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

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## Abstract

We estimate the modification of quarkonia yields in the medium produced in PbPb collisions at LHC energy. 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. Modification in yield due to change in parton distribution functions inside nucleus and due to collisions with 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 $J/\psi$ and $\Upsilon$ has been studied in PbPb collisions at $\sqrt{s}_{NN} = 2.76$ TeV. Both the suppression and regeneration due to deconfined medium strongly affect low $p_T$ range. The large observed suppression of $J/\psi$ at high $p_T$ far exceeds the estimates of suppression by deconfine 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 ($J/\psi$ and $\Upsilon$) 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' $J/\psi$ 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 $J/\psi$ 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 $J/\psi$ measurement at high transverse momentum ($p_T > 6.5$ GeV/$c$). The nuclear modification factor $R_{AA}$ of these high $p_T$ prompt $J/\psi$ 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 $J/\psi$ 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 $p_T$) $J/\psi$ has increased with collision energy. The ALICE results [12] of $J/\psi$ covers low $p_T$ range which have little or no centrality dependence. The ALICE $J/\psi$ 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 $p_T$ $J/\psi$ are less suppressed at LHC. These observations suggest regeneration of $J/\psi$ at low $p_T$ by recombination of independently produced charm pairs. The CMS measurements [13, 14] reveal that the higher $\Upsilon$ 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, 16]and alternatively in terms of dissociation of quarkonia by gluon collision process [17, 18]. The statistical models [6, 19] offer estimates of the regeneration of quarkonia from charm quark pairs. The inverse of gluon dissociation process is also used to estimate regeneration [20]. 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 [21]. There have been many recent calculations to explain the LHC results on quarkonia using a combination of above theoretical frameworks and models [23, 24].

In this paper, we calculate the quarkonia (both $J/\psi$ and $\Upsilon$) 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 charm 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. HEAVY QUARK PRODUCTION RATES

The production cross sections for heavy quark pairs are calculated to NLO in pQCD using the CTEQ6M parton densities [25, 26]. The central EPS09 parameter set [27] is used to calculate the modifications of the parton densities in PbPb 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. The production cross sections for heavy flavor and quarkonia at $\sqrt{s_{NN}} = 2.76$ TeV [30] 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

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

At 2.76 TeV, the total PbPb cross section, $\sigma^{\rm tot}_{\rm PbPb}$, is 7.65 b [33].

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 $N$ gives number of heavy quark pair/quarkonia per PbPb event.

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

## III. MODIFICATION OF QUARKONIA IN THE PRESENCE OF QGP

In the Kinetic approach [20], the proper time ($\tau$) evolution of the $J/\psi$ 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 $\lambda_D$ is the dissociation rate obtained by the dissociation cross-section averaged over the momentum distribution of gluons and $\lambda_F$ is the formation rate obtained by the formation cross-section averaged over the momentum distribution of $c$ and $\bar{c}$. $\rho_g$ is the density of thermal gluons. The number of $J/\psi$ at freeze-out time $\tau_f$ is given by solution of Eq. (2) as

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

Here $N_{J/\psi}^0(p_T)$ is the number of initially produced $J/\psi$ as a function of $p_T$ and $S(p_T)$ is their survival probability from gluon collisions at freeze-out time $\tau_f$ 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 $\tau_0$ to freeze-out time $\tau_f$ due to expansion of QGP. $N_{J/\psi}^F(p_T)$ is the number of regenerated $J/\psi$ per event and is given by

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

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

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

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

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

Here $p_{\text{Cut}}$ defines the $p_T$ range as per the experimental measurements. $N^{0}_{J/\psi}(p_T)$ is the unmodified $p_T$ distribution of $J/\psi$ obtained by NLO calculations which is scaled to a particular centrality of PbPb collisions.

The feed down correction from higher states are also taken into account while calculating $\mathrm{R}_{AA}$ for $J/\psi$

$$R_{AA}(J/\psi) = f_1\, R_{AA}(J/\psi) + f_2\, R_{AA}(\psi(2S)) + f_3\, R_{AA}(\chi_c) \tag{8}$$

$f_1$, $f_2$, $f_3$ are 0.60, 0.08 and 0.32 taken from CDF [31] and PHENIX measurements [32]. Feed down corrections are also applied for $\Upsilon$ states taken from Ref. [16].

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

$$V(\tau) = \tau\, \pi\, (R_0 + \frac{1}{2} a\, \tau^2)^2, \tag{9}$$

where $\mathrm{a}_T$=0.1c$^2$ fm$^{-1}$ is the transverse acceleration [23]. The initial transverse radius, $R_0$ as a function of centrality is obtained in terms of the radius of the Pb nucleus ($R_{\text{Pb}}$) as

$$R_0(N_{\text{part}}) = R_{\text{Pb}} \sqrt{\frac{N_{\text{part}}}{N_{\text{part0}}}}. \tag{10}$$

where $N_{\text{part0}}$ is the total number of participants in head-on collisions.

