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 up to upto Next-to-Leading Order (NLO) NLO are used in the study~~, and~~ Shadowing corrections are obtained with the by EPS09 parametrization. A kinetic model is employed which incorporates quarkonia suppression inside a QGP, suppression due to hadronic comovers, and regeneration from charm pairs. The 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 quarkonia yields due to collisions with hadronic comovers has been estimated assuming that the comovers are ~~it to be caused by~~ pions. The manifestations of these effects in different kinematic regions ion 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 a deconfined medium strongly affect the low and intermediate p_T range. The large observed suppression of J/ψ at p_T above 10 GeV/c exceeds the estimates of suppression by gluon dissociation.

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I. INTRODUCTION

PbPb → Pb+Pb Can you make $\sqrt{s_{NN}}$ like R_{AA} with subscripts?

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. the Quarkonia states (J/ψ and Υ) have been ~~one~~ some of the most popular tools since their suppression was proposed as a signal of QGP formation [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~~ a great deal of theoretical ~~activities~~ activity. (For recent reviews see Refs. [2–4].) Quarkonia are produced early in the heavy-ion collisions and, if they evolve through the deconfined medium, their yields should be suppressed in comparison with those in pp collisions. The first such measurement was the 'anomalous' J/ψ suppression discovered at the SPS which was considered ~~as~~ to be 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 scenario that, at higher collision energies, the expected ~~more~~ greater suppression is compensated by regeneration ~~of~~ J/ψ through recombination of two independently-produced charm quarks [6]. ~~After~~ Since the LHC ~~started~~ first ran 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 measurements 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 the J/ψ remains suppressed, even at very high p_T, up to ~ 16 GeV/c. ~~On~~ By 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 J/ψ results [12] ~~of J/ψ~~ covers low p_T ~~range which~~ and have little or no centrality dependence. The ALICE J/ψ suppression decreases substantially with decreasing p_T. When compared with PHENIX forward rapidity measurement at RHIC [5], it suggests that low p_T J/ψ's are less suppressed at the LHC. These observations suggest J/ψ regeneration ~~of J/ψ~~ at low p_T by recombination of independently-produced charm pairs. At LHC energy, the Υ states are produced with good statistics. 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~~ at forward rapidity ($2.5 \leq y^{\Upsilon} \leq 4.0$) are consistent before the LHC startup.

with CMS measurements ~~in~~ at mid rapidity ~~region~~ ($|y^\Upsilon| \le 2.4$).

Many ~~theoretical frameworks~~ models were ~~have been~~ developed ~~in pre-LHC years~~ for the modification of quarkonia due to different processes. The suppression of quarkonia in a QGP ~~are~~ is understood in terms of colour screening models e.g. Ref. [1, 15] and, alternatively, in terms of quarkonium dissociation ~~of quarkonia~~ by collisions with gluons ~~gluon collision process~~ [16, 17]. ~~The~~ Statistical models [6, 18] ~~offer~~ can estimate~~s~~ ~~of~~ the regeneration of quarkonia ~~from~~ by charm quark pairs. The inverse of the gluon dissociation process ~~is~~ can be also used to estimate regeneration [19]. The quarkonia yields in heavy-ion collisions are ~~also~~ modified ~~due to~~ by non-QGP effects such as shadowing, ~~an effect~~ due to the ~~change~~ modification 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 the 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 the yields due to shadowing ~~change in parton distribution functions inside nucleus~~ and due to collisions with comovers ~~hadrons~~. Regeneration by thermal heavy quark pairs is also taken into account. Our goal is obtain the nuclear modification factor of quarkonia as a function of transverse momentum and centrality ~~of~~ collision and compare it ~~with~~ to experimental data from CMS and ALICE.

II. THE PRODUCTION RATES AND COLD NUCLEAR MATTER EFFECTS

The heavy quark production cross sections ~~for heavy quark pairs~~ are calculated to NLO in pQCD using the CTEQ6M parton densities [23, 24]. different ref. CT10 actually. The ~~central~~ central EPS09 NLO parameter set [25] is used to calculate the modifications of the parton distribution functions (nPDF) in PbPb collisions, referred as cold nuclear matter (CNM) effects. The CNM Uncertainty ~~in CNM effect arises due to various sets of EPS09 and is calculated along with central value.~~ is calculated by adding ~~both the~~ the EPS09 NLO uncertainties in quadrature.

We use the same set of parameters as that of Ref. [26], with $m_c = 1.5$ GeV/c^2 and $m_b = 4.75$ GeV/c^2 along with $\mu_F/m_T = \mu_R/m_T = 1$ as central values for charm and bottom production, respectively. Here μ_F is the factorization scale, μ_R is the renormalization scale, and $\sqrt{m_T = m^2 + p_T^2}$. The uncertainties are calculated as in Ref. [26] ~~with the same mass and scale parameters.~~ However, ~~The~~ the large uncertainties ~~on these calculations~~ ~~noted in Ref. [2]~~ ~~can be~~ were reduced by fitting the

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^{PbPb} (including shadowing) gives the number of heavy quark pair/quarkonia per PbPb event.

