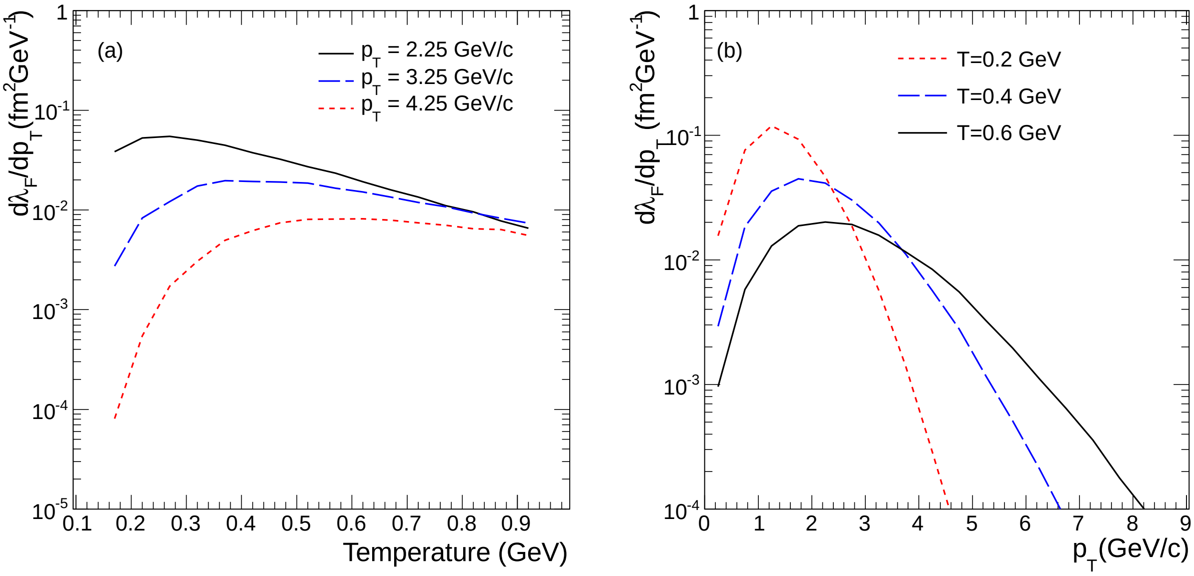

FIG. 4. (Color online) Formation rate of J/ψ as (a) a function of temperature and (b) as a function of transverse momentum.

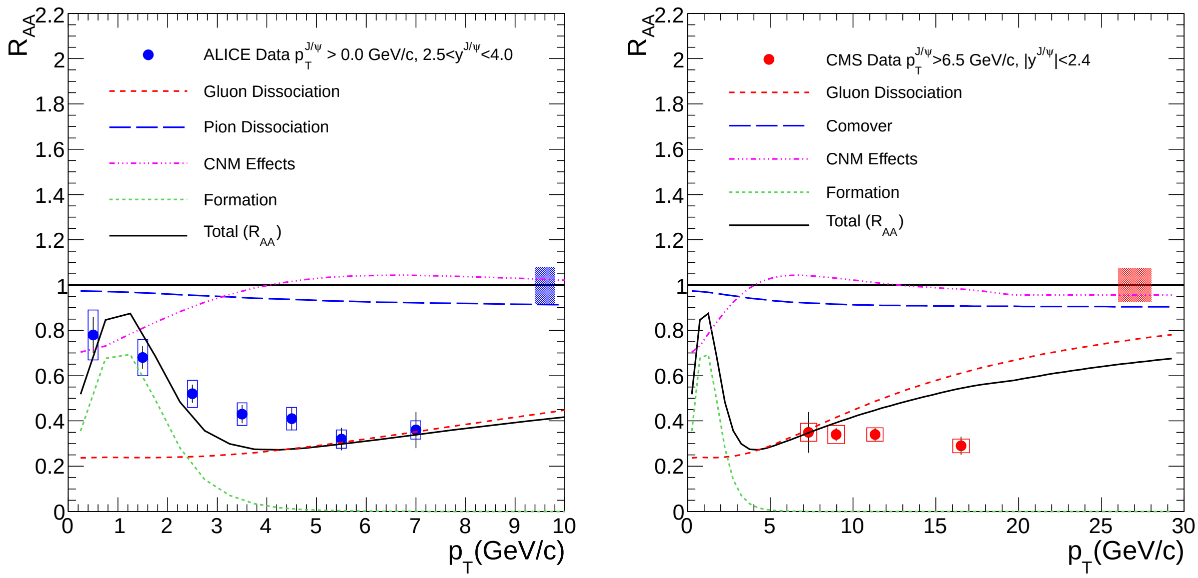

FIG. 5. (Color online) Calculated nuclear modification factor (R_{AA}) as a function of J/ψ transverse momentum compared with (a) ALICE and (b) CMS measurements.