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

$$[T(\tau)]^3 = \frac{S_{\text{QGP}}}{4a_q V(\tau)}. \tag{11}$$

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

$$S_{\text{QGP}} = 4a_q V(\tau_0)|_{0-5\%} T_0^3 = a_{\text{m}} \left(\frac{dN}{d\eta}\right)_{0-5\%}. \tag{12}$$

Here $\mathrm{a}_{\text{m}} = 5.0$ is proportionality factor between charge particle multiplicity and total entropy of the system [22]. Using $(dN/d\eta)_{0-5\%}$=1.5×1600 obtained from the charge particle

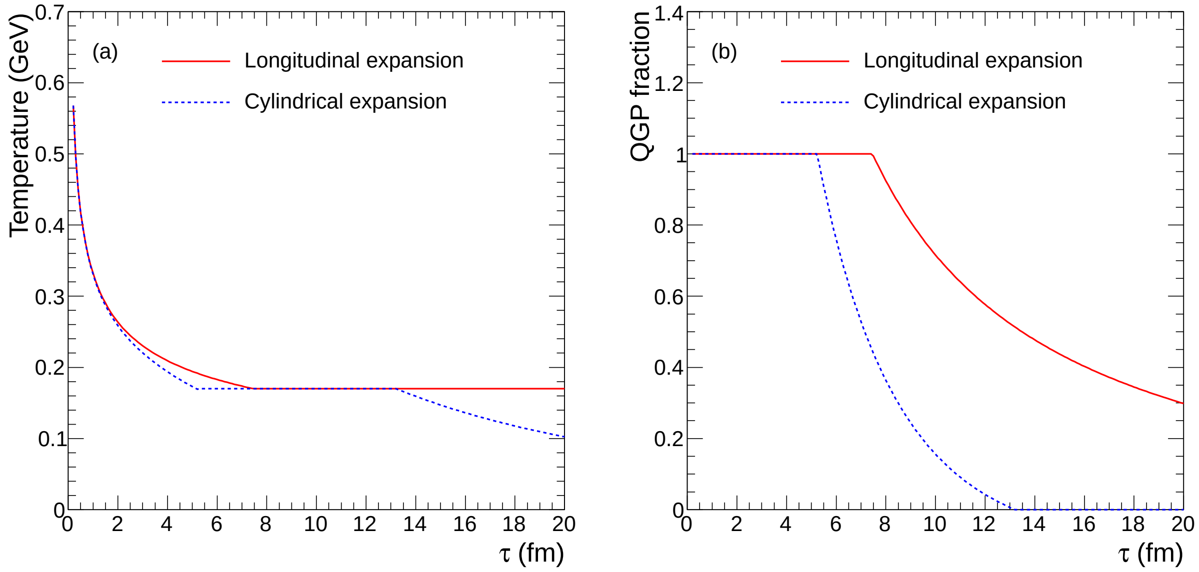


FIG. 1. (Color online) (a) Temperature and (b) QGP fraction in the system as a function of proper time in case of most central (0-5%) collisions for longitudinal and cylindrical expansions.

multiplicity measured in PbPb collisions at 2.76 TeV [34] and $N_f = 2.5$, we calculate initial temperature 0.570 GeV at time $\tau_0 = 0.2$ fm/c. Transverse size of the system for 0-5% centrality is $R_{0-5\%} = 0.92R_{\rm Pb}$, obtained from Eq. (10). The initial temperature for different centralities is calculated by

$$T_0^3(N_{\rm part}) = T_0^3 \left(\frac{dN/d\eta}{N_{\rm part}/2}\right) / \left(\frac{dN/d\eta}{N_{\rm part}/2}\right)_{0-5\%} \tag{13}$$

Figure 1 shows time evolution of the temperature and QGP fraction in case of most central (0-5%) collisions 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/$\psi$ rest frame is given by [17]

$$\sigma_D(q^0) = 4\pi \left(\frac{8}{3}\right)^3 \frac{1}{m_c^{3/2}}\, \epsilon_0^3 \frac{(q^0 - \epsilon_0)^{3/2}}{(q^0)^5}, \tag{14}$$

