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

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Abstract

We calculate the J/ψ and Υ suppression and regeneration assuming quark gluon plasma produced in PbPb collisions at LHC energy. The quarkonia suppression is estimated using well knowen 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 suppression factors due to cold nuclear matter effects have been obtained from measurements of quarkonia in pPb collisions. 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.

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I. INTRODUCTION

The heavy ion collisions produce matter at extreme temperatures and densities where it is expected to be in the form of Quark Gluon Plasma (QGP), a phase in which the quarks and gluons can move far beyond the size of a nucleon making color degrees of freedom dominant in the medium. The experimental effort to produce such matter started with low energy CERN accelerator SPS and evolved through voluminous results from heavy ion collision at Relativistic Heavy Ion Collider (RHIC) [1]. The recent results from Large Hadron Collider (LHC) experiments [2] are pointing towards formation of high temperature system in many ways similar to the matter produced at RHIC. One of the most important signal of QGP is the suppression of quarkonium states [3], both of the charmonium (J/ψ, $\psi(2S)$, χ_c, etc) and the bottomonium ($\Upsilon(1S)$, $\Upsilon(2S)$, χ_b, etc) families. This is thought to be a direct effect of deconfinement, when the binding potential between the constituents of a quarkonium state, a heavy quark and its antiquark, is screened by the colour charges of the surrounding light quarks and gluons. The ATLAS and CMS experiments have carried out detailed quarkonia measurements in Pb+Pb collisions with the higher energy and luminosity available at the LHC. The ATLAS measurements [4] show suppression of inclusive J/ψ with high transverse momenta p_T in central PbPb collisions compared to peripheral collisions at $\sqrt{s}_{NN} = 2.76$ TeV. Similarly, CMS measured a steady and smooth decrease of suppression of prompt J/ψ as a function of centrality with nuclear modification factor R_{AA} remaining < 1 even in the peripheral bin [5, 6]. ALICE shows that low p_T J/ψ are less suppressed and show very little centrality dependence[7]. The melting temperature of the quarkonia states depend on their binding energy. The ground states, J/ψ and $\Upsilon(1S)$ are expected to dissolve at significantly higher temperatures than the more loosely bound excited states. The $\Upsilon(2S)$ and $\Upsilon(3S)$ have smaller binding energies as compared to ground state $\Upsilon(1S)$ and hence are expected to dissolve at a lower temperature. With the 2011 Pb+Pb run the CMS published results on sequential suppression of $\Upsilon(nS)$ states as a function of centrality [8] with enlarged statistics over their first measurement [9], where a suppression of the excited Υ states with respect to the ground state have been observed in PbPb collisions compared to pp collisions at $\sqrt{s}_{NN} = 2.76$ TeV [10]. 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 nuclear or comover interaction [11]. If

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

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

large number of heavy quarks are produced in initial heavy ion collisions at LHC energy this could even lead to enhancement of quarkonia via statistical recombination [12–14].

In this paper, we calculate the charmonia suppression due to thermal gluon dissociation in an expanding Quark Gluon Plasma. Other sources which can alter the yield of charmonium are considered e.g. nuclear shadowing and comover interaction. We also consider the effect of J/ψ regeneration using the statistical hadronization model. J/ψ yield is studied as a function of impact parameter or centerality of events. 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 [15]. The central EPS09 parameter set [16] 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. [17] with the NLO calculation of Ref. [18] 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 [19] are given in Table I. The number of $Q\overline{Q}$ pairs in a minimum bias Pb+Pb event is obtained from the per nucleon cross section, σ_{PbPb}, by

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

At 2.76 TeV, the total Pb+Pb cross section, $\sigma^{\mathrm{tot}}_{\mathrm{PbPb}}$, is 7.65 b [20].

