Decoupling the rates of charmonium dissociation and recombination reactions in heavy-ion collisions at LHC energy

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IS2021

The VI[th] International Conference on the
INITIAL STAGES
OF HIGH-ENERGY NUCLEAR
COLLISIONS

JAN 10-15, 2021

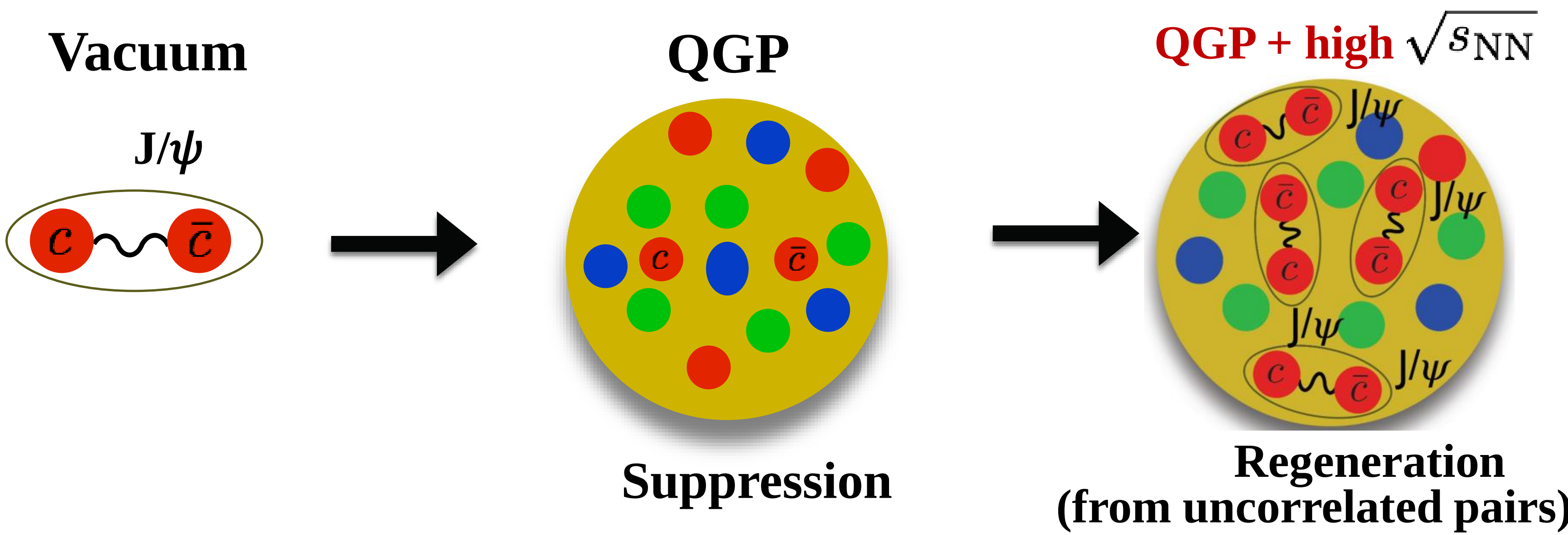
Charmonia in QGP

- Charmonia are particles are bound states of **$c\bar{c}$**

$$\tau^{c\bar{c}}_{\text{formation}} \lesssim \tau^{QGP}_{\text{formation}} < \tau^{QGP}_{\text{life}} < \tau^{\text{quarkonium}}_{\text{decay}}$$

- Color screening of charmonia is expected to prevent the formation of charmonium 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)



Outline

- ❖ The rate equations of dissociation and recombination are **Decoupled and solved separately** with a 2-dimensional accelerated expansion of fireball volume.

- ❖ To solve the recombination rate equation, we have used an approach of **Bateman solution** which ensures the dissociation of the recombined charmonium in the QGP medium.

- ❖ The modifications of charmonium states are estimated in an expanding QGP with the conditions relevant for Pb+Pb collisions in CMS/ALICE Experiments at LHC.

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

Charmonia-Survival Probability

- 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 $|\mathbf{r} + \frac{\tau_F \mathbf{p_T}}{M}| > r_D$, quarkonium formation will be suppressed. τ_F is formation time.
- The survival probability of quarkonia becomes

$$S(N_{\text{part}}) = \int S(p_T, R(N_{\text{part}}))\, dp_T$$

- The probability of charmonium formation in deconfinement medium is

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

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Decoupling dissociation and recombination

- The recombination mechanism is the inverse process of thermal gluon dissociation of charmonium states, that a free charm quark and anti-quark are captured in the ψ bound state, emitting a color octet gluon.

