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

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Abstract

We calculate the quarkonia yield modification in the medium produced in PbPb collisions at LHC energy. We use a kinetic model which incorporates quarkonia yield modifications due to suppression inside QGP, suppression due to hadronic comovers and regeneration of quarkonia 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. Modification in yield due to comovers has been estimated assuming it to be caused by pion collisions. The nuclear modification factors in PbPb collisions at $\sqrt{s}_{NN} = 2.76$ TeV for both J/ψ and Υ have been measured at different centralities and transverese momenta by different experiments. The calculations are carried in same measured kinematic regions to study the menifestation of medium effects in comparison with the measured data. Both the suppression and regeneration strongly affect J/ψ yields in low p_T range and the large high p_T suppression of J/ψ is much more than what is expected by gluon dissociation.

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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 an 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 a recent reviews see Refs. [2–5]].

The quarkonia are produced early in the heavy ion collisions and if they evolve through deconfined medium their yields should be suppressed in comparison with pp. The first such measurement was 'anomalous' J/ψ suppression discovered at the SPS which was considered as a hint of QGP formation. The RHIC results showed almost the same suppression at a much higher energy contrary to the expectation [4]. The suggestion then followed was the anomalous suppression could well be due to dissociation of excited charmonia states by hadronic interactions at both energies not requiring QGP. It was also suggested that at higher collision energy the expected more suppression is compensated by regeneration of J/ψ by the recombination of two independently produced charm quarks [6].

After the LHC started PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, wealth of results have become available on quarkonia production [7]. The CMS experiment carries out J/ψ measurement at high transverse momentum (p_T > 6.5 GeV/c). The high p_T prompt J/ψ is found to be suppressed substantially even in peripheral collisions with nuclear modification factor R_{AA} decreasing as a function of increasing centrality [8, 9]. Moreover the R_{AA} is found to be nearly independent of p_T (above 6 GeV/c) showing that J/ψ remain suppressed even at very high p_T upto 15 GeV/c. On comparing with STAR results [10] at RHIC it follows that the suppression of J/ψ has increased with collision energy. The ALICE results [13] of J/ψ covers low p_T and are complementary to CMS measurements. The suppression of low p_T J/ψ is found to have little or no centrality dependence. When compared with PHENIX forward rapidity measurement at RHIC [12], it suggests that low p_T J/ψ are less suppressed at LHC. The ALICE results also showed that J/ψ suppression decrease substantially with decreasing p_T and at very low p_T the suppression is small. It is consistent with the picture of regeneration of J/ψ at low p_T compensating the suppression due to deconfinement [13].

The bottomomia states are also measured by CMS [14, 15] and ALICE [16] experiments at LHC. CMS measurement is in mid rapidity region ($|y^{\Upsilon}| \leq 2.4$) while ALICE measured in forward rapidity ($2.5 \leq y^{\Upsilon} \leq 4.0$). Both measurements matches within uncertanity and CMS experiment that the excited Υ are more suppressed relative to the ground state. The quarkonium states with more binding energy should show less suppresion, a phenomenon referred as sequential suppression first time observed at LHC. Many theoertical framework 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, 17] and the dissociation of quarkonia by gluon collision process [18, 19]. The statistical models [6, 20] offer estimates of the regeneration of quarkonia from a charm quark pairs. Inverse of gluon dissociation process is also used to estimate regeneration [21, 22]. 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 [23]. There have been many recent calculations to explain the LHC results on quarkonia using a combination of above theoretical frameworks and models [24, 25].

In this paper, we calculate the quarkonia (both J/ψ and Υ) suppression due to thermal gluon dissociation in an expanding Quark Gluon Plasma. Other sources which can suppress the yield are considered e.g. nuclear shadowing and comover interaction. We also include the effect of J/ψ regeneration estimated from inverse of gluon dissociation process using the principle of detailed balance. The nuclear modification factor of J/ψ is obtained as a function of transverse momentum and centrality of collision. Calculations are compared with experimental data from CMS and ALICE.