III. MODIFICATION OF QUARKONIA IN PRESENCE OF QGP

The number of quarkonia $N(\tau_0, p_T)$ produced at initial time τ_0 is modified due to dissociation in the medium and thus the number at freeze out time τ_f can be written as

$$N(\tau_f, p_T) = S(p_T)\, N(\tau_0, p_T). \tag{2}$$

The survival probability $S(p_T)$ of quarkonia from gluon dissociation is given as

$$S(p_T) = \exp\left(-\int_{\tau_0}^{\tau_f} \Theta(\tau - \tau_{\rm F}) f(\tau) \lambda_{\rm D}(T)\, \rho_g(T)\, d\tau\right), \tag{3}$$

where $\tau_{\rm F} = \tau_{\rm Form}\; p_T/M$ in terms of formation time $\tau_{\rm Form}$ of quarkonium state, $\rho_g(T)$ is the gluon density of QGP at temperature T. We use vacuum formation time, $\tau_{\rm Form}$ 0.87 fm (0.76 fm) for J/ψ (Υ)[10]. τ_f is the freezeout time. Other properties of quarkonia are given in Table II. f(τ) repersent the QGP fraction at proper time τ. The dissociation rate λ_D is obtained by averaging the dissociation cross section over the gluon momentum distribution as follows

$$\lambda_{\rm D}(T) = \langle \sigma_D v_{\rm rel} \rangle. \tag{4}$$

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

$$R_{AA}(N_{\rm part}) = \frac{\int_{p_{Tmin}}^{p_{Tmax}} N(\tau_0, p_T) S(p_T) dp_T}{\int_{p_{Tmin}}^{p_{Tmax}} N(\tau_0, p_T) dp_T} \tag{5}$$

The R_{AA} including the regenration can be written as

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

where $N_{J/\psi}^{\rm Regen}$ is number of J/ψs per event produced from uncorrelated pairs of Q$\overline{Q}$ at the time of hadronization as explained in section VI.

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

$$V(\tau) = \tau\, \pi\, (r_0 + \frac{1}{2} a\, \tau^2)^2 \Delta y, \tag{7}$$

where a$_T$=0.1c^2 fm^{-1} is the transverse acceleration [21]. The initial transverse radius, r_0 as a function of centrality is obtained in terms of the radius of the Pb nucleus (R_0) as

$$r_0(N_{\rm part}) = R_0 \sqrt{\frac{N_{\rm part}}{N_{\rm part0}}}. \tag{8}$$

TABLE II. Quarkonia properties as predicted by non-relativistic potential model using "Cornell" potential[10].

	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
Radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39
Formation time $\tau_{\rm Form}$ [fm]	0.89	2.0	1.5	0.76	2.6	1.9	2.6	2.4

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

The temperature variation with time is obtained by

$$s(\tau)\,V(\tau) = s(\tau_0)\,V(\tau_0) = S. \tag{9}$$

Using $s(\tau) = 4a_q T^3$

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

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

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

Using $(dN/d\eta)_{0-5\%}$=1.5×1600 obtained from the charge particle multiplicity measured in Pb+Pb collisions at 2.76 TeV [22] and $\mathrm{N}_f = 2.5$, we calculate initial temperature 0.641 GeV at time $\tau_0 = 0.1$ fm/c. Transverse size of the system for 0-5% centrality is $R_{0-5\%} = 0.92R_0$, obtained from Eq. (8). The initial temperature for different centralities is calculated by

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

IV. DISSOCIATION RATE

The gluon-J/ψ dissociation cross section in dipole approximation is given by [23]

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

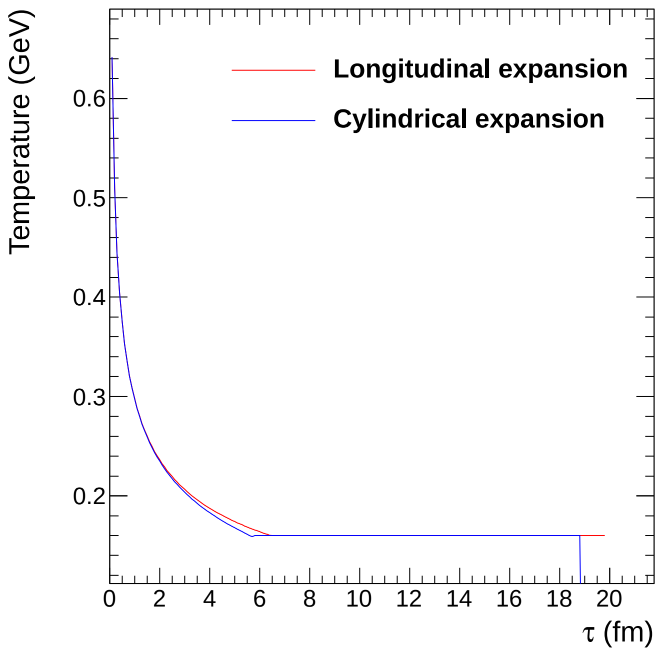

FIG. 1. (Color online) Temperature of the system as a function of proper time in case of longitudinal expansion and cylindrical expansions.

where m_Q is the heavy quark mass, and q^0 the gluon energy in the J/ψ rest frame; its value must be larger than the J/ψ binding energy ϵ_0.