where $f_\pi(p,T)$ is taken as the thermal pion distribution and the pion density ρ_π is given by

$$\rho_\pi = \frac{g_\pi}{(2\pi)^3}\int d^3p\, f_\pi(p) \tag{20}$$

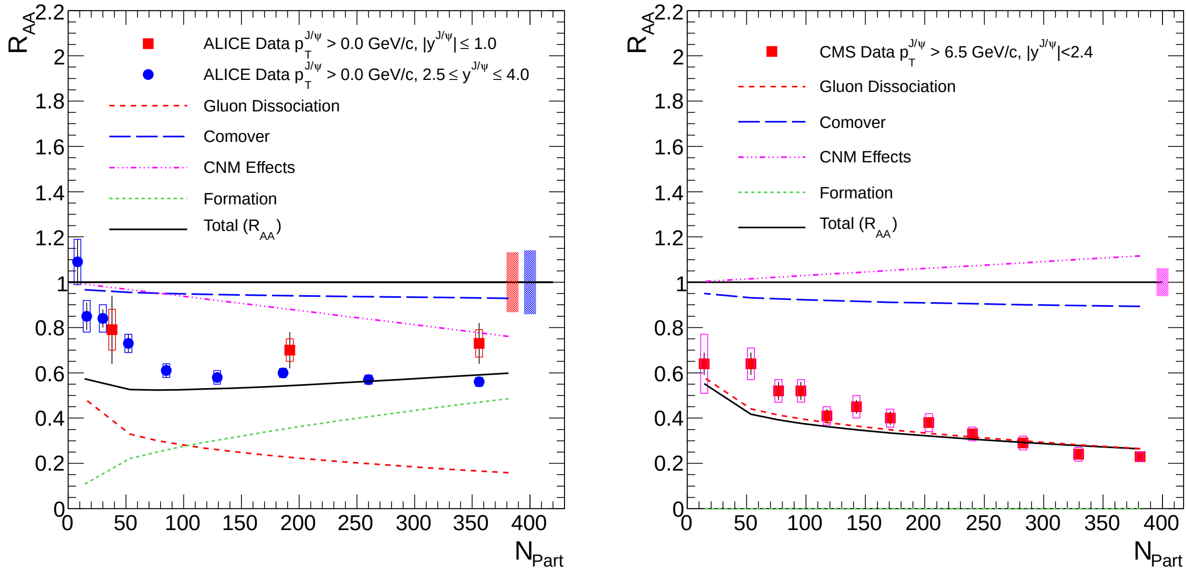

FIG. 6. (Color online) Calculated nuclear modification factor (R_{AA}) compared with (a) ALICE and (b) CMS measurements at LHC. The regeneration for high p_T CMS comparison is negligible. Similar cold nuclear matter effects are assumed for both ALICE and CMS rapidity ranges.

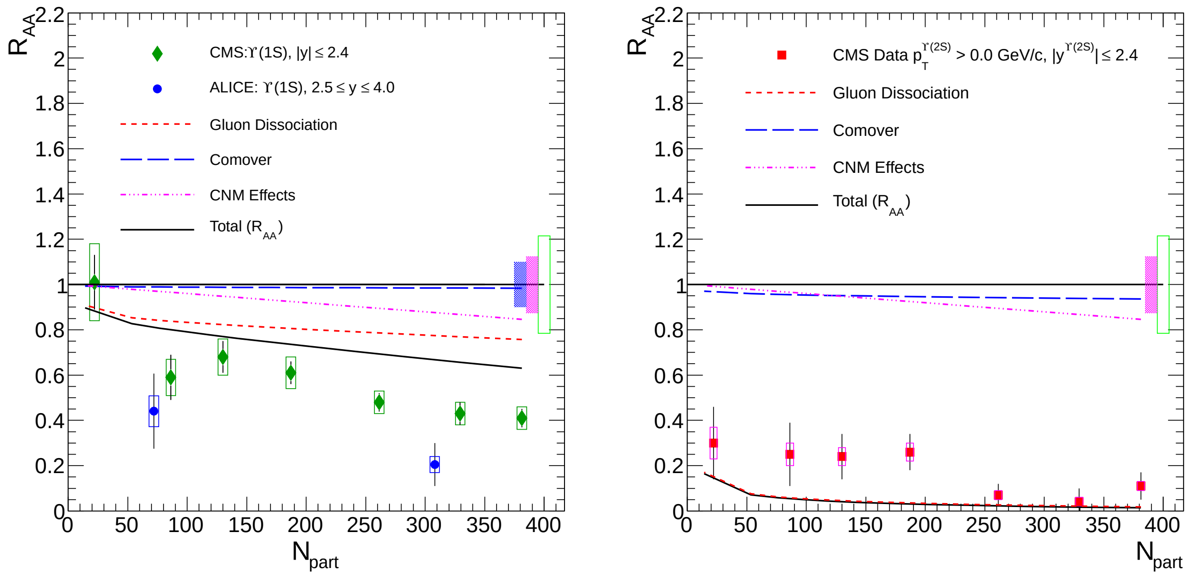

FIG. 7. (Color online) Calculated nuclear modification factor (R_{AA}) compared with CMS (a) Υ(1S) and (b) Υ(2S) measurements. We assume small cold nuclear matter suppression than Jψ and no regeneration due to small production cross section of beauty quark as shown in Table I.