II. HEAVY QUARK PRODUCTION RATES

The production cross sections for heavy quark pairs are calculated to NLO in pQCD using the CTEQ6M parton densities [26]. The central EPS09 parameter set [27] is used to calculate the modifications of the parton densities in Pb+Pb collisions. We use the same set of parameters as that of Ref. [28] with the NLO calculation of Ref. [29] to obtain the exclusive $Q\overline{Q}$ pair rates as well as their decays to dileptons. The production cross sections for heavy flavor and quarkonia at $\sqrt{s_{NN}} = 2.76$ TeV [30] are given in Table I. The number

TABLE I. Heavy quark and quarkonia cross sections at $\sqrt{s_{NN}} = 2.76$ TeV. The cross sections are given per nucleon pair while N gives number of heavy quark pair/quarkonia per Pb+Pb event.

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

of $Q\overline{Q}$ pairs in a minimum bias Pb+Pb event is obtained from the per nucleon cross section, $\sigma_{\rm PbPb}$, by

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

At 2.76 TeV, the total Pb+Pb cross section, $\sigma^{\rm tot}_{\rm PbPb}$, is 7.65 b [31].

III. MODIFICATION OF QUARKONIA IN THE PRESENCE OF QGP

In Kinetic approach [22] the proper time (τ) evolution of the J/ψ population is given by the rate equation

$$\frac{dN_{J/\psi}}{d\tau} = -\lambda_D \rho_g N_{J/\psi} + \lambda_F \frac{N_{c\bar{c}}^2}{V(\tau)}, \tag{2}$$

where $V(\tau)$ is the volume of the deconfined spatial region and $N_{c\bar{c}}$ is the number of initial charm quark pairs produced per event. The λ_D is the dissociation rate obtained by the cross-section averaged over the momentum distribution of gluons and λ_F is the regeneration rate obtained by the cross-section averaged over the momentum distribution of c and $\bar{c}$. ρ_g is the density of thermal gluons. The number of J/ψ at freeze-out time τ_f is given by solution of Eq. (2)

$$N(p_T) = S(p_T)\, N^0_{J/\psi}(p_T) + N^{\rm regen}_{J/\psi}(p_T). \tag{3}$$

Here $N^0_{J/\psi}(p_T)$ is the number of initially produced J/ψ 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. $N^{\rm regen}_{J/\psi}(p_T)$ is the number of regenerated J/ψ per event and is given by

$$N_{J/\psi}^{\rm regen}(p_T) = S(\tau_f, p_T) N_{c\bar{c}}^2 \int_{\tau_0}^{\tau_f} \frac{\lambda_{\rm F}}{V(\tau)\, S(\tau, p_T)} d\tau \tag{5}$$

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

$$R_{AA}(p_T) = S(p_T) + \frac{N_{J/\psi}^{\rm regen}(p_T)}{N_{J/\psi}^{0}(p_T)} \tag{6}$$

R_{AA} as a function of collision centrality, including the regeneration will be

$$R_{AA}(N_{\rm part}) = \frac{\int_{p_{T\,\rm Cut}} N_{J/\psi}^{0}(p_T) S(p_T) dp_T}{\int_{p_{T\,\rm Cut}} N_{J/\psi}^{0}(p_T) dp_T} + \frac{\int_{p_{T\,\rm Cut}} N_{J/\psi}^{\rm regen}(p_T) dp_T}{\int_{p_{T\,\rm Cut}} N_{J/\psi}^{0}(p_T) dp_T} \tag{7}$$

Here $p_{\rm Cut}$ defines the p_T range as per the experimental measurements. $N_{J/\psi}^{0}(p_T)$ is the unmodified p_T distribution of J/ψ calculated by Pythia [32, 33].

The temperature evolution for different centralities of collision is obtained by assuming an isentropical cylindrical expansion with volume element

$$V(\tau) = \tau\, \pi\, (R_0 + \frac{1}{2} a\, \tau^2)^2 \Delta y, \tag{8}$$

where a_T=0.1c^2 fm^{-1} is the transverse acceleration [24]. The initial transverse radius, R_0 as a function of centrality is obtained in terms of the radius of the Pb nucleus ($R_{\rm Pb}$) as

$$R_0(N_{\rm part}) = R_{\rm Pb} \sqrt{\frac{N_{\rm part}}{N_{\rm part0}}}. \tag{9}$$

where $N_{\rm part0} = 2A$ is the total number of participants in head-on collisions.