	$c\bar{c}$	J/ψ	$b\bar{b}$	Υ
σ_{pp}	$4.11^{+2.69}_{-2.50}$ mb	$21.6^{+10.6}_{-10.4}\mu$b	$110.5^{+15.1}_{-14.2}\mu$b	$0.22^{+0.07}_{-0.06}\mu$b
σ_{PbPb}	$3.21^{+2.1}_{-1.95}$ mb	$16.83^{+8.26}_{-8.10}\mu$b	$100.5^{+13.7}_{-12.9}\mu$b	$0.199^{+0.063}_{-0.054}\mu$b
N^{PbPb}	18.12^{+12}_{-11}	$0.0952^{+0.047}_{-0.046}$	$0.57^{+0.08}_{-0.07}$	$0.001123^{+0.0004}_{-0.0003}$

spaces seem tight for μb

renorm. and fact. scales to the total cross section data, as done in Ref. [27] for charm. The fiducial parameters of Ref. [26] encompass the new results but the central charm result [27] gives a larger total charm cross section than the central result after using $m_c = 1.5$ GeV/c^2. Heavy-quarkonium production cross section is computed using the Color Evaporation model ~~[27]~~. with the same mass + scale parameters [27].

The production cross sections for heavy flavor and quarkonia at $\sqrt{s_{NN}} = 2.76$ TeV [29] are given in Table I. The ~~number of $q\bar{q}$ pairs~~ yields in a minimum bias PbPb event is obtained from the per nucleon cross section, σ_{PbPb}, ~~by~~ in Table 1.

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

At 2.76 TeV, the total PbPb cross section, $\sigma^{\mathrm{tot}}_{\mathrm{PbPb}}$, is 7.65 b [30].

III. MODIFICATION OF QUARKONIA IN THE PRESENCE OF QGP

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

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

no - in cross section

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 defined by the number of participants N_{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 heavy quark ~~pair~~ 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 the solution of Eq. (2) as

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

Here $N_Q^{\rm PbPb}(p_T)$ is the number of initially produced quarkonia (including shadowing factor) 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 temperature and the evolution is dependent on $N_{\rm part}$. $N_Q^F(p_T)$ is the number of regenerated quarkonia per event and is given by

collision centrality

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

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

$$R_{AA}(p_T) = S(p_T)\, R(p_T) + \frac{N_Q^F(p_T)}{N_Q^{pp}(p_T)}. \tag{6}$$

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

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

subscript

Here p_TCut defines the p_T range as per the experimental measurements. $N_Q^{pp}(p_T)$ is the unmodified p_T distribution of quarkonia obtained by NLO calculations which is scaled to a particular ~~centrality~~ ($N_{\rm part}$) of the PbPb collisions.

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

If you use eq. below, then put T subscript here

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

$a_T = 0.1\, c^2$ fm $^{-1}$

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~~ then

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

where $R_{0-5\%} = 0.96\, R_{\rm Pb}$, and $R_{\rm Pb}$ is ~~being~~ the radius of the lead ~~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 (EOS) obtained by Lattice QCD, along with a hadronic resonance gas, [31], is used 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 $N_{\rm part}$ [32, 33] are used in the calculations.

The initial entropy density $s(\tau_0)|_{0-5\%}$ for 0-5% centrality is ~~obtained~~ as

not \rm m here

don't use \frac in text, harder to read

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

We obtain the total multiplicity at midrapidity

Here a_m $(= 5)$ is a constant which relates the total entropy to ~~with~~ the total multiplicity $\frac{dN}{d\eta}$. It is obtained from hydrodynamic calculations [34]. Using $(dN/d\eta)_{0-5\%}$=1.5×1600 obtained from the charged particle multiplicity measured in PbPb collisions [32, 33] 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. To estimate the initial temperature T_0 in forward rapidity we use measured charged particle density $(dN/d\eta)$ in forward rapidity [35]. For ALICE rapidity coverage $[2.5 \leq y \leq 4]$ the average temperature in most central 0-5% collisions is found to be 0.434 GeV at time $\tau_0 = 0.3$ fm/c.

move

The (proper) time evolution of temperature is shown in Fig. 1(a) and that of QGP fraction in Fig. 1(b), in the case of the most central (0-5%) collisions. Here we compare the evolutions obtained with longitudinal and cylindrical expansions using both a first order and the lattice ~~Equation of state~~ (EOS). For the first order EOS, T_c = 0.170 GeV, and the QGP fraction (c, not C) goes from 1 to 0 at T_c ~~this temperature~~, assuming a mixed phase of QGP and hadrons. The QGP fraction in case of lattice EOS governs the number of degrees of freedom, decided by the entropy density. It is fixed to unity ~~1~~ above an entropy density corresponding to a 2-flavour QGP and fixed to zero below entropy density for a hot resonance gas. The freeze out temperature in all cases is T_f = 0.140 GeV.