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

| | $J/\psi$ | $\chi_c$ | $\psi(2S)$ | $\Upsilon(1S)$ | $\chi_b(1P)$ | $\Upsilon(2S)$ | $\chi_b(2P)$ | $\Upsilon(3S)$ |
|---|---|---|---|---|---|---|---|---|
| Mass [GeV/$c^2$] | 3.10 | 3.53 | 3.68 | 9.46 | 9.99 | 10.02 | 10.26 | 10.36 |
| Binding Energy $\epsilon_0$ [GeV] | 0.64 | 0.20 | 0.05 | 1.10 | 0.67 | 0.54 | 0.31 | 0.20 |

where $\epsilon_0$ is the quarkonia binding energy and $m_c$ is the charm/bottom quark mass. The values of $\epsilon_0$ for different quarkonia states are given in Table II. Figure 2 shows the gluon dissociation cross section of $J/\psi$ 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 $J/\psi$. 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 $s$, of $J/\psi$-gluon system as

$$q^0 = \frac{s - M_{J/\psi}^2}{2\, M_{J/\psi}}. \tag{15}$$

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

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

$$\begin{aligned} \lambda_D\rho_g = \langle\sigma v_{\rm rel}\rangle\,\rho_g &= \frac{g_g}{(2\pi)^3}\int d^3p\, f_g(p) v_{\rm rel}\,\sigma_D(s) \\ &= \frac{g_g}{(2\pi)^3}\int 2\pi p^2 dp f_g(p)\int \sigma_D(s) v_{\rm rel}(s) d(\cos\theta) \end{aligned} \tag{16}$$

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

$$v_{\rm rel} = \frac{s - M_{J/\psi}^2}{2E_{J/\psi}E_g} \tag{17}$$

Figure 3 shows gluon dissociation rate for $J/\psi$ as a function of medium temperature and $J/\psi$ transverse momentum. Dissociation rate increases with temperature due to increase in gluon density. Dissociation rate of $J/\psi$ is maximum at rest and decreases with transverse momentum.

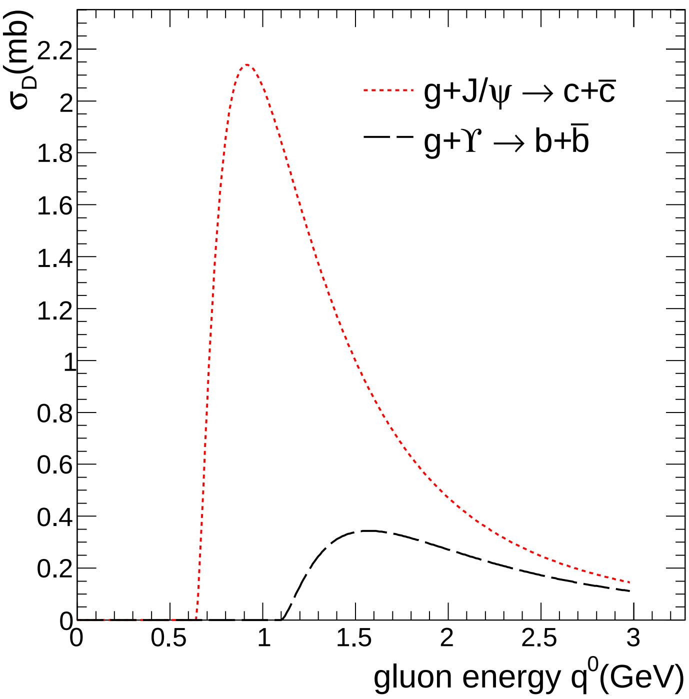


FIG. 2. Gluon dissociation cross-section of quarkonia as a function of gluon energy ($q^0$) in quarkonia rest frame.

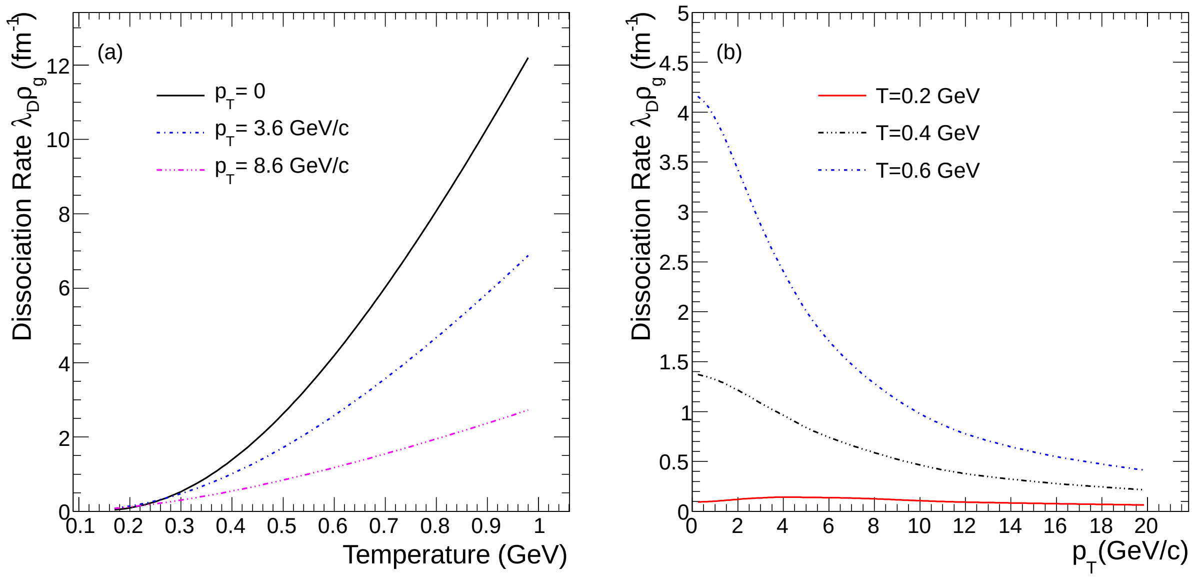


FIG. 3. (Color online) Gluon dissociation rate of $J/\psi$ as a function of a) temperature and b) transverse momentum.