The temperature variation with time is governed by $s(\tau)\, V(\tau) = s(\tau_0)\, V(\tau_0) = S_{\rm QGP}$. Using $s(\tau) = 4 a_q T^3$ for entropy density in QGP the temperature evolution is obtained as

$$T(\tau)^3 = \frac{S_{\rm QGP}}{4 a_q V(\tau)}. \tag{10}$$

where $a_q = (7N_f/60 + 16/90)\pi^2$ is the degrees of freedom in quark gluon phase. We relate initial temperature with measured charged particle multiplicity as

$$S_{\rm QGP} = 4 a_q V(\tau_0)|_{0-5\%} T_0^3 = 3.6 \left(\frac{dN}{d\eta}\right)_{0-5\%}. \tag{11}$$

Using $(dN/d\eta)_{0-5\%}$=1.5×1600 obtained from the charge particle multiplicity measured in Pb+Pb collisions at 2.76 TeV [34] and N$_f$ = 2.5, we calculate initial temperature 0.643 GeV at time $\tau_0 = 0.1$ fm/c. Transverse size of the system for 0-5% centrality is $R_{0-5\%} = 0.92 R_{\rm Pb}$, obtained from Eq. (9). The initial temperature for different centralities is calculated by

$$T_0^3(N_{\rm part}) = T_0^3 \left(\frac{dN/d\eta}{N_{\rm part}/2}\right) / \left(\frac{dN/d\eta}{N_{\rm part}/2}\right)_{0-5\%} \tag{12}$$

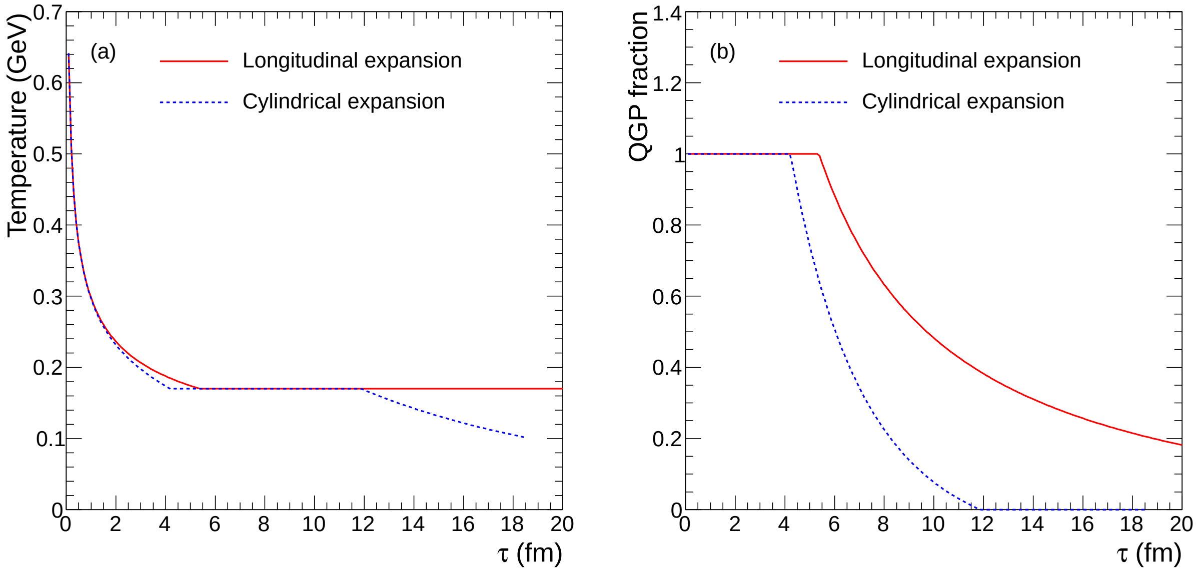

FIG. 1. (Color online) (a) Temperature and (b) QGP fraction in the system as a function of proper time in case of most central (0-5%) collisions for longitudinal and cylindrical expansions.

TABLE II. Quarkonia properties as predicted by non-relativistic potential model using "Cornell" potential [35].

	J/ψ	χ_c	$\psi(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
Mass [GeV/c^2]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
Binding Energy [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20

Figure 1 shows variation of temperature and QGP fraction as a function of proper time τ for both longitudinal and cylindrical expansions. The temperature decreases more rapidily for cylindrical expansion than in case of longitudinal expansion. It becomes constant at T_C = 0.170 GeV, while QGP fraction keeps decreasing. Once the hadronization is completed the temperature starts decreasing again till kinetic freeze out at temperature T_f = 0.100 GeV.