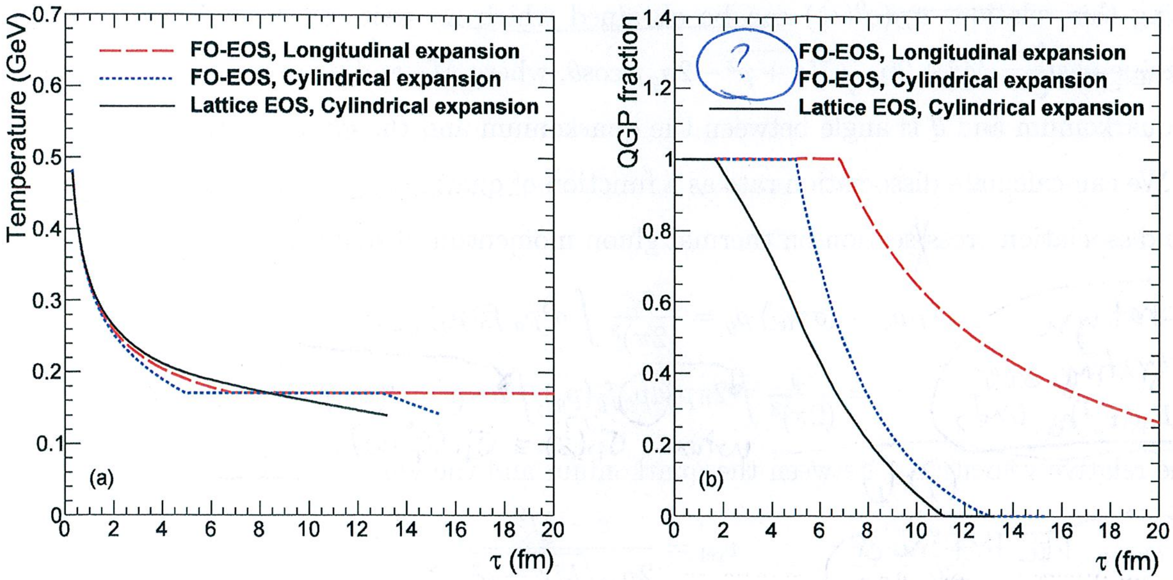


FIG. 1. (Color online) (a) Temperature and (b) QGP fraction in the system as a function of proper time τ in case of the most central (0-5%) collisions for longitudinal and cylindrical expansions using first order and lattice equation of state .

A. Dissociation Rate

the color - use American English spelling for Phys. Rev.

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 the ground states (,) J/ψ and $\Upsilon(1S)$, respectively [36]. For the first excited state of bottomonia (,) Υ(2S) (,) we use the dissociation cross section from Ref. [37].

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

$$q^0 = \frac{s - M_Q^2}{2\,M_Q} \tag{13}$$

where ... (A)

~~Using this relation~~

~~Using this relation,~~ $\sigma_D(q^0(s))$ can be obtained which ~~we write as $\sigma_D(s)$ where s can be obtained as~~ ($s = M_Q^2 + 2p_g\sqrt{M_Q^2+p^2} - 2p_g\, p\cos\theta$, where M_Q and p are mass and momentum of quarkonium and θ is angle between the quarkonium and the gluon.) – (A)

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

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

put what you are integrating over either all at the end, like in Eq.(4), or at the beginning, like first line of this eqn.

just $d\cos\theta$

where $\sigma_D(s) \equiv \sigma_D(q^0(s))$.

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

$$v_{\rm rel} = \frac{s - M_Q^2}{2p_g\sqrt{M_Q^2+p^2}} . \qquad (15)$$

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

B. Formation Rate

We can calculate the formation cross section from the dissociation cross section using detailed balance ~~relation~~ [19, 38], ~~as~~.

$$\sigma_F = \frac{48}{36}\sigma_D(q^0)\frac{(s-M_Q^2)^2}{s(s-4m_q^2)}. \qquad (16)$$

