Bottomonium dissociation and recombination reactions in heavy-ion collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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Outline

- Introduction to QGP and Heavy-Ion collisions
- Quarkonia in QGP
- Decoupling the rates of Dissociation and recombination reactions
- Results
- Summary

Heavy Ion collisions and Quark Gluon Plasma

- Relativistic Heavy-Ion Collisions make it possible to study the properties of strongly interacting matter at energy density far above those of nuclear matter.

- QCD predicts that when the temperature of nuclear matter is increased above a certain threshold (a critical temperature $\boldsymbol{T_C}$ ~ 170 MeV) the strongly interacting matter undergoes a phase transition to a "new" state of matter referred to as the Quark-Gluon Plasma (QGP) .

- Phase transition: The degrees of freedom change from color-neutral hadrons to color-charged partons which are no longer confined to exist only inside color-neutral hadrons.

Quarkonia in QGP

- One of the key signatures for the QGP formation is suppression of quarkonium states due to color screening in hot/dense QGP medium created just after the HIC.
  - Quarkonia are bound states of Charm/Beauty quark & its anti-quarks, produced in initial stages of the collisions.
  - Mainly Charmonium and Bottomonium

- Since quarkonia are produced in the early stage of the collisions, they are expected to experience the whole QGP evolution.

$$\tau_{\mathrm{formation}}^{\mathbf{bb}} \lesssim \tau_{\mathrm{formation}}^{QGP} < \tau_{\mathrm{life}}^{QGP} < \tau_{\mathrm{decay}}^{\mathrm{quarkonium}}$$

0.1-0.3 fm	**0.2-0.5 fm**	**~10 fm**	**~ 2000 fm**

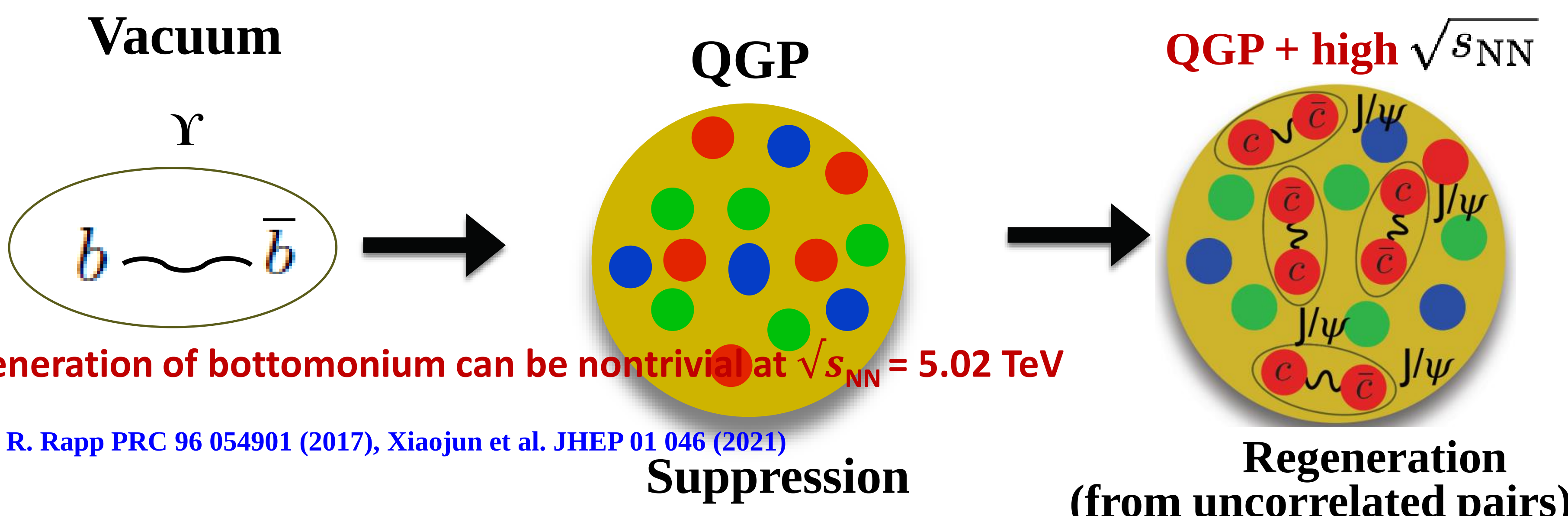
https://arxiv.org/pdf/0807.2470.pdf

Quarkonia in QGP

- Color screening of quarkonia is expected to prevent the formation of quarkonium states in deconfined matter (QGP)

  ► If screening length $\lambda_D(T) < r_0$ (quarkonium radius)

Matsui and Satz PLB 178 416 (1986), Digal PRD 64 0940150 (2001)