A. Dissociation Rate

In colour dipole approximation the gluon dissociation cross section as function of gluon energy q^0 in the J/ψ rest frame is given by [18]

$$\sigma_D(q^0) = 4\pi \left(\frac{8}{3}\right)^3 \frac{1}{m_c^{3/2}}\, \epsilon_0^3 \frac{(q^0 - \epsilon_0)^{3/2}}{(q^0)^5}, \tag{13}$$

where ϵ_0 is the J/ψ binding energy and m_c is the charm quark mass. The values of ϵ_0 for different quarkonia states are given in Table II. Figure 2 shows the gluon dissociation cross section ($\sigma_D(q^0)$) 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 J/ψ. It increases with gluon energy and reaches maximum at 1.2 (1.5) GeV for $J/\psi\,(\Upsilon)$. At higher gluon energy gluons the interaction probability decreases. q^0 is related to centre of mass energy s, of J/ψ-gluon system as

$$q^0 = \frac{s - M_{J/\psi}^2}{2\, M_{J/\psi}}, \tag{14}$$

Using this relation $\sigma_D(q^0(s))$ can be obtained which we write as $\sigma_D(s)$. The centre of mass energy square s, of J/ψ-gluon system can be written as $s = m_{J/\psi}^2 + 2E_{J/\psi}E_g(1 - \cos\theta)$ here $E_g\,(E_{J/\psi})$ is energy of gluon (J/ψ) and θ is angle between them.

We can calculate dissociation rate by folding the dissociation cross-section on thermal gluon distribution $f_g(p)$ as

$$\begin{aligned}\lambda_D\rho_g = \langle\sigma v_{\rm rel}\rangle\, \rho_g &= \frac{\lambda_g}{(2\pi)^3}\int d^3p\, f_g(p) v_{\rm rel}\, \sigma_D(s) \\ &= \frac{\lambda_g}{(2\pi)^3}\int 2\pi p^2 dp f_g(p) \int \sigma_D(s) v_{\rm rel}(s) d(\cos\theta)\end{aligned} \tag{15}$$

The relative velocity $v_{\rm rel}$ between the J/ψ and gluon can be given by

$$v_{\rm rel} = \frac{s - M_{J/\psi}^2}{2E_{J/\psi}E_g} \tag{16}$$

Figure 3 shows variation of gluon dissociation rate for J/ψ as a funcion of medium temperature and J/ψ transverse momentum. Dissociation rate increases with temperature because increase in gluon density. Dissociation is maximum if we consider J/ψ at rest and decreases with transverse momentum of J/ψ.

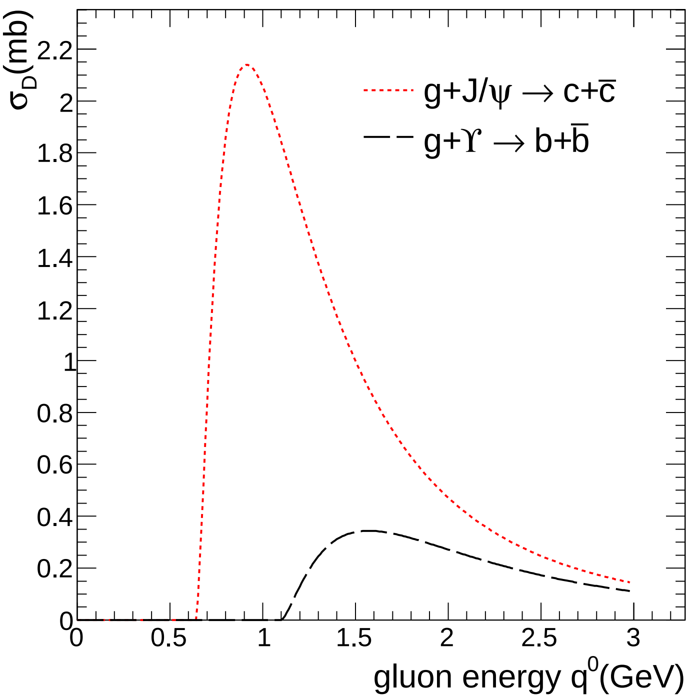

FIG. 2. Gluon dissociation cross-section of quarkonia as a function of gluon energy (q^0) in quarkonia rest frame.