## B. Formation Rate

We can calculate formation cross section from dissociation cross section using detailed balance relation [20, 36] as

$$\sigma_F = \frac{48}{30}\,\sigma_D(q^0)\frac{(s-M_{J/\psi})^2}{s(s-4m_c^2)}. \tag{18}$$

The formation rate can be written as

$$\lambda_F = \langle \sigma_F\ v_{\rm rel}(s)\rangle = \frac{\int \sigma_F(s)\, v_{\rm rel}\, f_c(p_1)\, f_{\bar{c}}(p_2)\, d^3p_1\, d^3p_2\, \delta^3(\vec{p}-(\vec{p_1}+\vec{p_2}))}{\int\ f_c(p_1)\, d^3p_1\ \ \int f_{\bar{c}}(p_2)\, d^3p_2}. \tag{19}$$

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

$$\begin{aligned} v_{\rm rel} &= \frac{\sqrt{(p_1.p_2)^2 - m_c^4}}{E_1\, E_2} \\ &= \frac{\sqrt{s(s-4m_c^2)}}{2E_1E_2}. \end{aligned} \tag{20}$$

Here $p_1 = (E_1, \vec{p_1})$, $p_2 = (E_2, \vec{p_2})$ are four momenta 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 $J/\psi$ generated from recombination of uncorrelated heavy quark pairs will have softer $p_T$ distributions than that of $J/\psi$ 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 $J/\psi$, we use same formalism to calculate these rates for $\Upsilon$ also.

# IV. COLD MATTER EFFECTS

The suppression of quarkonia by comoving pions can be calculated by folding the $J/\psi$-pion dissociation cross section $\sigma_{\rm I}$ over thermal pion distributions [37]. It is expected that at LHC energies cross-section of comover suppression will be small [38]. We take 1 mb cross-section for both $J/\psi$ and $\Upsilon$ states. The dissociation rate $\lambda_{D_\pi}$ can be written as

$$\begin{aligned} \lambda_{D_\pi}\, \rho_\pi &= \frac{g_\pi}{(2\pi)^3}\int d^3p f_\pi(p) v_{\rm rel}\sigma_I \\ &= \frac{g_\pi}{(2\pi)^3}\int 2\pi p^2 dp f_\pi(p)\int \sigma_{\rm I} v_{\rm rel}(s)\Theta(s-4m_D^2)d(cos\theta) \end{aligned} \tag{21}$$

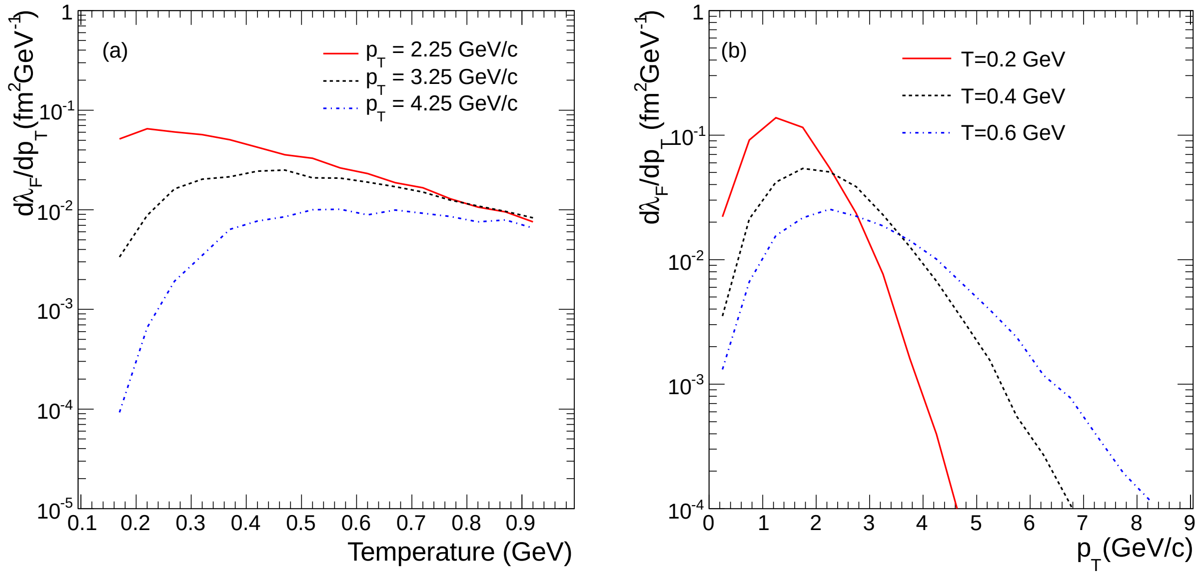


FIG. 4. (Color online) Formation rate as a function of (a) temperature and (b) transverse momentum.