Regeneration of bottomonium can be nontrivial at $\sqrt{s_{NN}}$ = 5.02 TeV

X. Du, R. Rapp PRC 96 054901 (2017), Xiaojun et al. JHEP 01 046 (2021)

Bottomonia-Debey color screening

- Assuming QGP formed with initial conditions (τ_0, T_0),
- The time at which the plasma cools to T_D is

$$\tau_D = \tau_0 \left(\frac{s_0}{s_D}\right) = \tau_0 \left(\frac{T_0}{T_D}\right)^3$$

- As longs as $|\mathbf{r} + \frac{\tau_F \mathbf{p_T}}{M}| > r_D$, the bottom-quark pair can escape the color-charge screening region and form a bound state. τ_F is formation time and $\boldsymbol{r_D}$ is is the boundary of the suppression region.

- The survival probability of bottomonia becomes

$$S(p_T, R) = \frac{\int_0^R dr\, r\rho(r)\phi(r, p_T)}{\int_0^R dr\, r\rho(r)}$$

- A range of angle $\boldsymbol{\Phi}$ for which the bottom quark pair can escape the screening region:

$$\cos\phi \geq z \quad \text{where} \quad z = \frac{r_D^2 - r^2 - (\tau_F p_T/M)^2}{2r(\tau_F p_T/M)}$$

Decoupling Dissociation and Formation rates

- According to the Boltzmann equation, the time evolution of bottomonia states and beauty quarks in the deconfined region is

$$\frac{dN_\Upsilon}{d\tau} = \Gamma_F N_b N_{\bar{b}} [V(\tau)]^{-1} - \Gamma_D N_\Upsilon n_g$$

- The dissociation and recombination are two inverse-competing processes
  - Consider them as two separate processes and solve corresponding differential equations (decoupling the rate equations).

- The gluon dissociation of bottomonium is significant at RHIC and LHC energies.

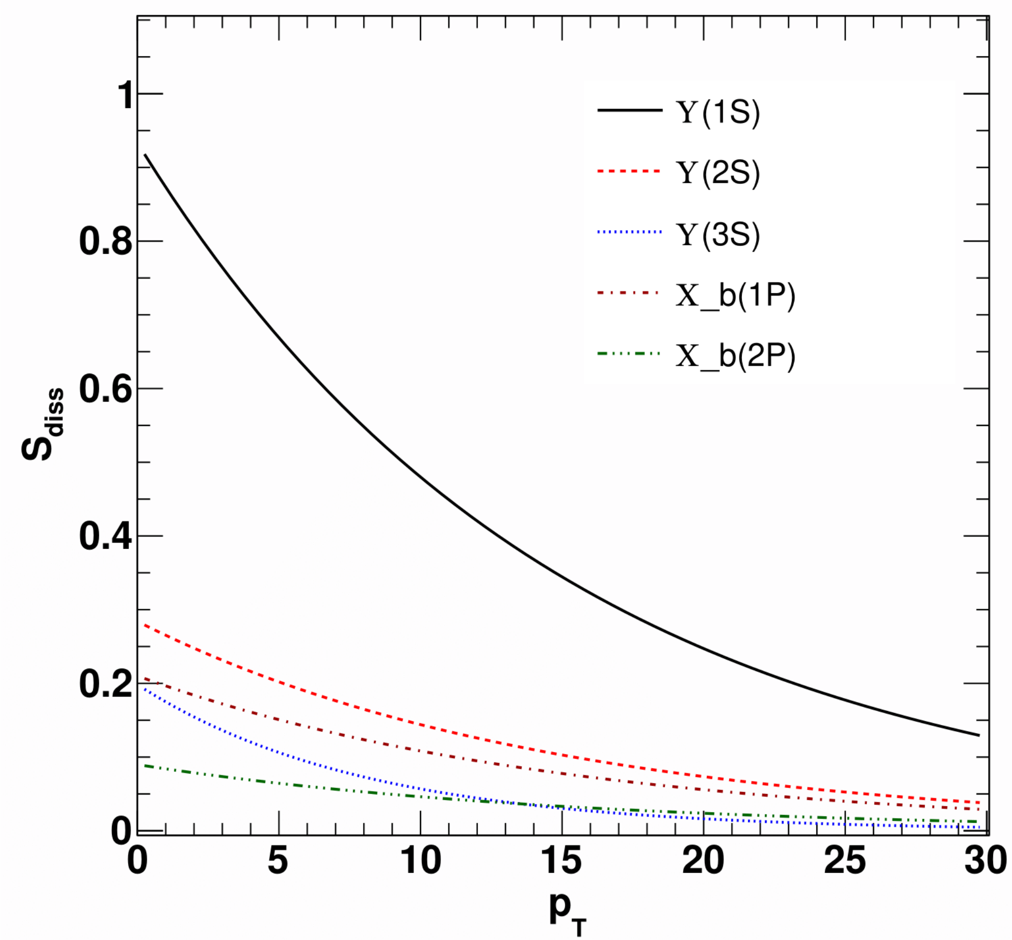
- The number of bottom quarks/pairs produced at LHC energy is ***O***(100) times more than that at RHIC energy collisions, indicating that the recombination can be nontrivial and to be taken well separately.