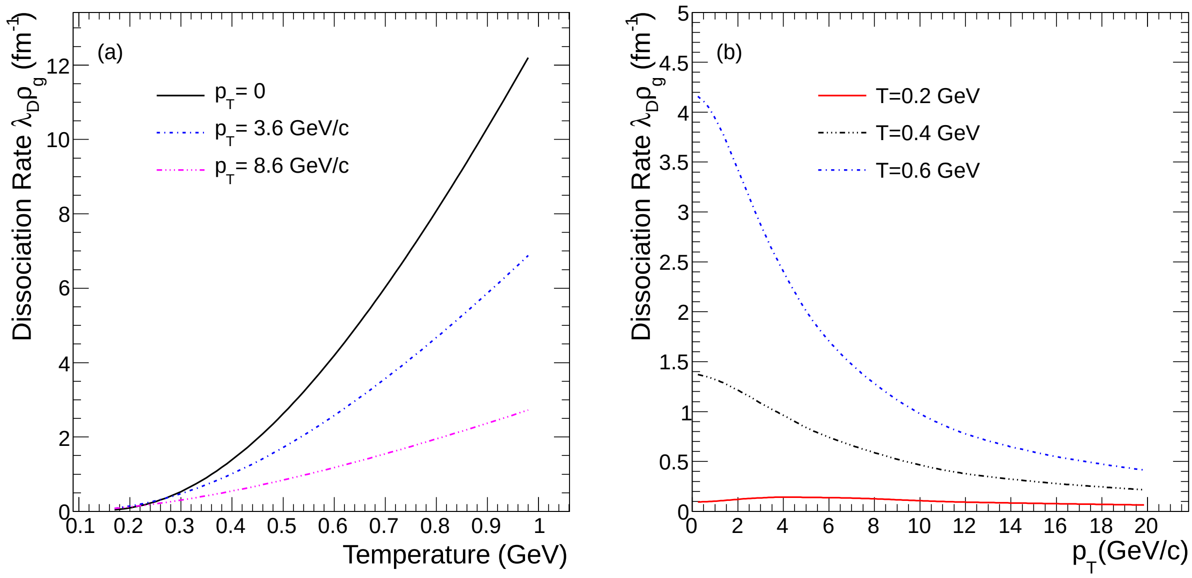

FIG. 3. (Color online) Gluon dissociation rate of J/ψ as a function of a) temperature and b) transverse momentum.

B. Formation Rate

We can calculate formation cross section from dissociation cross section using detailed balance relation [22, 36] as

$$\sigma_F = \frac{48}{30}\,\sigma_D(q^0)\frac{(s - M_{J/\psi})^2}{s(s-4m_c^2)}. \tag{17}$$

The formation rate can be written as

$$\lambda_F = \langle \sigma_F\ v_{\rm rel}\rangle = \frac{\int \sigma_F(s)\, v_{\rm rel}\, f_c(p_1)\, f_{\bar{c}}(p_2)\, d^3p_1\, d^3p_2\, \delta^3(\vec{p} - (\vec{p_1} + \vec{p_2}))}{\int\ f_c(p_1)\, d^3p_1\ \int f_{\bar{c}}(p_2)\, d^3p_2}. \tag{18}$$

Here $f_{c/\bar{c}}(p)$ are taken as thermal distribution function of $c/\bar{c}$. $v_{\rm rel}$ is relative velocity between c $\bar{c}$ quark pair and is given by

$$\begin{aligned} v_{\rm rel} &= \frac{\sqrt{(p_1.p_2)^2 - m_c^4}}{E_1\, E_2} \\ &= \frac{\sqrt{s(s-4m_Q^2)}}{2E_1E_2}. \end{aligned} \tag{19}$$

Here $p_1 = (E_1, \vec{p_1})$, $p_2 = (E_2, \vec{p_2})$ are four vectors of charm and anti-charm quarks respectively. The centre of mass energy square of c$\bar{c}$ system is $s = 2\, m_c^2 + 2E_1E_2 - 2|\vec{p_1}||\vec{p_2}|cos\theta$.

Figure 4 shows variation of formation rate as a funcion of medium temperature and transverse momentum. 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.

The formation and dissociation rates are shown for J/ψ, we use same formalism to calculate these rates for Υ also.