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

\frac works here

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

$\frac{\partial\lambda_F}{\partial p} = \frac{fm^2}{GeV}\cdot\frac{1}{fm^3}$

$= \frac{1}{GeV\cdot fm}$ ħc

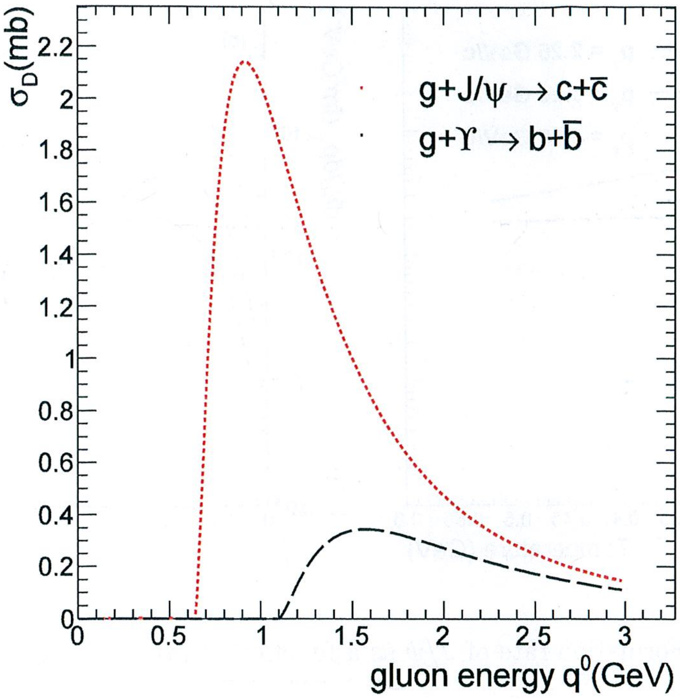
(so in Eq.(2) + Eq.(5) you integrate this expression over some range of momentum? not clear

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

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

Here $p_1 = (E_1, \mathbf{p_1})$ and $p_2 = (E_2, \mathbf{p_2})$ are the four momenta of the heavy quark and antiquark~~s~~, respectively.

Figure 4 (a) shows the variation of the J/ψ formation rate ~~of J/ψ~~ as a function of ~~medium temperature~~ T and Fig. 4 (b) shows as a function of ~~transverse momentum of~~ J/ψ. p_T The J/ψ generated



what happened to the legends here and on the rest?

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

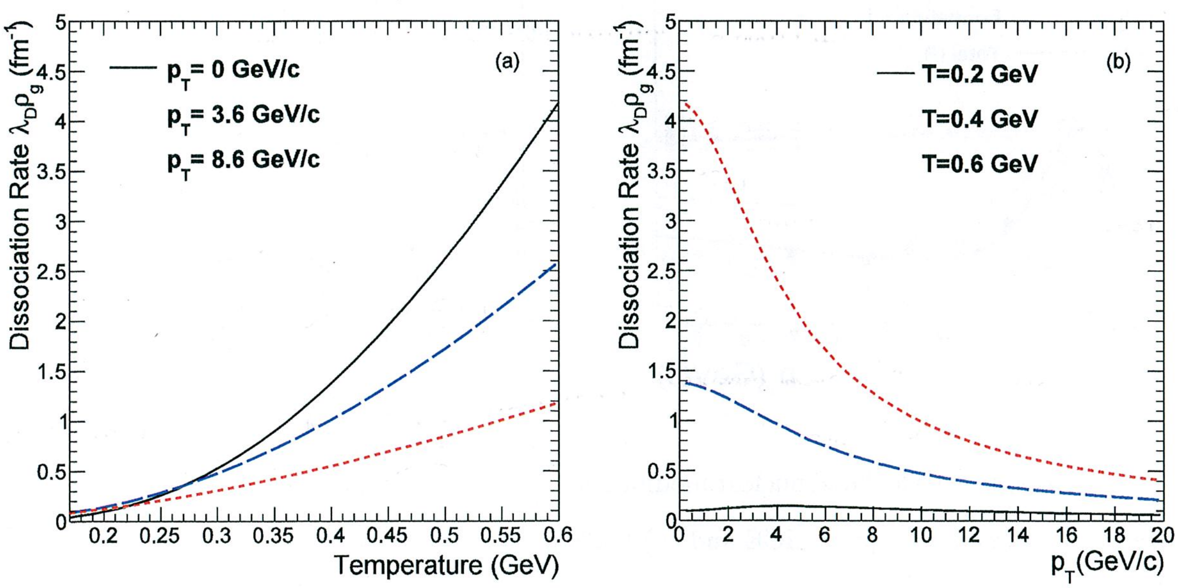


FIG. 3. (Color online) Gluon dissociation rate of J/ψ as a function of (a) temperature and (b) transverse momentum.