If we consider that the J/ψ moves in the transverse direction with a four-velocity $u = (M_T, \vec{P_T}, 0)/M_{J/\psi}$, where $M_T = \sqrt{p_T^2 + M_{J/\psi}^2}$ is defined as the J/ψ's transverse mass. A gluon with a four-momentum $k = (k^0, \vec{k})$ in the rest frame of the parton gas has an energy $q^0 = k \cdot u$ in the rest frame of the J/ψ given by

$$\begin{aligned} q^0 &= \frac{k^0\, m_T + \vec{k} \cdot \vec{p_T}}{M_{J/\psi}}, \\ &= \frac{s - M_{J/\psi}^2}{2\, M_{J/\psi}}, \end{aligned} \tag{14}$$

The dissociation rate is given by

$$\lambda_D = \langle v_{\rm rel} \sigma_D(k \cdot u) \rangle_k = \frac{\int d^3k v_{\rm rel} \sigma_D(k \cdot u) f(k^0, T)}{\int d^3k f(k^0, T)}, \tag{15}$$

where the gluon distribution in the rest frame of the parton gas is

$$f(k^0, T) = \frac{\lambda_g(=16)}{e^{k^0/T} - 1}. \tag{16}$$

The relative velocity $v_{\rm rel}$ between the J/ψ and a gluon is

$$v_{\rm rel} = \frac{P_{J/\psi}\cdot k}{k^0 M_T} = 1 - \frac{\vec{k}\cdot\vec{P}_T}{k^0 M_T} = \frac{s - M_{J/\psi}}{2E_1E_2} \tag{17}$$

Changing the variable to the gluon momentum, $q = (q^0, \vec{q})$, in the rest frame of the J/ψ, and writing $\rho_g = \int d^3k f(k^0, T)$, the Eq. (15) can be rewritten as

$$\lambda_D \rho_g = \int d^3q \frac{M_{J/\psi}}{m_T}\sigma_D(q^0) f(k^0, T). \tag{18}$$

Using $k^0 = (q^0 M_T + \vec{q}\cdot\vec{P}_T)/M_{J/\psi}$ in Eq. 18 and solving

$$\begin{aligned}
\lambda_D\,\rho_g &= \frac{M_{J/\psi}}{m_T}\int d^3q\,\sigma_D(q^0)\frac{\lambda_g}{e^{\frac{q^0 m_T}{M_{J/\psi}T}}e^{\frac{\vec{q}\cdot\vec{p_T}}{M_{J/\psi}T}} - 1} \\
&= \frac{\lambda_g}{2\pi^3}\frac{M_{J/\psi}}{m_T}\int d^3q\,\sigma_D(q^0)\sum_{n=1}^{\infty} e^{\frac{-n\,q^0 m_T}{M_{J/\psi}T}}\,e^{\frac{-n\,\vec{q}\cdot\vec{p_T}}{M_{J/\psi}T}} \\
&= \frac{\lambda_g}{2\pi^3}\frac{M_{J/\psi}}{m_T}\sum_{n=1}^{\infty}2\pi\int (q^0)^2 dq^0\,\sigma_D(q^0)\,e^{\frac{-n\,q^0 m_T}{M_{J/\psi}T}}\int_1^{-1} e^{\frac{-n\,q^0\,p_T cos\theta}{M_{J/\psi}T}}\,d(cos\theta) \\
&= \frac{\lambda_g}{2\pi^3}\frac{M_{J/\psi}}{m_T}\sum_{n=1}^{\infty}2\pi\int (q^0)^2 dq^0\,\sigma_D(q^0)\,e^{\frac{-n\,q^0 m_T}{M_{J/\psi}T}}\left[e^{-\frac{nq^0 p_T}{M_{J/\psi}T}} - e^{\frac{nq^0 p_T}{M_{J/\psi}T}}\right]\frac{M_{J/\psi}T}{nq^0 p_T} \\
&= \frac{\lambda_g}{2\pi^3}\frac{M^2_{J/\psi}}{m_T}2\pi\sum_{n=1}^{\infty}\frac{T}{n}\int_{\epsilon_0}^{\infty} q^0 dq^0\,\sigma_D(q^0)\,e^{\frac{-n\,q^0 m_T}{M_{J/\psi}T}}\frac{1}{p_T}\left[e^{\frac{nq^0 p_T}{M_{J/\psi}T}} - e^{-\frac{nq^0 p_T}{M_{J/\psi}T}}\right]
\end{aligned} \tag{19}$$