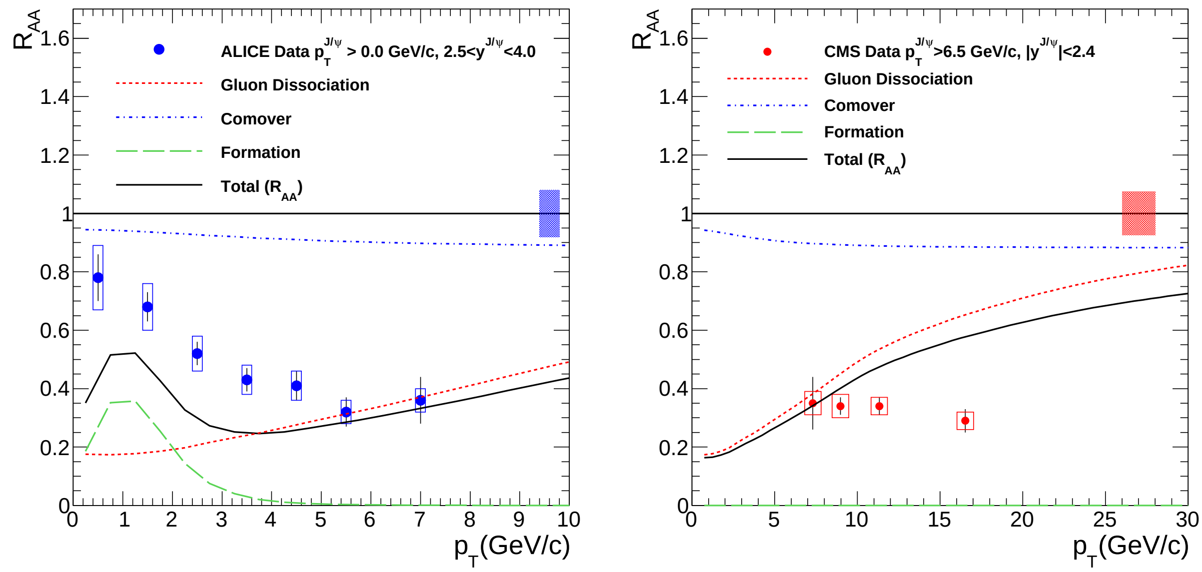


FIG. 5. (Color online) Calculated nuclear modification factor ($R_{AA}$) as a function of $J/\psi$ transverse momentum. Calculations are compared with ALICE and CMS measurements.