IV. COLD MATTER EFFECTS

The suppression of quarkonia by comoving pions can be calculated by folding the J/ψ-pion dissociation cross section over thermal pion distributions [38]. If we assume a constant dissociation cross section σ_I, the dissociation rate λ_{D_π} can be written as

$$\begin{aligned} \lambda_{D_\pi}\, \rho_\pi &= \frac{g_\pi}{(2\pi)^3}\int d^3p f_\pi(p) v_{\rm rel}\sigma_I \qquad (20) \\ &= \frac{1}{(2\pi)^3}\int 2\pi p^2 dp f_\pi(p) \int \sigma_I v_{\rm rel}(s)\Theta(s-4m_D^2) d(cos\theta) \end{aligned}$$

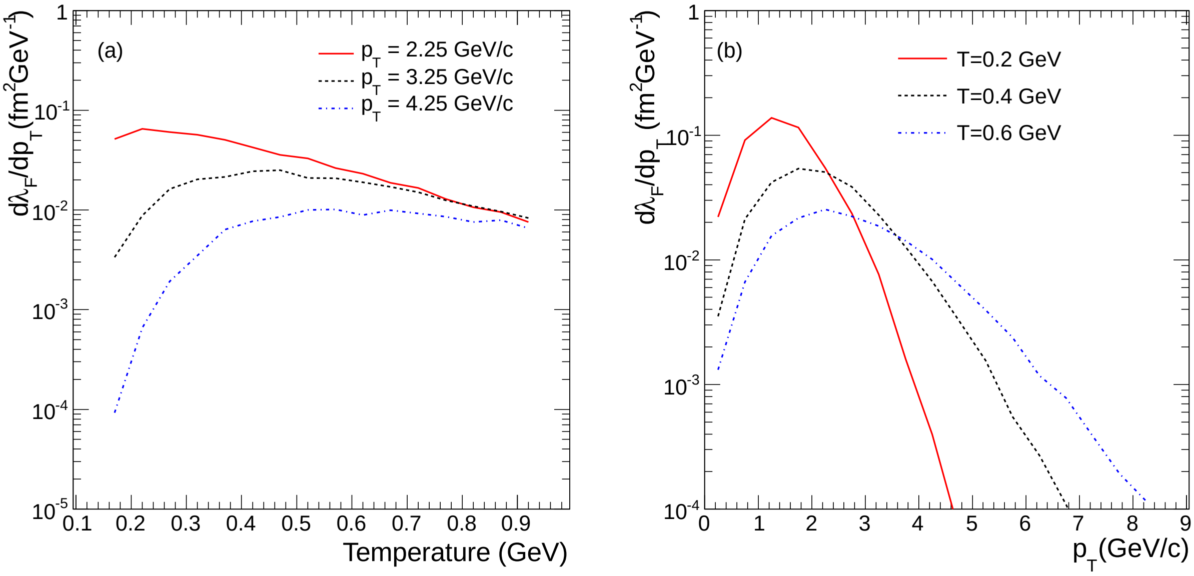

FIG. 4. (Color online) Formation rate as a function of (a) temperature and (b) transverse momentum.