- To evaluate the dissociation of newly formed bottomonium states.

Dissociation rates

- **Dissociation of bottomonium**: $$\frac{dN_{\Upsilon}^{D}}{d\tau} = -\Gamma_D N_{\Upsilon}(0)\; n_g$$

Then the number of bottomonium states survived is (solution)



$$= N_{\Upsilon}(0)\; exp^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau}$$

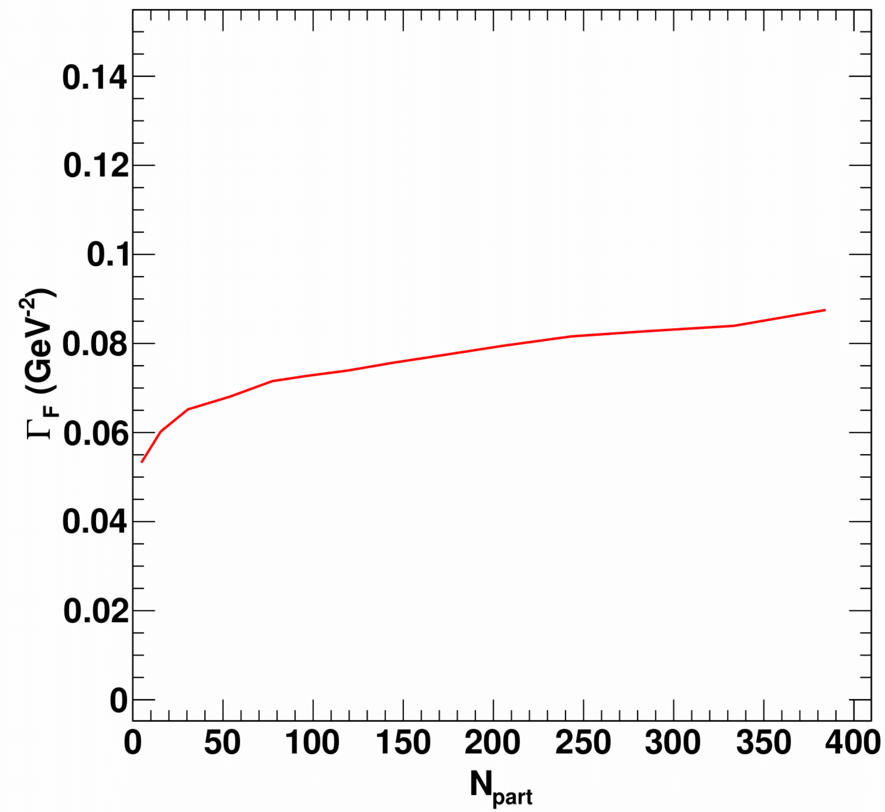
he dissociation reaction, averaged

$$\frac{{}^{R(N_{\text{part}},\tau)}\; dr\; r\; exp^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau}}{\int_0^{R(N_{\text{part}},\tau)} dr\; r}$$

Formation/Recombination rates

- **Formation/Recombination of bottomonium (**taking the dissociation of newly formed Υ states**):**

$$\frac{dN_{\Upsilon}^{F}}{d\tau} = \Gamma_F N_{b\bar{b}}^2 (Tot)[V(\tau)]^{-1} - \Gamma_D N_{\Upsilon}^{F} n_g$$



Decoupling dissociation and recombination

- **Formation/Recombination of bottomonium (**taking the dissociation of newly formed Υ states**)**:

$$\frac{dN^F_\Upsilon}{d\tau} = \Gamma_F N^2_{b\bar{b}}(Tot)[V(\tau)]^{-1} - \Gamma_D N^F_\Upsilon n_g$$

Nuclear decay process	Recombination process
$\frac{dN_1}{dt} = -\lambda_1 N_1$ with $N_1 = N_1^0 e^{\lambda_1 t}$	$\frac{dN^F_\Upsilon}{dt} = -\lambda_{b\bar{b}} N_{b\bar{b}}$ (creation from b & $\bar{b}$)
$\frac{dN_2}{dt} = -\lambda_2 N_2 + \lambda_1 N_1$	$\frac{dN^F_\Upsilon}{dt} = \lambda_{b\bar{b}} N_{b\bar{b}} - \lambda_D N^F_\Upsilon$
(Daughter nuclei decay)	(Recombination & Dissociation of newly created Υ)
$N_2 = \frac{\lambda_1}{\lambda_2 - \lambda_1} N_0 (e^{\lambda_1 t} - e^{\lambda_1 t}) + N_2 e^{\lambda_1 t}$ (Bateman Solution)	N^F_Υ is calculated in Eq. (15)