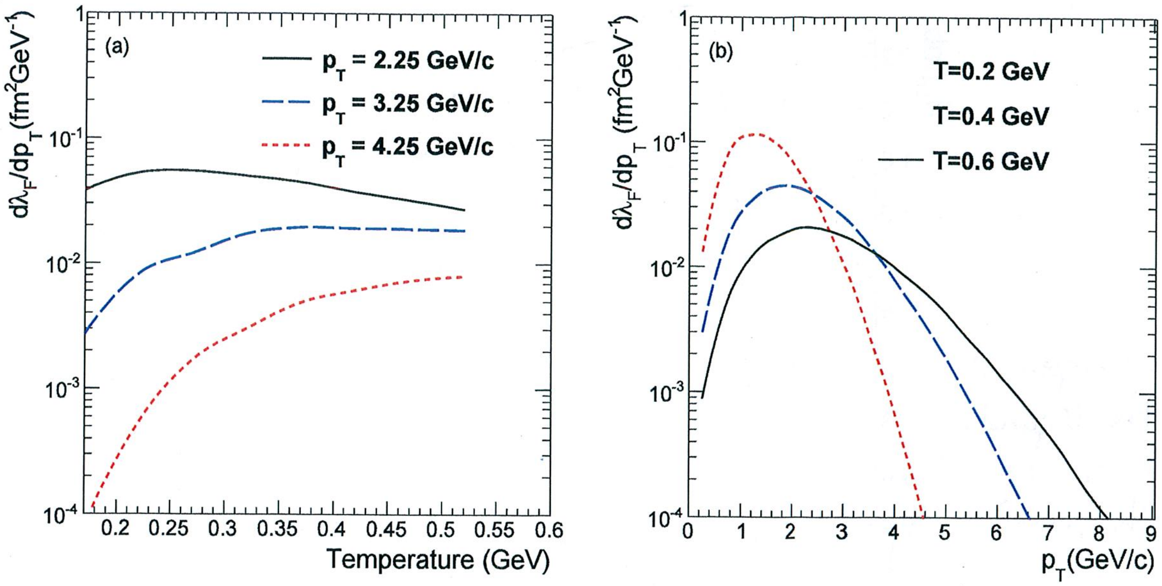
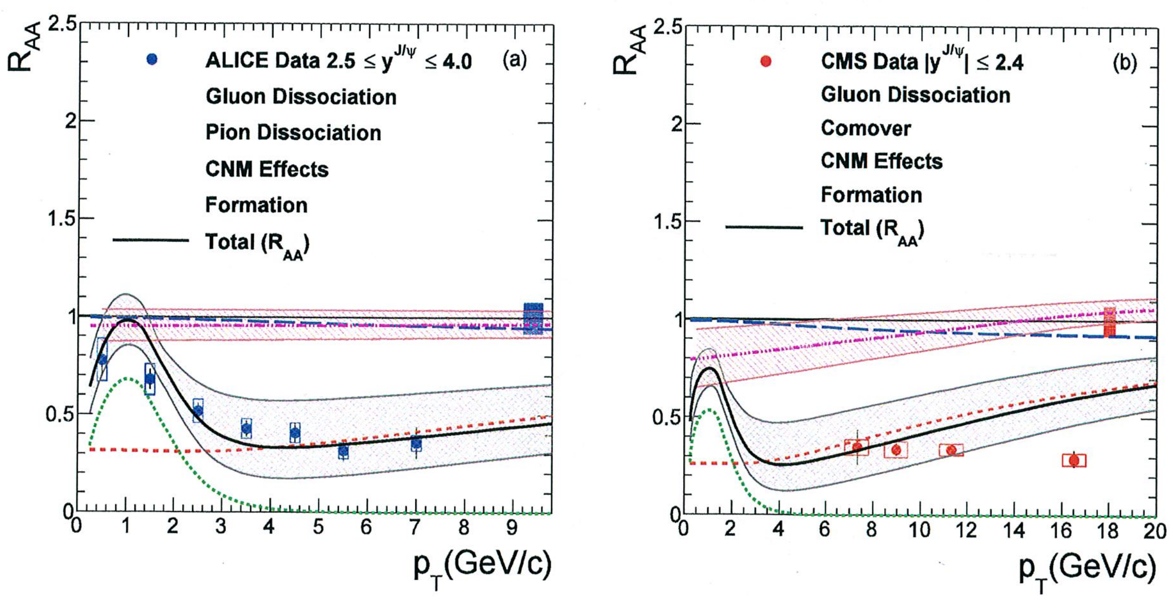


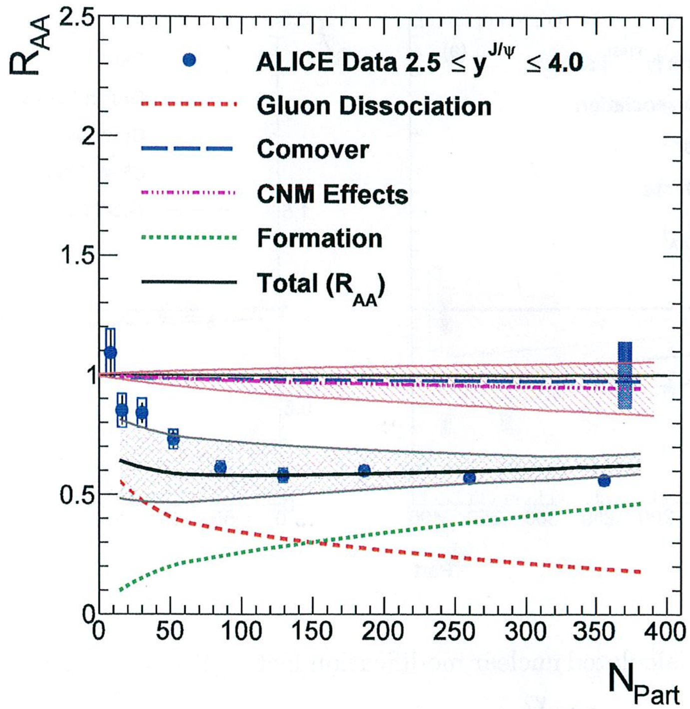
FIG. 4. (Color online) Formation rate of J/ψ as a function of (a) temperature and (b) transverse momentum.