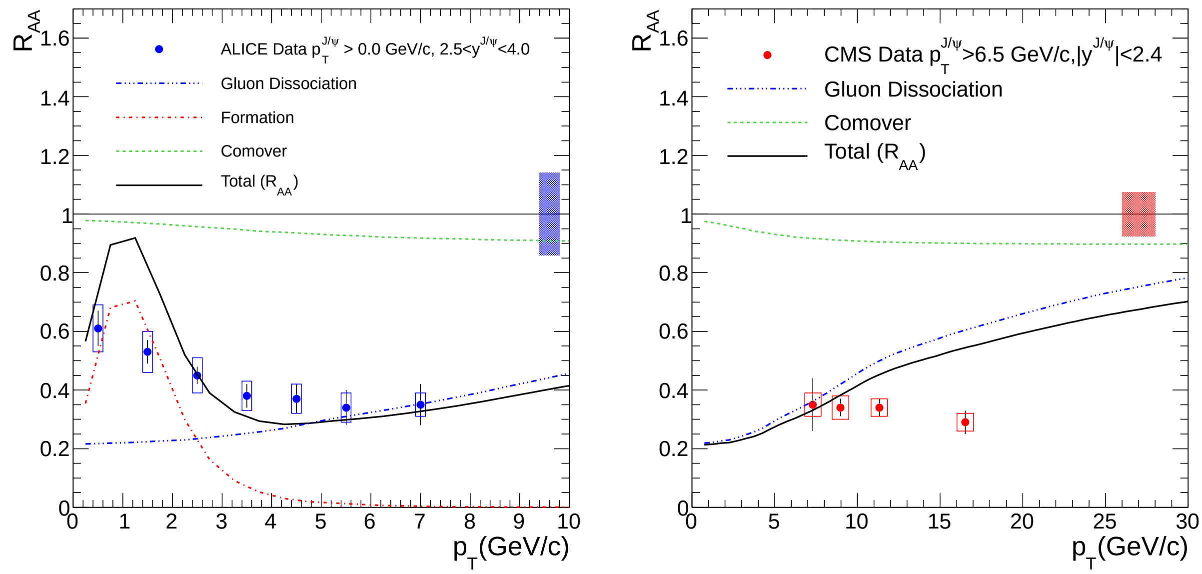

FIG. 5. (Color online) Calculated nuclear modification factor (R_{AA}) as a function of J/ψ transverse momentum. Calculations are compared with ALICE and CMS measurements.

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

$$\rho_\pi = \frac{g_\pi}{(2\pi)^3} \int d^3p \, f_\pi(p) \tag{21}$$

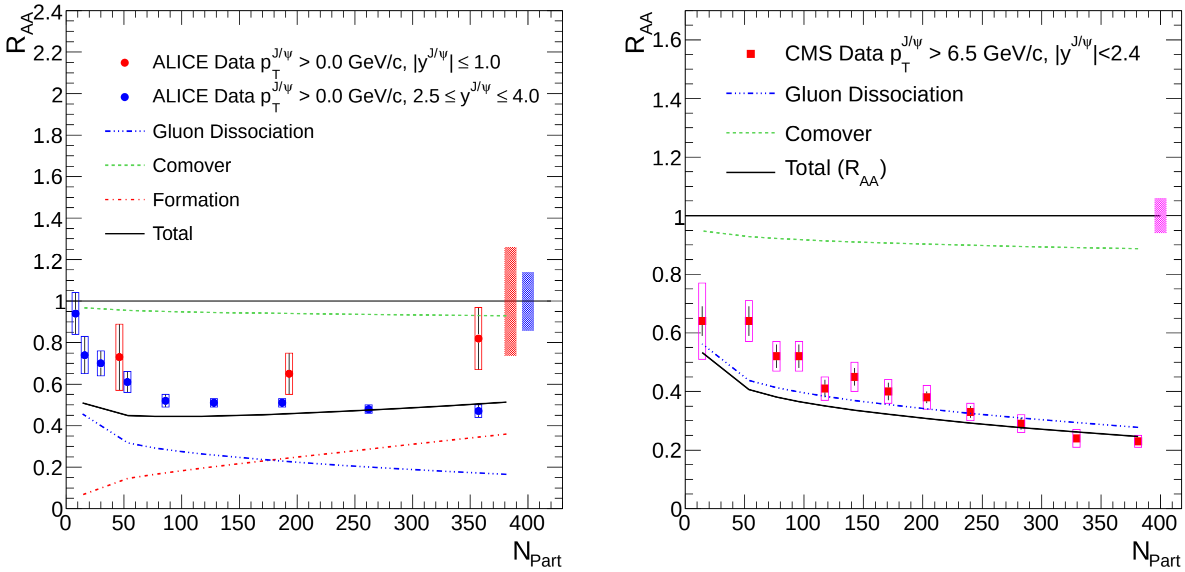

FIG. 6. (Color online) Calculated nuclear modification factor (R_{AA}) compared with ALICE and CMS measurements at LHC. No regeneration is considered for high p_T CMS data. We assume similar cold nuclear matter effects for both ALICE and CMS rapidity ranges.