Decoupling dissociation and recombination

- ✓ The the solution is

$$N_{\Upsilon}^{F} = \frac{\Lambda_F}{\Lambda_D - \Lambda_F} N_{b\bar{b}}(Tot)[e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_F N_{b\bar{b}}^2(Tot)[V(\tau)]^{-1} d\tau} - e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau}]$$
$$+ N_{b\bar{b}}^{Diss} e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau}$$

with $\Lambda_F = \int_{\tau_0}^{\tau_{QGP}} \Gamma_F N_{b\bar{b}}^2(Tot)[V(\tau)]^{-1} d\tau$ and $\Lambda_D = \int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau$.

- ✓ The probability of recombination (fractional of the formation/recombination) in the medium becomes

$$S_F(N_{\text{part}}) = \frac{N_{\Upsilon}^{F}}{N_{\Upsilon}(0) + N_{b\bar{b}}(Tot)} =$$
$$\frac{N_{b\bar{b}}(Tot)}{N_{\Upsilon}(0) + N_{b\bar{b}}(Tot)} \frac{\Lambda_F}{\Lambda_D - \Lambda_F} [e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_F N_{b\bar{b}}^2(Tot)[V(\tau)]^{-1} d\tau} -$$
$$e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau}] + \frac{N_{b\bar{b}}^{Diss}}{N_{\Upsilon}(0) + N_{b\bar{b}}(Tot)} e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau}.$$

The survival

- Suppose the probability of charmonium formation in deconfinement medium is

$$N_{\psi}/N_{c\bar{c}} \approx N_{c\bar{c}}/N_{ch} \approx P_{c\to\psi}$$

- The same relation can be used to get the survival probability of the bottomonium from all medium effects.

- The net survival probability of the bottomonium in the medium is the combined effects from all interactions.

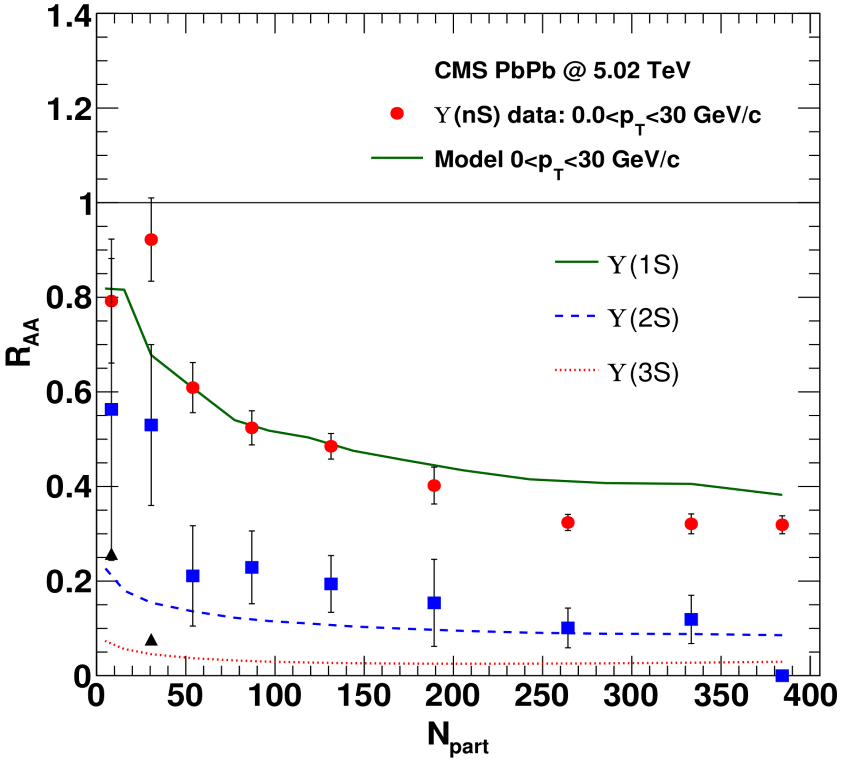
$$S(N_{part}) = S_{col}(N_{\rm part}) * S_{diss}(N_{\rm part}) + S_F(N_{\rm part})$$