The special case of Eq. (20) for J/$\psi\, p_T = 0$ is

$$\frac{1}{p_T}\left[e^{\frac{nq^0 p_T}{M_{J/\psi}T}} - e^{-\frac{nq^0 p_T}{M_{J/\psi}T}}\right] = \frac{2nq^0}{M_{J/\psi}T}. \tag{20}$$

Using this we get

$$\lambda_D\,\rho_g = 4\pi\int (q^0)^2\,dq^0\,\sigma_D(q^0)\frac{\lambda_g}{e^{\frac{q^0}{T}} - 1} \tag{21}$$

V. FORMATION RATE

We can calculate formation rate from dissociation rate using detailed balance relation [24]

$$\sigma_F = \frac{48}{30}\,\sigma_D(q^0)\frac{(s - M_{J/\psi})^2}{s(s - 4m_c^2)}. \tag{22}$$

The formation rate can be written as

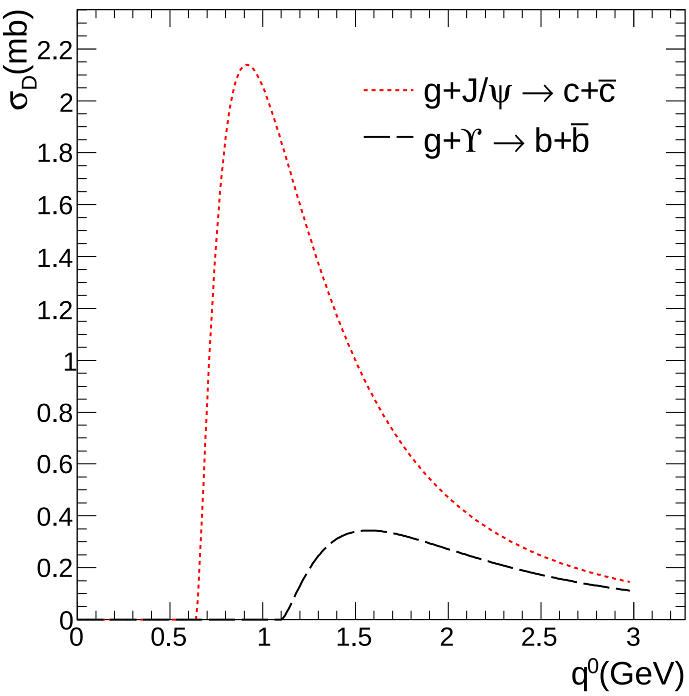

FIG. 2. Cross section for gluon dissociation of quarkonia as a function of gluon energy q^0 in quarkonia rest frame.