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

$$\rho_\pi = \frac{g_\pi}{(2\pi)^3}\int d^3p\, f_\pi(p) \tag{22}$$

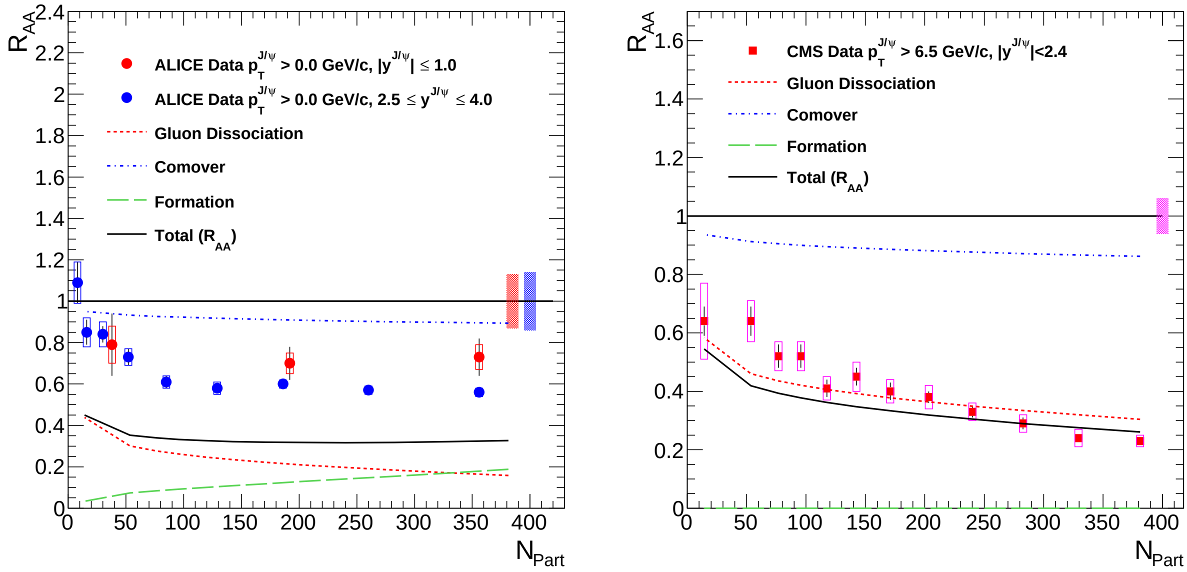


FIG. 6. (Color online) Calculated nuclear modification factor ($R_{AA}$) compared with ALICE and CMS measurements at LHC. No regeneration is considered for high $p_T$ CMS data. We assume similar cold nuclear matter effects for both ALICE and CMS rapidity ranges.

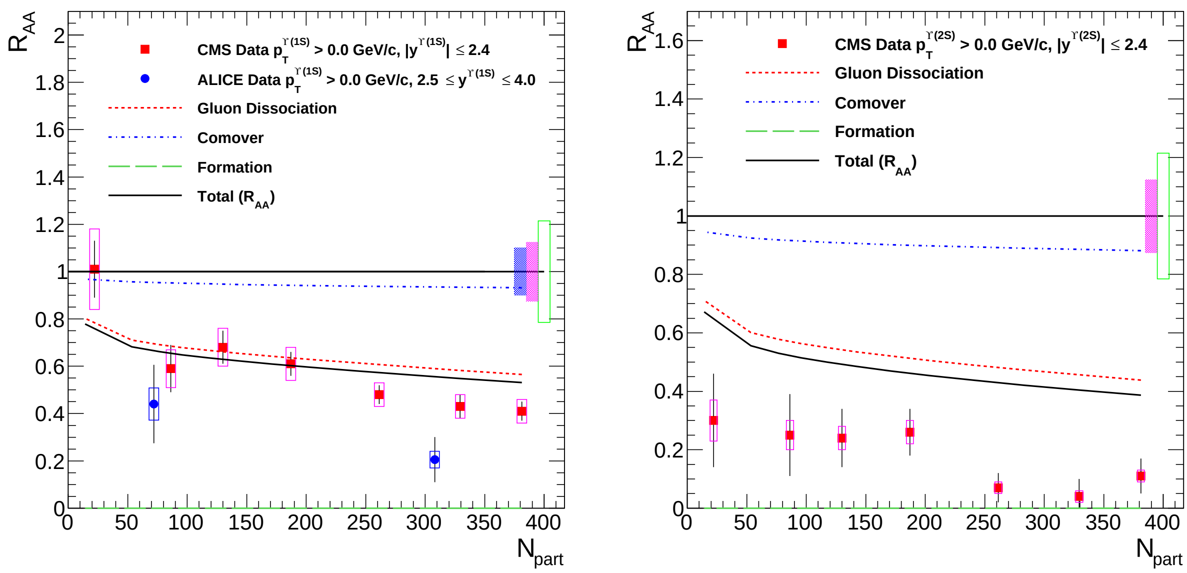


FIG. 7. (Color online) Calculated nuclear modification factor ($R_{AA}$) compared with CMS $\Upsilon(1S)$ and $\Upsilon(2S)$ measurements. We assume small cold nuclear matter suppression than J$\psi$ and no regeneration due to small production cross section of beauty quark as shown in Table I.

The survival probability from pion collisions at freeze-out time $\tau_f$ is written as

$$S(p_T) = \exp\left(-\int_{\tau_0}^{\tau_f}(1-f(\tau))\lambda_{D_\pi}(T,p_T)\,\rho_\pi(T)\,d\tau\right). \tag{23}$$

The temperature $T(\tau)$ and the hadronic fraction (1-$f(\tau)$) evolve from phase transition time to freeze-out time.