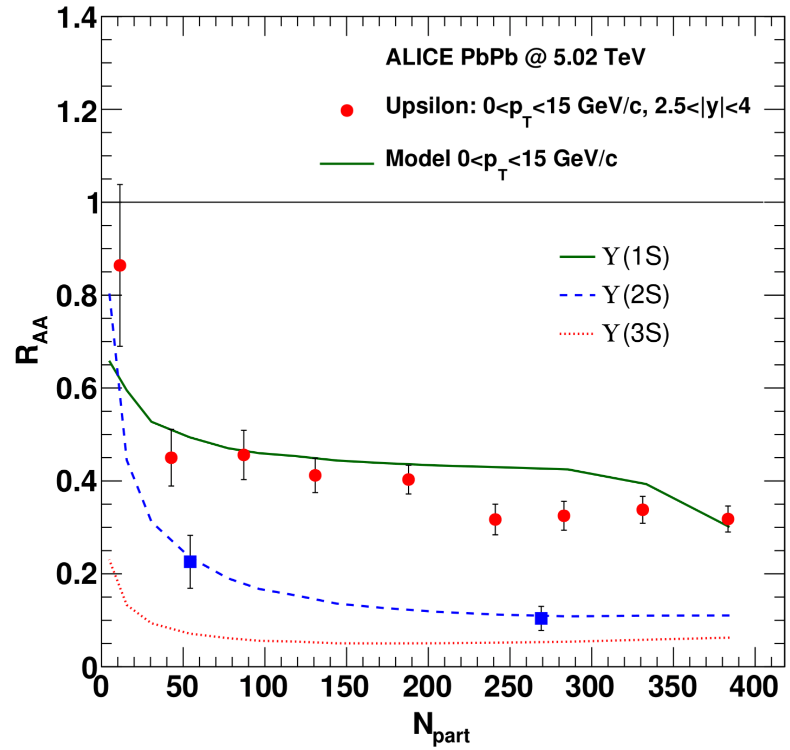
- The total survival probability of the bottomonium in the medium is the combined effect of all mechanisms.

More details: https://doi.org/10.1016/j.nuclphysa.2020.122130

Nuclear Modification Factor- R_{AA}

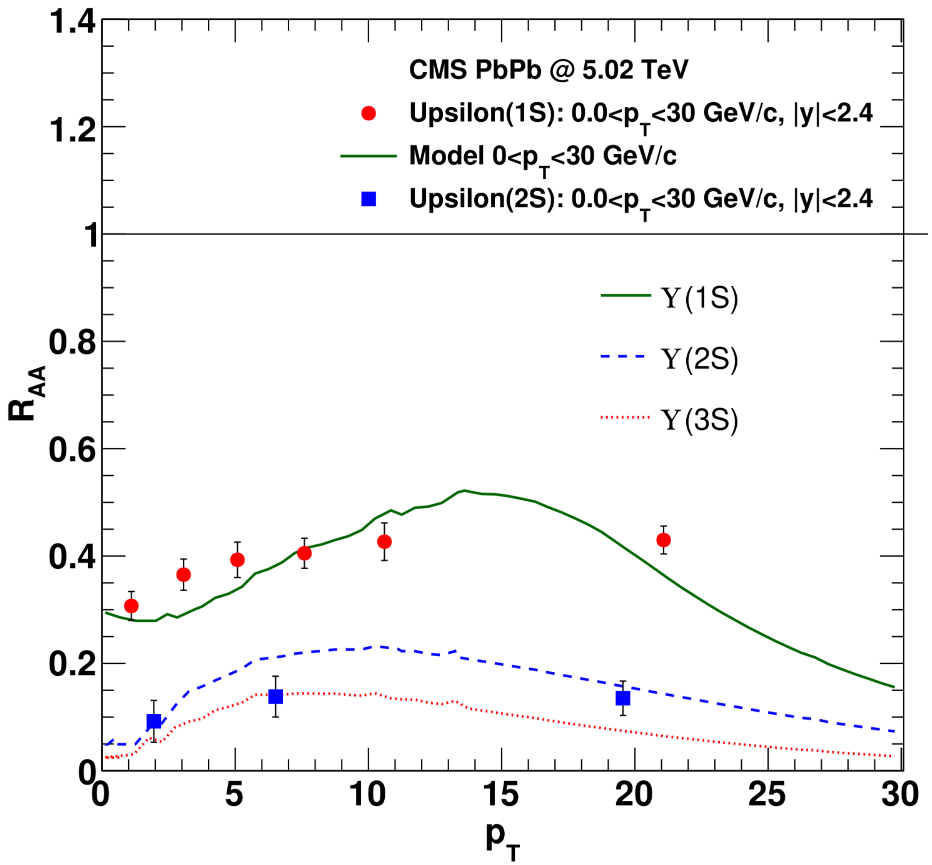
- The nuclear modification factor is obtained from survival probability taking into account the feed-down corrections





- The solid and dashed lines are the model calculations for in the respective regions.
- The model replicates the measured R_{AA} (Left-CMS, Right-ALICE).
- Mismatch in some bins: variation of initial parameters or shadowing effect

Nuclear Modification Factor- R_{AA}



- The solid and dashed lines are the model calculations for in the respective pT regions.
- The model reproduces the measured R_{AA} well in most of bins, some discrepancy may be because of less energy loss of high pT bottomonia.