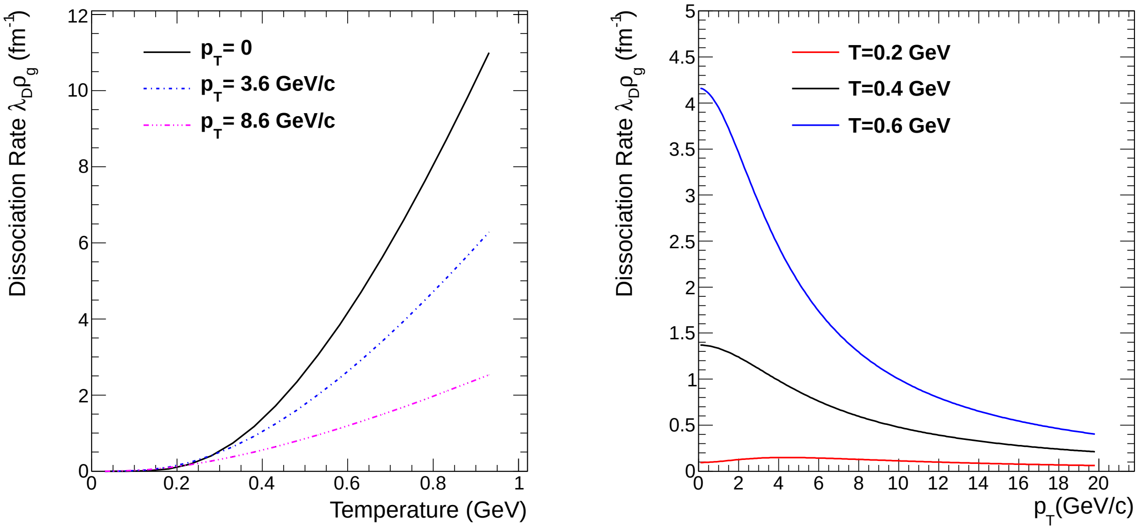

FIG. 3. (Color online)Variation of dissociation rate with a) temperature and with b) transverse momentum.

$$\lambda_F = < \sigma_F \; v_{\rm rel} > \tag{23}$$

$v_{\rm rel}$ is relative velocity between c $\bar{c}$ quark pair and is given by

$$\begin{aligned} v_{\rm rel} &= \frac{\sqrt{(p_1.p_2)^2 - m_Q^4}}{E_1\, E_2} \\ &= \frac{\sqrt{s(s-4m_Q^2)}}{2E_1 E_2}. \end{aligned} \tag{24}$$

Here

$$\begin{aligned} s &= (E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2})^2 \\ &= m_Q^2 + m_Q^2 + 2E_1E_2 - 2|\vec{p_1}||\vec{p_2}|cos\theta \end{aligned} \tag{25}$$

where $\vec{p_1}$ and $\vec{p_2}$ are three momentum of quarks.

The final expression for formation rate can be written as

$$\lambda_F = \frac{\int \sigma_F(s)\, v_{\rm rel}\, f_c(p_1)\, f_{\bar{c}}(p_2)\, d^3p_1\, d^3p_2}{\int\; f_c(p_1)\, d^3p_1 \;\; \int f_{\bar{c}}(p_2)\, d^3p_2} \tag{26}$$

$$= \frac{\int \sigma_F(s)\, v_{\rm rel}\, f_c(p_1)\, f_{\bar{c}}(p_2)\, 4\pi p_1^2 dp_1\, 2\pi p_2^2 dp_2 d(cos\theta)}{4\pi \int p_1^2 dp_1\, f_c(p_1)\;\; 4\pi \int p_2^2 dp_2\, f_{\bar{c}}(p_2)}. \tag{27}$$

and $f_c(p)$ and $f_{\bar{c}}(p)$ are parton distribution function of c and $\bar{c}$ respectively and are given by

$$f_c(p) = \frac{g_c(=6)}{1 + \exp[\frac{(p^2+m^2)^{1/2}}{T}]}. \tag{28}$$

VI. FORMATION OF QUARKONIA BY STATISTICAL HADRONIZATION MODEL

The heavy quark production at LHC is substantial which may lead to incoherent recombination of uncorrelated pairs of heavy quarks and anti quarks which result from multiple pair production. In statistical approach [25] the number of J/ψ produced is given by

$$N_{J/\psi} = 4\frac{n_{ch} n_{J/\psi}}{n_{\rm open}^2}\frac{N_{c\bar{c}}^2}{N_{ch}} \tag{29}$$

$$= \frac{N_{c\bar{c}}^2}{V}\frac{4n_{J/\psi}}{n_{open}^2}. \tag{30}$$

where n_i's are the thermal densities, $N_{c\bar{c}}$ is the number of charm pairs produced and N_{ch} is the number of total charged particle produced. The freeze out parameters are $T = 170$ MeV