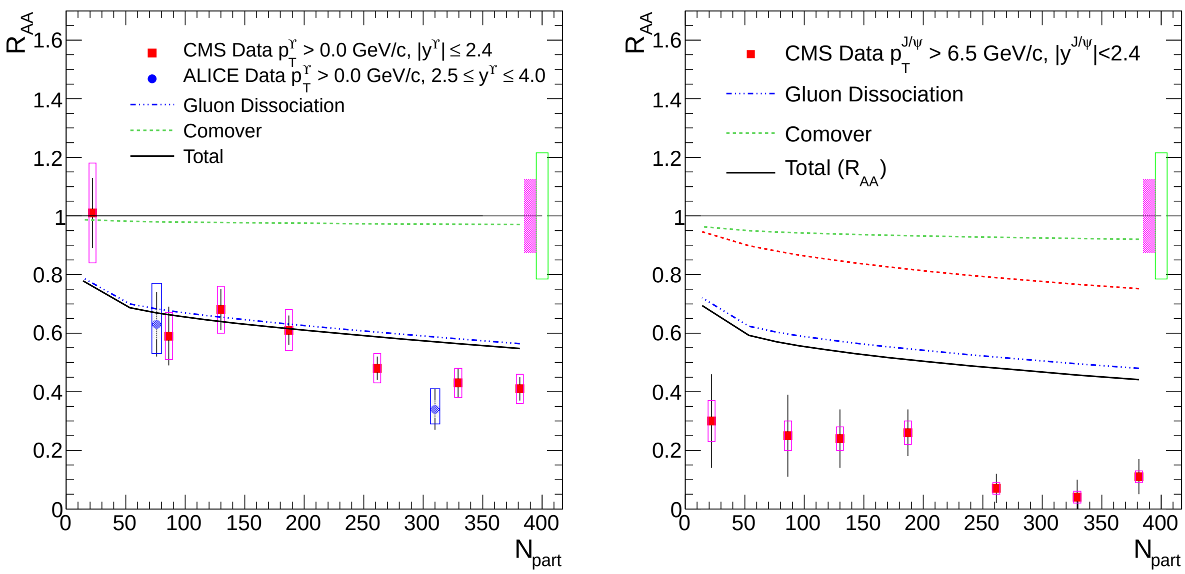

FIG. 7. (Color online) Calculated nuclear modification factor (R_{AA}) compared with CMS $\Upsilon(1S)$ and $\Upsilon(2S)$ measurements. We assume small cold nuclear matter suppression than Jψ and no regeneration due to small production cross section of beauty quark as shown in Table I.

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

$$S(p_T) = \exp\left(-\int_{\tau_0}^{\tau_f} (1-f(\tau))\lambda_{D_\pi}(T,p_T)\,\rho_\pi(T)\,d\tau\right). \tag{22}$$

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.

V. RESULTS AND DISCUSSION

Figure 5 shows comparison of our calculations with J/ψ Nuclear Modification Factor (R_{AA}) as a function of transeverse momentum measured by ALICE [13] and CMS [9] experiments. Our model with gluon dissociation, J/ψ regenration and comover suppression describes the ALICE data very well. However only gluon dissociation is not enough to explain the J/ψ high p_T data mesured by CMS experiment and shown in Figure 5 (b). We consider the contributions of recombined J/ψ only for low p_T measurements made by ALICE detector as shown in Fig. 5 (a). We can see from this Figure that regenrated J/ψ have very soft p_T distribution and do not contribute much after 4 GeV/c. So We do not consider effect of regenration for high p_T measurement made by CMS detector as shown in Figure 5 (b). Figure 6 (a) shows comparison of our calculations with J/ψ Nuclear Modification Factor as a function of event centrality measured by ALICE [13] experiment in forward and central rapidities. R_{AA} is lower in forward rapidity region (most central collisions) in comparison to the mid rapidity region. It indicate persence of additional cold nucler matter effects in forward rapidity or stronger recombination in mid rapidity. Our calculations explain the data very well in both mid and forward rapidity region. Figure 6 (b) shows high p_T J/ψ R_{AA} measured by CMS experiment [**?**]. It shows large suppression with strong centrality dependence. Our calculations matches very nicely with measured J/ψ R_{AA}. Figure 7 (a) shows centrality dependence of $\Upsilon(1S)$ nuclear modification factor measured in mid rapidity by CMS experiment[15] and in forward rapidity by ALICE experiment [16]. Figure 7 (b) shows the transeverse momentum dependence of Υ nuclear modification factor measured by CMS experiment [8]. As production cross section of bottom quark is small even at LHC energies, we do not consider effect of recombination for Υ calculations. Our calculations give good description of data.

VI. SUMMARY

The J/ψ and Υ modification in medium are calculated and compared to the data measured by CMS and ALICE. The J/ψ suppression is estimated using process of gluon dissociation in medium. The rate of regeneration has been obtained using principle of detailed balance and is compared with that obtained using statistical hadronization model. 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. Our model with both, gluon dissociation and nuclear absorption describes the data very well although, slight difference in most central collisions may be due to reduction of binding energy of quarkonia with temperature and lowering of quark mass.

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