## V. RESULTS AND DISCUSSION

Figure 5 shows our calculations of nuclear modification factor ($R_{AA}$) of $J/\psi$ as a function of transverse momentum along with the measurements by ALICE [12] and CMS [10] experiments. Our model with gluon dissociation, $J/\psi$ regeneration and comover suppression describes the ALICE data very well in (a). However only gluon dissociation is not enough to explain the $J/\psi$ high $p_T$ data measured by CMS experiment in (b). We consider the contributions of recombined $J/\psi$ only for low $p_T$ measurements made by ALICE. We can notice from figure 5 (a) that regenerated $J/\psi$ have very soft $p_T$ distribution and contribution after 4-5 GeV/c is negligible Figure 6 (a) shows comparison of our calculations with $J/\psi$ nuclear modification factor as a function of event centrality measured by ALICE [12] experiment in forward and central rapidities. Our calculations predict stronger suppression than observed in ALICE measurement. Figure 6 (b) shows $R_{AA}$ of $J/\psi$ with $p_T \geq 6.5$ GeV/c, measured by CMS experiment [10]. It shows large suppression with strong centrality dependence. Our calculations are in good agreement with measured data. Figure 7 (a) shows centrality dependence of $\Upsilon(1S)$ nuclear modification factor measured in mid rapidity by CMS experiment[14] and in forward rapidity by ALICE experiment [15]. Our calculations matches very well with measurement except in most central collisions. Figure 7 (b) shows centrality dependence of $\Upsilon(2S)$ nuclear modification factor measured in mid rapidity by CMS experiment. Only gluon dissociation is not enough to explain the strong suppression observed in measurement. There may be higher oreder effects like lowering of binding energy of bound states at high tempreture, which we do not consider in this calculation. As production cross section of bottom quark is small even at LHC energies, we do not consider effect of recombination for $\Upsilon$ calculations.

## VI. SUMMARY

We have carried out detailed calculations of $J/\psi$ and $\Upsilon$ modifications in PbPb collisions at LHC. The $J/\psi$ 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 a function of medium temperature and transverse momentum of particles. The nuclear modification factor as a function of centrality and transverse momentum has been calculated and compared to $J/\psi$ and $\Upsilon$ nuclear modification factors measured in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

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[1] T. Matsui and H. Satz, "$J/\psi$ Suppression by Quark-Gluon Plasma Formation", Phys. Lett. B **178**, 416 (1986).

[2] J. Schukraft, "Heavy Ion Physics at the LHC: What's new ? What's next ?", arXiv:1311.1429 [hep-ex].

[3] L. Kluberg and H. Satz, "Color Deconfinement and Charmonium Production in Nuclear Collisions," arXiv:0901.3831 [hep-ph].

[4] N. Brambilla, S. Eidelman, B. K. Heltsley, R. Vogt, G. T. Bodwin, E. Eichten, A. D. Frawley and A. B. Meyer *et al.*, "Heavy quarkonium: progress, puzzles, and opportunities," Eur. Phys. J. C **71**, 1534 (2011) [arXiv:1010.5827 [hep-ph]].

[5] A. Adare *et al.* [PHENIX Collaboration], "$J/\psi$ suppression at forward rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV," Phys. Rev. C **84**, 054912 (2011) [arXiv:1103.6269 [nucl-ex]].

[6] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, "Statistical hadronization of charm in heavy ion collisions at SPS, RHIC and LHC," Phys. Lett. B **571**, 36 (2003) [nucl-th/0303036].

[7] B. Muller, J. Schukraft and B. Wyslouch, "First Results from Pb+Pb collisions at the LHC," Ann. Rev. Nucl. Part. Sci. **62**, 361 (2012) [arXiv:1202.3233 [hep-ex]].

[8] P. Shukla [CMS Collaboration], "Overview of quarkonia and heavy flavour measurements by CMS," arXiv:1405.3810 [nucl-ex].

[9] S. Chatrchyan *et al.* [CMS Collaboration], "Suppression of non-prompt $J/\psi$, prompt $J/\psi$, and Y(1S) in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV," JHEP **1205**, 063 (2012) [arXiv:1201.5069

[nucl-ex]].

[10] C. Mironov [CMS Collaboration], "Overview of results on heavy flavour and quarkonia from the CMS Collaboration," Nucl. Phys. A **904-905**, 194c (2013).

[11] Z. Tang [STAR Collaboration], "$J/\psi$ production and correlation in p+p and Au+Au collisions at STAR," J. Phys. G **38**, 124107 (2011) [arXiv:1107.0532 [hep-ex]].

[12] B. B. Abelev *et al.* [ALICE Collaboration], "Centrality, rapidity and transverse momentum dependence of J/$\psi$ suppression in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV," Phys. Lett. **743**, 314 (2014) [arXiv:1311.0214 [nucl-ex]].

[13] S. Chatrchyan *et al.* [CMS Collaboration], "Indications of suppression of excited $\Upsilon$ states in PbPb collisions at $\sqrt{S_{NN}} = 2.76$ TeV," Phys. Rev. Lett. **107**, 052302 (2011) [arXiv:1105.4894 [nucl-ex]].

[14] S. Chatrchyan *et al.* [CMS Collaboration], "Observation of sequential Upsilon suppression in PbPb collisions," Phys. Rev. Lett. **109**, 222301 (2012) [arXiv:1208.2826 [nucl-ex]].

[15] B. B. Abelev *et al.* [ALICE Collaboration], "Suppression of $\Upsilon$(1S) at forward rapidity in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV," arXiv:1405.4493 [nucl-ex].