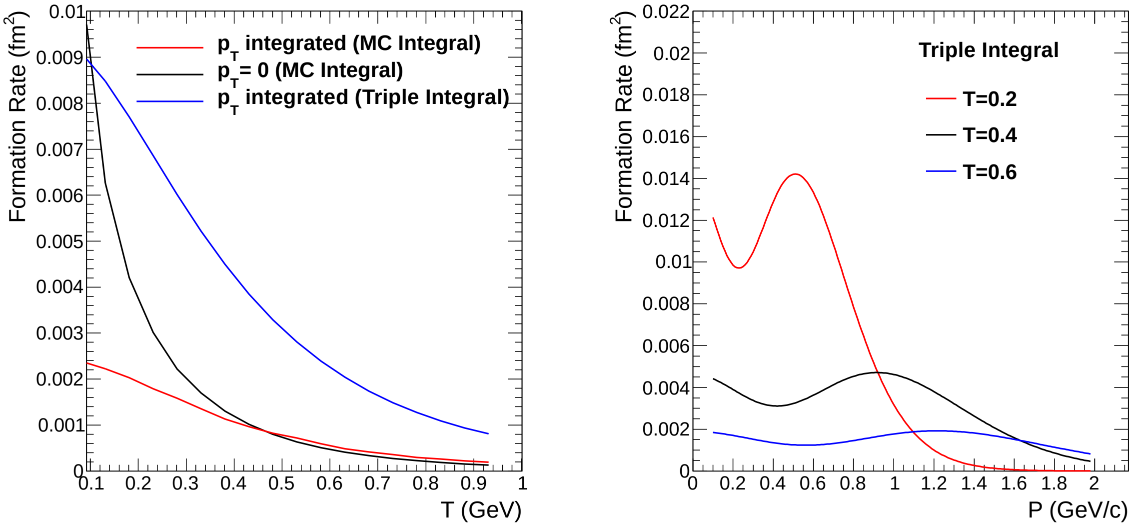

FIG. 4. (Color online) Formation rate as a function of (a) temperature and (b) transverse momentum.

and $\mu_B = 0$. For $dN_{ch}/dy = 1600$ [22] and $dN_{c\bar{c}}/dy = 14.0$, we obtain $dN_{J/\psi}/dy = 0.0092$. The densities can be calculated using thermal distributions of various particles.

$$n_{open} = \frac{4\pi\, g_D}{(2\pi)^3} \int_0^\infty f_D(p) p^2 dp \tag{31}$$

by the same method we can calculate the J/ψ number density as

$$n_{J/\psi} = \frac{4\pi\, g_{J/\psi}}{(2\pi)^3} \int_0^\infty f_{J/\psi}(p) p^2 dp \tag{32}$$

For total charge particle density we can use

$$n_{ch} = 2\, n_\pi + 2\, n_K + 2\, n_p, \tag{33}$$

where

$$n_\pi = \frac{4\pi\, g_\pi}{(2\pi)^3} \int_0^\infty f_\pi(p) p^2 dp. \tag{34}$$

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. 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 do not consider effect of recombination for high p_T measurement made by CMS detector [6, 26]

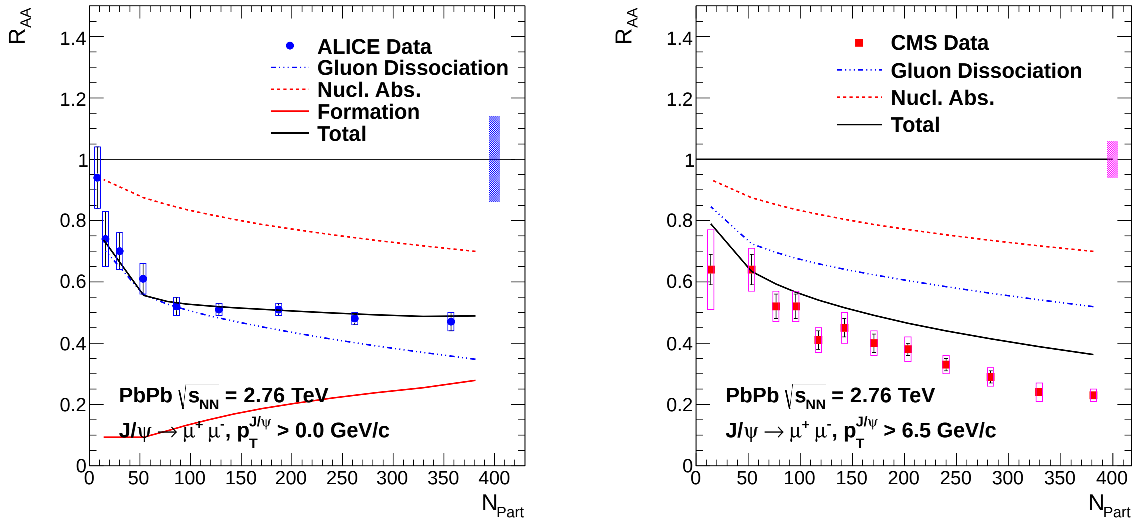

FIG. 5. (Color online) Nuclear modification factor (R_{AA}) compared with ALICE and CMS data.