\R{AA} here and elsewhere

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.

from recombination of uncorrelated heavy quark pairs will have softer p_T distributions than ~~that~~ those of J/ψ's coming from the initial hard scatterings. ~~and thus~~ Thus the effect of recombination will be important only at low p_T.



R_{AA}

FIG. 6. (Color online) Calculated nuclear modification factor (R_{AA}) compared with ALICE measurements at LHC.

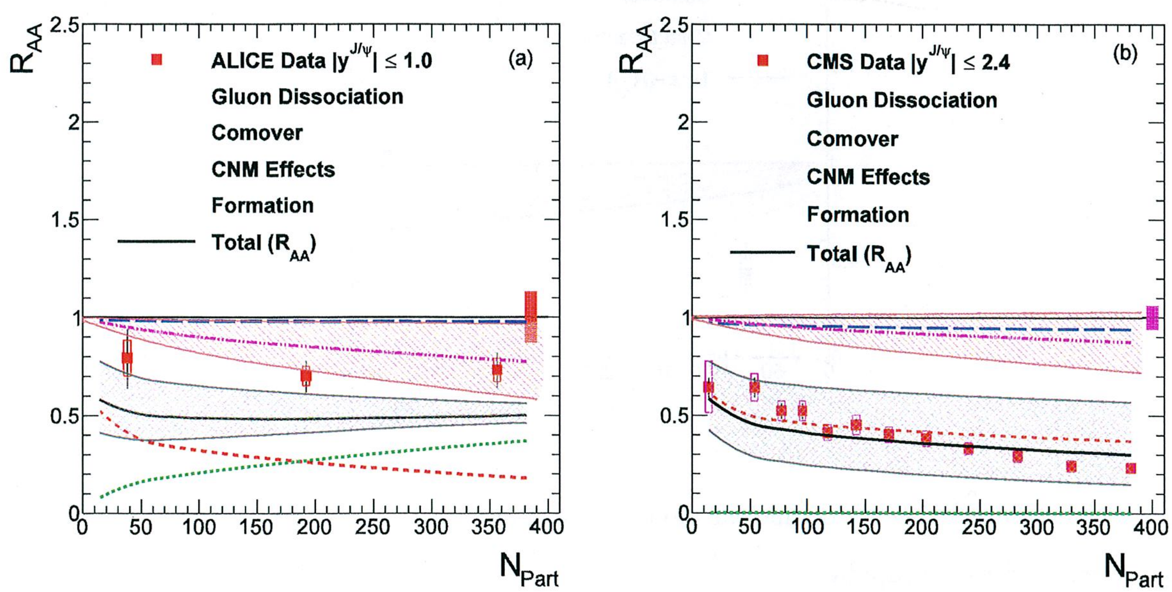
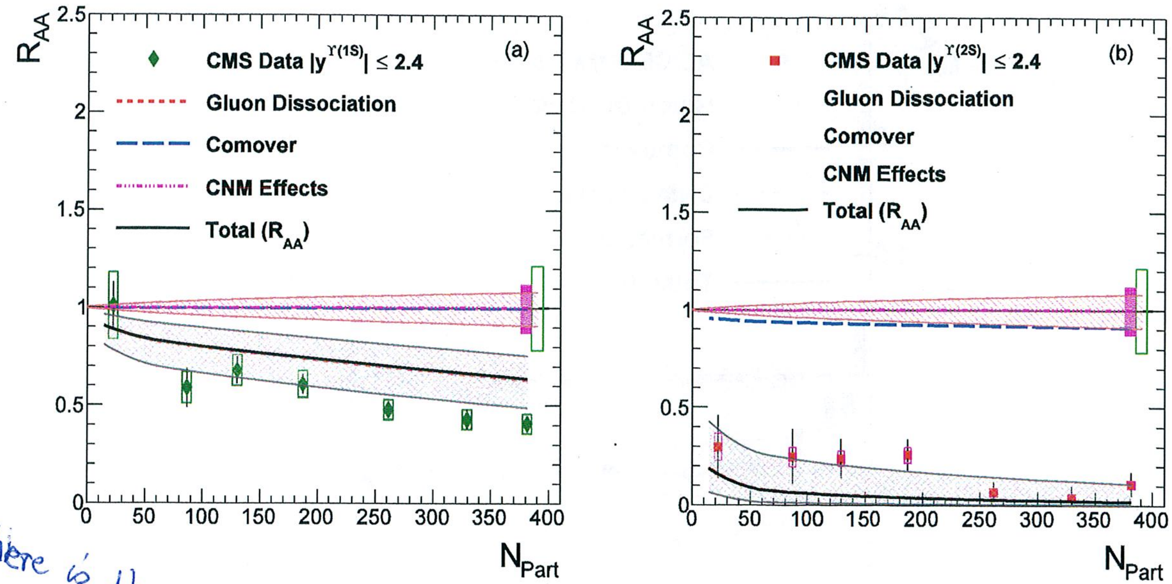