Summary

- ✓ We have studied bottomonia suppression in QGP medium using a model in which the rate equations of dissociation and recombination are decoupled and solved separately.

- ✓ The model calculation reproduces well the measured Nuclear Modification factors at CMS & ALICE experiments.

- ✓ The model supports the assumption that regeneration of the bottomonium can be nontrivial at higher energy collisions (>= 5.02 TeV).

- ✓ There could be other reasons like variation of initial parameters that can have significant impact on the trends of the suppression model.

Thank you

Quarkonia in QGP

- **Gluonic Dissociation :** Mechanism is based on the excitation of singlet state to octet state as a result of absorption of soft gluons by a singlet state.

$$\sigma(q^0) = \frac{2\pi}{3}\left(\frac{32}{3}\right)^2\left(\frac{16\pi}{3g_s^2}\right)\frac{1}{m_Q^2}\frac{(q^0/\epsilon_0 - 1)^{3/2}}{(q^0/\epsilon_0)^5}$$

- **Regeneration :** The de-excitation of octet state to singlet state via emitting a gluon. The recombination cross-section for charmonium/bottomonium in QGP by using the detailed balance from the gluonic dissociation cross-section.

$$\sigma_{f,nl} = \frac{48}{36}\sigma_{d,nl}\frac{(s - M_{nl}^2)^2}{s(s - 4\ m_c^2)}$$

Bateman solution

The parent nucleus decays according to the equations of radioactive decay which we have treated in this section:

$$A_1 = -\frac{dN_1}{dt} = \lambda_1 N_1$$

and

$$N_1 = N_1^0 e^{-\lambda_1 t} \qquad \text{and} \qquad A_1 = A_1^0 e^{-\lambda_1 t}$$

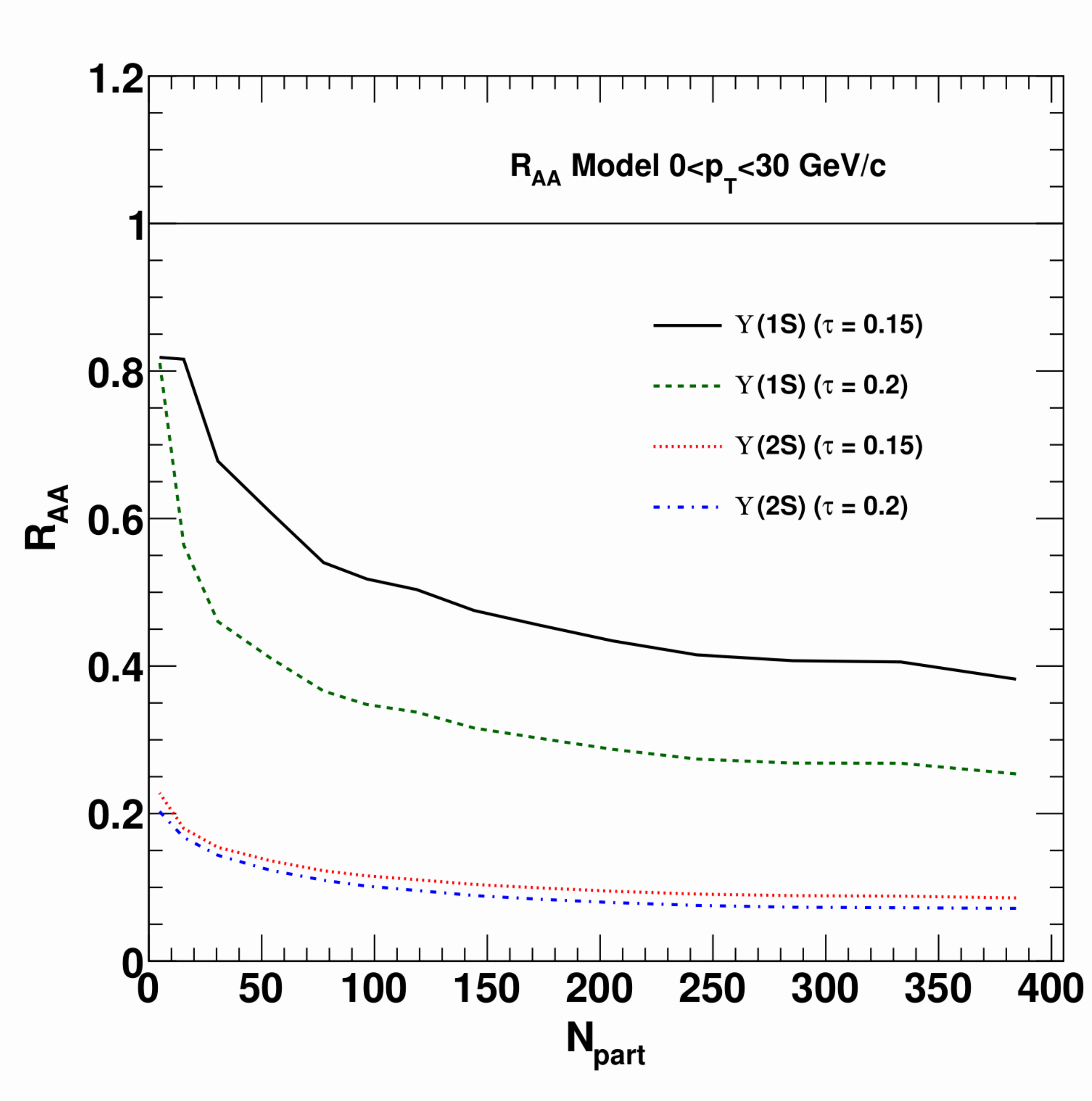
The amount of daughter nuclei is determined by two processes: (i) radioactive decay and (ii) radioactive growth by decay of the parent nuclei, respectively:

$$\frac{dN_2}{dt} = -\lambda_2 N_2 + \lambda_1 N_1$$

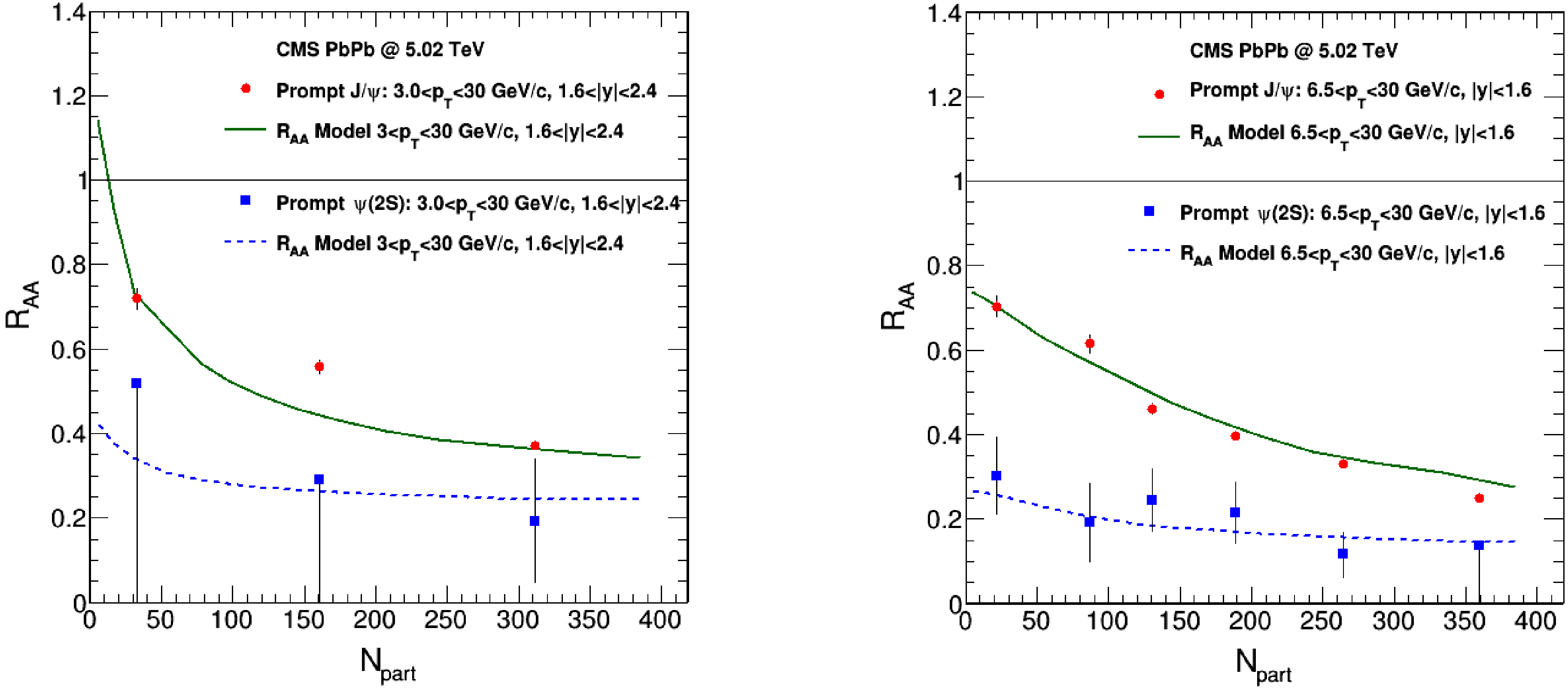
The solution of this differential equation is:

$$N_2 = \frac{\lambda_1}{\lambda_2 - \lambda_1} N_1{}^0 \left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right) + N_2{}^0 e^{-\lambda_2 t}$$