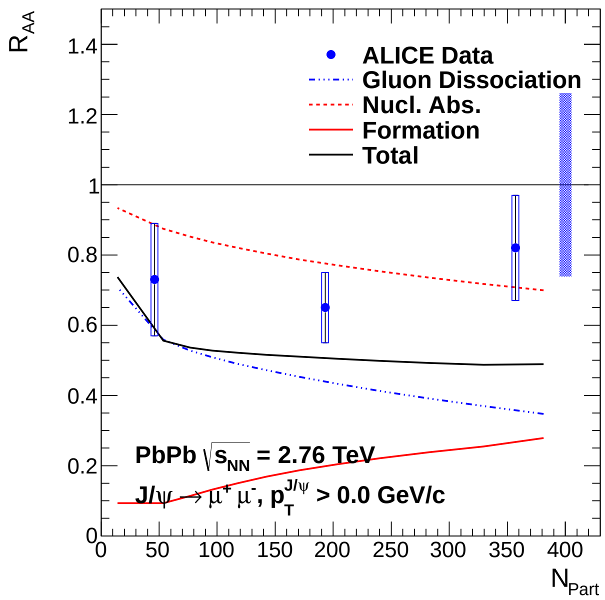

FIG. 6. (Color online) Nuclear modification factor (R_{AA}) compared with ALICE data at mid rapidity.

as shown in Fig. 5 (b). As production cross section of bottom quark is small even at LHC energies, we do not consider effect of recombination for Υ measurement shown in Fig. 7(c).

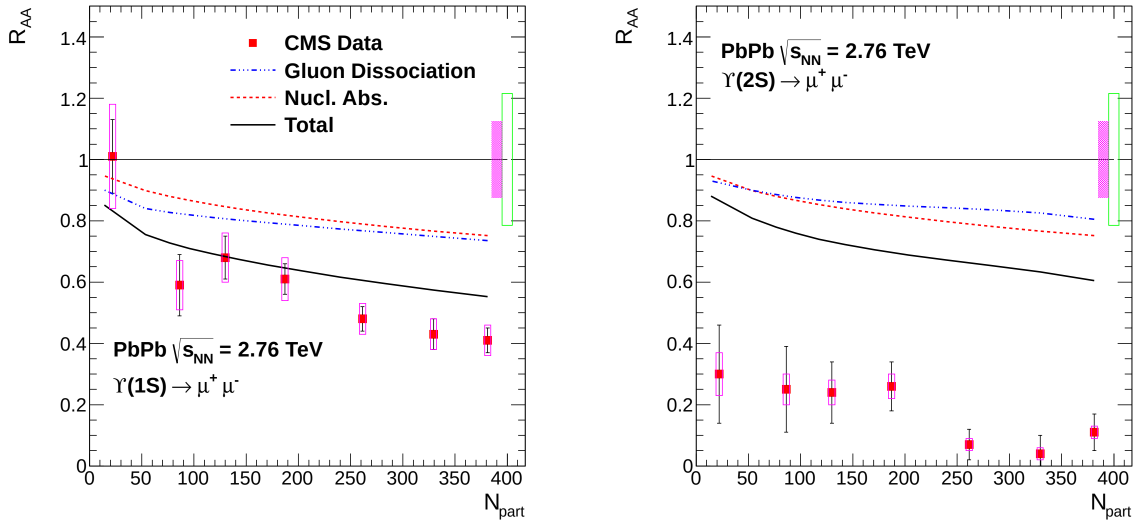

FIG. 7. (Color online) Nuclear modification factor (R_{AA}) compared with CMS Υ data.

VII. COLD MATTER EFFECTS

The quarkonia can be suppressed due to cold matter effects such as shadowing and due to nuclear matter and comover interaction. For simplicity we approximate the combination of all CNM effects by a suppression factor,

$$S_{Nucl} = \exp[-\rho_N \sigma_{abs} L(b)] \tag{35}$$

with an effective nuclear absorption cross section, σ_{abs}. We take absorption cross section, σ_{abs} = 3 mb (2 mb) for J/ψ(Υ). The other parameters in Eq. 35 are the nuclear density, ρ_N=0.14 fm^{-3}, and the impact-parameter dependent path length, L(b), evaluated with a Glauber model [27] for the nuclear overlap.

VIII. 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 suppression factors due to cold nuclear matter effects have been obtained from measurements of quarkonia in pPb collisions. 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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