FIG. 7. (Color online) Calculated nuclear modification factor (R_{AA}) compared with (a) ALICE and (b) CMS measurements at mid rapidity. The regeneration for ~~high p_T CMS case~~ the CMS high p_T measurement is negligible in comparison to the low ~~p_T~~ p_T ALICE ~~case.~~ measurement



where is the red curve on these plots

FIG. 8. (Color online) Calculated nuclear modification factor (R_{AA}) compared with CMS (a) Υ(1S) and (b) Υ(2S) measurements. ~~The~~ Regeneration is assumed to be ~~small~~. negligible

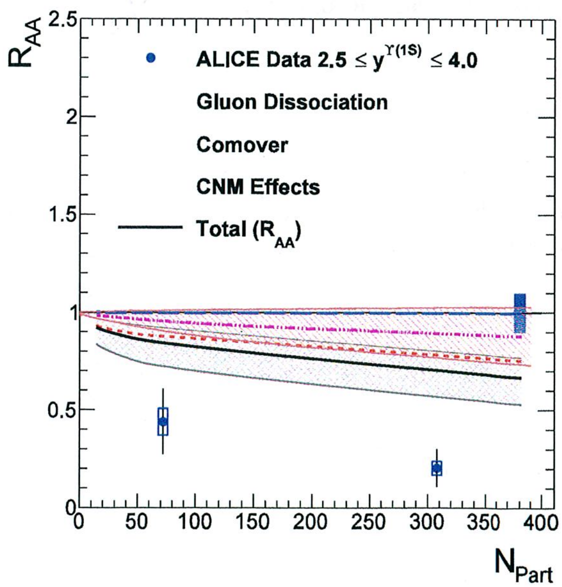


FIG. 9. (Color online) Calculated nuclear modification factor (R_{AA}) compared with ALICE Υ(1S) measurement in forward rapidity.

IV. EFFECT OF HADRONIC COMOVERS

The suppression of quarkonia by comoving pions can be calculated by folding the quarkonium-pion dissociation cross section $\sigma_{\pi Q}$ over thermal pion distributions [39]. It comover

is expected that at LHC energies, the cross-section ~~of comover suppression~~ will be small [40]. The pion-quarkonia cross section is calculated by convoluting the gluon-quarkonia cross section σ_D over the gluon distribution inside the pion [37], ~~as~~

$$\sigma_{\pi Q}(p_\pi) = \frac{p_+^2}{2(p_\pi^2 - m_\pi^2)} \int_0^1 dx\, G(x)\, \sigma_D(xp_+/\sqrt{2}), \tag{19}$$

where $p_+ = (p_\pi + \sqrt{p_\pi^2 - m_\pi^2})/\sqrt{2}$. The gluon distribution, $G(x)$, inside a pion is given by the GRV parameterization [41]. The pion momentum p_π is related to center of mass energy $\sqrt{s}$ of pion-J/ψ system ~~as~~ by $p_\pi = (s - M_Q^2 - m_\pi^2)/(2M_Q)$. The dissociation rate λ_{D_π} can be written as

See comment by Eq. (15)

$$\lambda_{D_\pi}\, \rho_\pi = \frac{g_\pi}{(2\pi)^3} \int d^3p\, f_\pi(p) \sigma_{\pi Q}(s) v_{\rm rel}(s) \tag{20}$$

$$= \frac{g_\pi}{(2\pi)^3} \int 2\pi p^2 dp\, f_\pi(p) \int \sigma_{\pi Q}(s)\, v_{\rm rel}(s) \Theta(s - 4m_D^2)\, d(\cos\theta)$$

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

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

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

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

The hadronic fraction (1-$f(\tau)$) is zero in QGP phase. The probability $S_\pi(p_T)$ is used along with the factor $S(p_T)$ ~~term~~ in Eq. (6).

multiplies?