[16] A. Abdulsalam and P. Shukla, "Suppression of bottomonia states in finite size quark gluon plasma in PbPb collisions at Large Hadron Collider," Int. J. Mod. Phys. A **28**, 1350105 (2013) [arXiv:1210.7584 [hep-ph]].

[17] G. Bhanot and M. E. Peskin, "Short Distance Analysis for Heavy Quark Systems. 2. Applications," Nucl. Phys. B **156**, 391 (1979).

[18] X. -M. Xu, D. Kharzeev, H. Satz and X. -N. Wang, "J/$\psi$ suppression in an equilibrating parton plasma," Phys. Rev. C **53**, 3051 (1996) [hep-ph/9511331].

[19] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, "The statistical model in Pb-Pb collisions at the LHC," Nucl. Phys. A **904-905**, 535c (2013) [arXiv:1210.7724 [nucl-th]].

[20] R. L. Thews, M. Schroedter and J. Rafelski, "Enhanced $J/\psi$ production in deconfined quark matter," Phys. Rev. C **63**, 054905 (2001) [hep-ph/0007323].

[21] R. Vogt, "Cold Nuclear Matter Effects on $J/\psi$ and $\Upsilon$ Production at the LHC," Phys. Rev. C **81**, 044903 (2010) [arXiv:1003.3497 [hep-ph]].

[22] E. V. Shuryak, "Two stage equilibration in high-energy heavy ion collisions," Phys. Rev. Lett. **68**, 3270 (1992).

[23] X. Zhao and R. Rapp, "Medium Modifications and Production of Charmonia at LHC," Nucl.

Phys. A **859**, 114 (2011) [arXiv:1102.2194 [hep-ph]].

[24] A. Emerick, X. Zhao and R. Rapp, "Bottomonia in the Quark-Gluon Plasma and their Production at RHIC and LHC," Eur. Phys. J. A **48**, 72 (2012) [arXiv:1111.6537 [hep-ph]].

[25] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. M. Nadolsky and W. K. Tung, "New generation of parton distributions with uncertainties from global QCD analysis," JHEP **0207**, 012 (2002) [hep-ph/0201195].

[26] J. Pumplin, D. R. Stump and W. K. Tung, "Multivariate fitting and the error matrix in global analysis of data," Phys. Rev. D **65**, 014011 (2001) [hep-ph/0008191].

[27] K. J. Eskola, H. Paukkunen and C. A. Salgado, "EPS09: A New Generation of NLO and LO Nuclear Parton Distribution Functions," JHEP **0904**, 065 (2009) [arXiv:0902.4154 [hep-ph]].

[28] M. Cacciari, P. Nason and R. Vogt, "QCD predictions for charm and bottom production at RHIC," Phys. Rev. Lett. **95**, 122001 (2005) [hep-ph/0502203].

[29] M. L. Mangano, P. Nason and G. Ridolfi, "Heavy quark correlations in hadron collisions at next-to-leading order," Nucl. Phys. B **373**, 295 (1992).

[30] V. Kumar, P. Shukla and R. Vogt, "Components of the dilepton continuum in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV," Phys. Rev. C **86**, 054907 (2012) [arXiv:1205.3860 [hep-ph]].

[31] F. Abe *et al.* [CDF Collaboration], "Production of $J/\psi$ mesons from $\chi_c$ meson decays in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV," Phys. Rev. Lett. **79**, 578 (1997).

[32] E. T. Atomssa [PHENIX Collaboration], "J/psi production measurements by the PHENIX experiment at RHIC," Eur. Phys. J. C **61**, 683 (2009) [arXiv:0805.4562 [nucl-ex]].

[33] S. Chatrchyan *et al.* [CMS Collaboration], "Observation and studies of jet quenching in PbPb collisions at nucleon-nucleon center-of-mass energy = 2.76 TeV," Phys. Rev. C **84**, 024906 (2011) [arXiv:1102.1957 [nucl-ex]].

[34] K. Aamodt *et al.* [ALICE Collaboration], "Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV," Phys. Rev. Lett. **106**, 032301 (2011) [arXiv:1012.1657 [nucl-ex]].

[35] F. Karsch, M. T. Mehr and H. Satz, "Color Screening and Deconfinement for Bound States of Heavy Quarks," Z. Phys. C **37**, 617 (1988).

[36] R. L. Thews and M. L. Mangano, "Momentum spectra of charmonium produced in a quark-gluon plasma," Phys. Rev. C **73**, 014904 (2006) [nucl-th/0505055].

[37] R. Vogt, M. Prakash, P. Koch and T. H. Hansson, "$J/\psi$ Interactions With Hot Hadronic

Matter," Phys. Lett. B **207**, 263 (1988).

[38] C. Lourenco, R. Vogt and H. K. Woehri, "Energy dependence of J/$\psi$ absorption in proton-nucleus collisions," JHEP **0902**, 014 (2009) [arXiv:0901.3054 [hep-ph]].