The survival probability from pion collisions at freeze-out time τ_f is written as

$$S_\pi(p_T) = \exp\left(-\int_{\tau_0}^{\tau_f} (1 - f(\tau))\lambda_{D_\pi}(T, p_T)\, \rho_\pi(T)\, d\tau\right). \tag{21}$$

The temperature $T(\tau)$ and the hadronic fraction (1-$f(\tau)$) evolve from phase transition time to freeze-out time. The probability $S_\pi(p_T)$ is used along with $S(p_T)$ term in Eq. (6).

V. RESULTS AND DISCUSSION

Figure 5(a) show different contributions in nuclear modification factor (R_{AA}) of J/ψ as a function of transverse momentum compared with ALICE measurements [12] and the Fig. 5(b) shows the same along with high p_T measurements of CMS experiment [10]. At low p_T, regeneration of J/ψ is the dominant process and this seems to be the process for the enhancement of J/ψ in the ALICE low p_T data. The gluon suppression is also more at low p_T and it reduces as we move to high p_T. Both of these processes (regeneration and dissociation) due to the presence of QGP are at play low and intermediate p_T. The high p_T suppression ($p_T > 10$ GeV/c) of J/ψ measured by CMS does not seem to be originating due to dissociation by gluons in QGP.

We have also calculated R_{AA} as a function of system size. Figure 6 (a) shows different contributions of J/ψ nuclear modification factor as a function of system size along with the measurements by ALICE [12]. Figure 6 (b) shows the same for $p_T \geq 6.5$ GeV/c, measured by CMS experiment [10]. From Fig. 6 (a) indicates that J/ψ's are increasingly suppressed when system size grows. Since the number of regenerated J/ψ's also grow the nuclear modification factor remains flat for most of the centrality regions. Our model calculations overestimate the suppression in the most peripheral data. The centrality dependence of R_{AA} of J/ψ by CMS is well described by the model. Most of the contribution to CMS data comes from J/ψ p_T between 6.5 and 10 GeV/c where the suppression seems to be due to gluon dissociation process.

Figure 7 (a) demonstrates contribution of different processes in the centrality dependence of $\Upsilon(1S)$ nuclear modification factor alongwith the data measured in mid rapidity by CMS experiment[14] and in forward rapidity by ALICE experiment [38]. The calculations underestimate the suppression but reproduce the shape of centrality dependence. Figure 7 (b) shows the same for $\Upsilon(2S)$ nuclear modification factor along with the measurements in mid rapidity by CMS experiment. The excited $\Upsilon(2S)$ states are highly suppressed . The effect of regeneration (not shown here) is negligible for Υ states.

VI. SUMMARY

We have carried out detailed calculations of J/ψ and Υ modifications in PbPb collisions at LHC. The quarkonia and heavy flavour cross sections calculated upto NLO are used in the study and shadowing corrections are obtained by EPS09 parameterization. A kinetic model is employed which incorporates quarkonia suppression inside QGP, suppression due to hadronic comovers and regeneration from charm pairs. Their suppression is estimated using process of gluon dissociation in medium. The rate of regeneration has been obtained using principle of detailed balance. The dissociation and formation rates have been studied as a function of medium temperature and transverse momentum of particles. In addition, the modification in quakonia yields due to collisions with hadronic comovers has been estimated assuming it to be caused by pion.

The nuclear modification factor as a function of centrality and transverse momentum has been calculated and compared to J/ψ and Υ nuclear modification factors measured in PbPb collisions at $\sqrt{s}_{NN} = 2.76$ TeV. At low p_T, regeneration of J/ψ is the dominant process and this seems to be the process for the enhancement of J/ψ in the ALICE low p_T data. The gluon suppression is also more at low p_T and it reduces as we move to high p_T. Both of these processes (regeneration and dissociation) due to the presence of QGP are at play low and intermediate p_T. The high p_T suppression ($p_T > 10$ GeV/c) of J/ψ measured by CMS does not seem to be originating due to dissociation by gluons in QGP.

The centrality dpendence of nuclear modification indicates that J/ψ's are increasingly suppressed when system size grows. Since the number of regenerated J/ψ's also grow the nuclear modification factor in case of low p_T measurements remains flat for most of the centrality regions. The centrality dependence of R_{AA} of high p_T J/ψ is also well described by the model. The centrality dependence of suppression of Υ states are reproduced by model calculations.

VII. ACKNOWLEDGEMENT

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