Nuclear decay process	Recombination process
$\frac{dN_1}{dt} = -\lambda_1 N_1$ with $N_1 = N_1^0 e^{\lambda_1 t}$ $\frac{dN_2}{dt} = -\lambda_2 N_2 + \lambda_1 N_1$ (Daughter nuclei decay)	$\frac{dN_\Upsilon^F}{dt} = -\lambda_{b\bar{b}} N_{b\bar{b}}$ (creation from b & $\bar{b}$) $\frac{dN_\Upsilon^F}{dt} = \lambda_{b\bar{b}} N_{b\bar{b}} - \lambda_D N_\Upsilon^F$ (Recombination & Dissociation of newly created Υ)
$N_2 = \frac{\lambda_1}{\lambda_2 - \lambda_1} N_0 (e^{\lambda_1 t} - e^{\lambda_1 t}) + N_2 e^{\lambda_1 t}$ (Bateman Solution)	N_Υ^F is calculated in Eq. (15)


R_AA Model 0<p_T<30 GeV/c
Υ(1S) (τ = 0.15)
Υ(1S) (τ = 0.2)
Υ(2S) (τ = 0.15)
Υ(2S) (τ = 0.2)
R_AA
N_part
0
0.2
0.4
0.6
0.8
1
1.2
0
50
100
150
200
250
300
350
400

Nuclear Modification Factor- R_{AA}

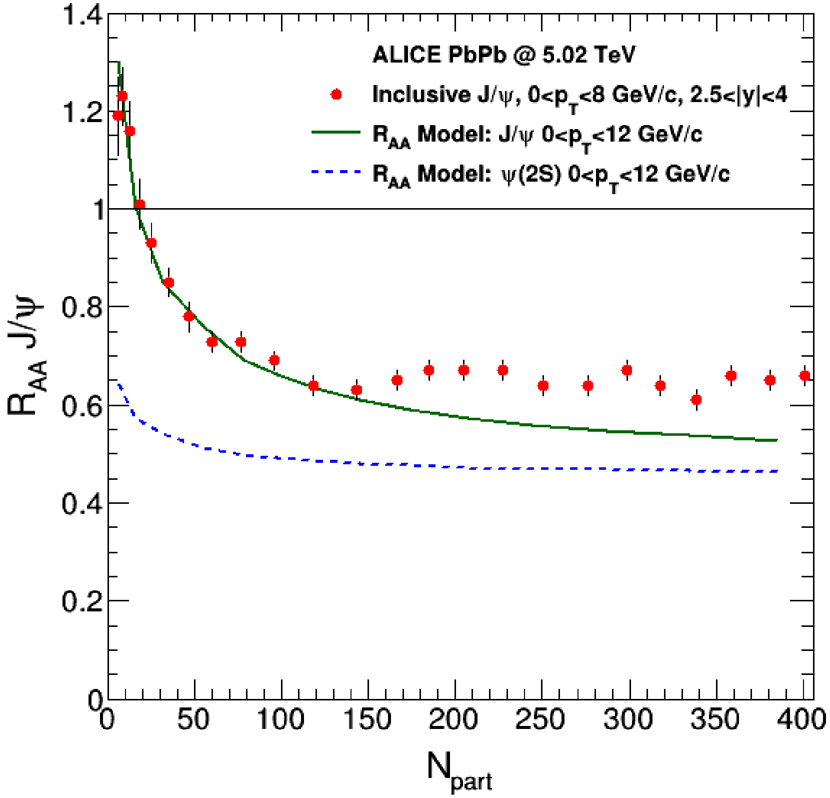


The model reproduces well the measured nuclear modification factors (CMS Experiment) of both J/ψ and ψ(2S)in all centralities.

Right : High pT and mid rapidity

Left : Low pT and forward rapidity

Nuclear Modification Factor- R_{AA}



- The solid line (present model calculation) agrees well with the measured data (ALICE Experiment) keeping in mind that the measured R_{AA} is for inclusive J/ψ while the model calculation is for prompt J/ψ and ψ(2S).
- Recombination reaction is more prominent at low-pT region.

$$R_{\mathrm{AA}}(\chi_c(1P)) = S(\chi_{c1} + \chi_{c2})$$

$$R_{\mathrm{AA}}(\psi(2S)) = S(2S)$$

$$R_{\mathrm{AA}}(\psi(1S)) = g_1\ S(1S) + g_2\ S(1P) + g_3\ S(2S)$$