V. RESULTS AND DISCUSSION

Figure 5(a) shows ~~different~~ the contributions ~~in~~ to the nuclear modification factor, R_{AA}, ~~of~~ for the J/ψ as a function of ~~transverse momentum~~ p_T compared with ALICE measurements [12] and the Figure ~~Fig.~~ 5(b) shows the same ~~along with~~ for the CMS 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 reason for the enhancement of J/ψ in the ALICE low p_T data. The gluon suppression is also substantial at low p_T and reduces as we move to high p_T. Both of these processes (regeneration and dissociation) due to the presence of QGP are at play ~~in~~ at low and intermediate p_T. The high

p_T suppression ($p_T > 10$ GeV/c) of J/ψ measured by CMS is ~~far more to be originating~~ greater than that due to ~~the~~ the dissociation by gluons in the QGP. The dominant sources of the uncertainties come from the gluon ~~quarkonia~~ dissociation cross section, (σ_D), and initial temperature T_0. We change the quarkonium-gluon cross section by a factor of 0.5 and 1.5 around the calculated value and obtain the variation in the final R_{AA} calculations. The initial temperature is obtained using measured charged particle density and assuming a value for τ_0. We vary τ_0 from 0.1 to 0.6 fm/c to quantify the uncertainty in R_{AA} due to variation in the initial temperature. Both of these uncertainties are added in quadrature to obtain the final uncertainty band around the central value. The uncertainty in the CNM effect is not added in the final uncertainty band since the CNM effects are not dominant ~~effects~~. See email

We have also calculated R_{AA} as a function of centrality ~~of~~ collision~~s~~ (system size). Figure 6 shows different contributions of J/ψ nuclear modification factor as a function of system size along with the measurements by ALICE in forward rapidity [12]. Figure 6 indicates that J/ψ's are increasingly suppressed by the QGP when the system size grows. Since the number of regenerated J/ψ's also grows, the nuclear modification factor remains ~~flat~~ over for most of the centrality range.

Figure 7 (a) shows the J/ψ nuclear modification factor along with the ALICE measurement ~~in~~ at mid-rapidity ~~region~~ [12]. Similar to forward rapidity, the nuclear modification factor is flat in the measured range of $N_{\rm part}$ due to the competitive effects of gluon dissociation and regeneration. Our calculations reproduce the measured data within uncertainty. Figure 7 (b) shows the same for $p_T \geq 6.5$ GeV/c, measured by CMS experiment [10]. The centrality dependence of R_{AA} of J/ψ by CMS is well described by the model. Most of the contribution to the CMS data comes from J/ψ's with ~~p_T between~~ 6.5 $< p_T <$ ~~and~~ 10 GeV/c where the suppression ~~seems~~ is ~~to be~~ predominantly due to gluon dissociation ~~process~~.

Figure 8 (a) demonstrates the contribution~~s~~ ~~of~~ from different processes ~~in~~ to the centrality dependence of the $\Upsilon(1S)$ nuclear modification factor, along with the data ~~measured in~~ mid-rapidity ~~by~~ from CMS ~~experiment~~ [14]. The calculations underestimate the suppression but reproduce the shape of centrality dependence. This may be due to the feed down effects from the excited states. Figure 8 (b) shows the same for the Υ(2S) nuclear modification factor along with the CMS measurements ~~in~~ at mid-rapidity. ~~by CMS experiment~~. The excited Υ(2S) states are highly suppressed. The effect of regeneration, ~~(~~not shown, ~~here)~~ is negligible for the Υ states.

Figure 9 shows the forward rapidity ALICE measurement of the Υ(1S) nuclear modification factor

[42] along with our calculations. The suppression due to thermal gluon dissociation is smaller than the measured suppression which may be due to the effect of feed down from the ~~excited states~~ $\Upsilon(2S)$ + higher states. We did not include feed down corrections as the dissociation cross sections for excited states specially for charmonia are not reliable. Also the feed down fractions in different states are not very well known. However, the measurement is consistent with the suppression of the $\Upsilon(2S)$ + $\Upsilon(3S)$ contribution, along with suppression of the $\Upsilon(1S)$ by gluon dissociation.

VI. SUMMARY

We have carried out detailed calculations of the 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~~ with the EPS09 NLO parametrization. A kinetic model is employed which incorporates quarkonia suppression inside QGP, suppression due to hadronic comovers and regeneration from charm pairs. The dissociation and formation rates have been studied as a function of medium temperature and transverse momentum ~~of particles~~.

The nuclear modification factor for J/ψ and Υ as a function of centrality and transverse momentum have been compared to the measurements 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 substantial at low p_T and becomes small as we move to high p_T. Both of these processes (regeneration and dissociation) due to the presence of QGP are affecting the yields of quarkonia in low and intermediate p_T. The high p_T suppression ($p_T > 10$ GeV/c) of J/ψ measured by CMS is far more than expected due to the dissociation by gluons in QGP.

The centrality dependence of nuclear modification indicates that J/ψ's are increasingly suppressed when system size grows. Since the number of regenerated J/ψ's also grows, the nuclear modification factor ~~in case of~~ of low p_T measurements (ALICE case) remains flat for most of the centrality regions. The centrality dependence of R_{AA} ~~of~~ for high p_T J/ψ's is also well described by the model. The centrality dependence of suppression of Υ states are reproduced by model calculations. Feed down corrections seems to important for $\Upsilon(1S)$.

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