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

$$\frac{dN_\psi}{d\tau} = \Gamma_F N_c N_{\bar{c}} [V(\tau)]^{-1} - \Gamma_D N_\psi n_g$$

- Decoupling: Motivation
  - ✓ The gluon dissociation of charmonium is significant at RHIC and LHC energies.
  - ✓ The recombination of charmonium is prominent only when number of charm and anti-charm quarks (pairs) are produced in large amount ~ $\boldsymbol{O}(100)$.
  - ✓ The number of charm quarks/pairs produced at LHC energy is $\boldsymbol{O}(100)$ times more than that at RHIC energy collisions, indicating that the recombination is an active process to be taken well separately.

Decoupling dissociation and recombination

Dissociation of charmonium: $$\frac{dN_\psi^D}{d\tau} = -\Gamma_D N_\psi(0)\, n_g$$

Then the number of charmonium states survived is (solution)

$$N_\psi^D = N_\psi(0)\; exp^{-\int_{\tau_0}^{\tau_f} \Gamma_D n_g d\tau}$$

Formation/Recombination of charmonium:

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

- ✓ The formation equation is analogous to that of radioactive decay chain reaction.
- ✓ The solution of such differential equation can be found by **Bateman equation** which take into account the effects of correlated mechanism of recombination from two charm quarks and the dissociation of newly formed pairs. Then the solution is

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

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

The survival

- To get the total number of ψ survived at the end of QGP lifetime, the number of ψ survived/recombined from the respective reactions are added together.

$$N_{\psi}(\tau_{QGP}) = \frac{\Lambda_F}{\Lambda_D - \Lambda_F} N_{c\bar{c}}(Tot)[e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_F N_{c\bar{c}}^2(Tot)[V(\tau)]^{-1} d\tau} - e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau}]$$
$$+ N_{c\bar{c}}^{Diss} \, e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau}$$
$$+ N_{\psi}(0) \, e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau}.$$

- The total survival probability of the charmonium in the medium

$$S(p_T, R(N_{part})) = \frac{1}{N_{\psi}(0) + N_{c\bar{c}}(Tot)} \int_0^R dr \, r \, \rho(r) \, \phi(r, p_T)$$
$$(\frac{\Lambda_F}{\Lambda_D - \Lambda_F} N_{c\bar{c}}(Tot)[e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_F N_{c\bar{c}}^2(Tot)[V(\tau)]^{-1} d\tau} - e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau}])$$
$$N_{\psi}(0) e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau}$$

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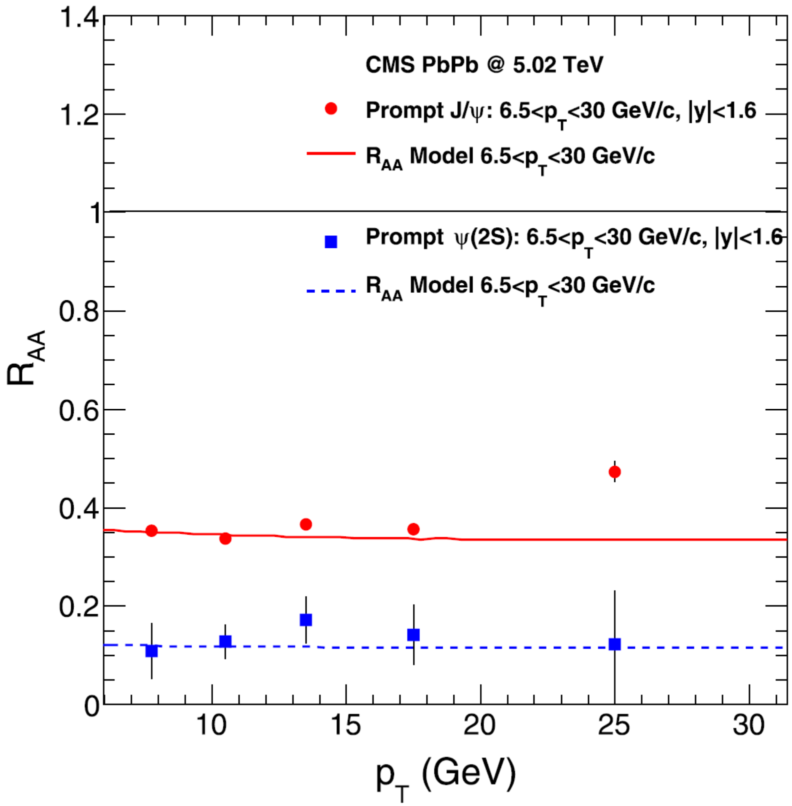
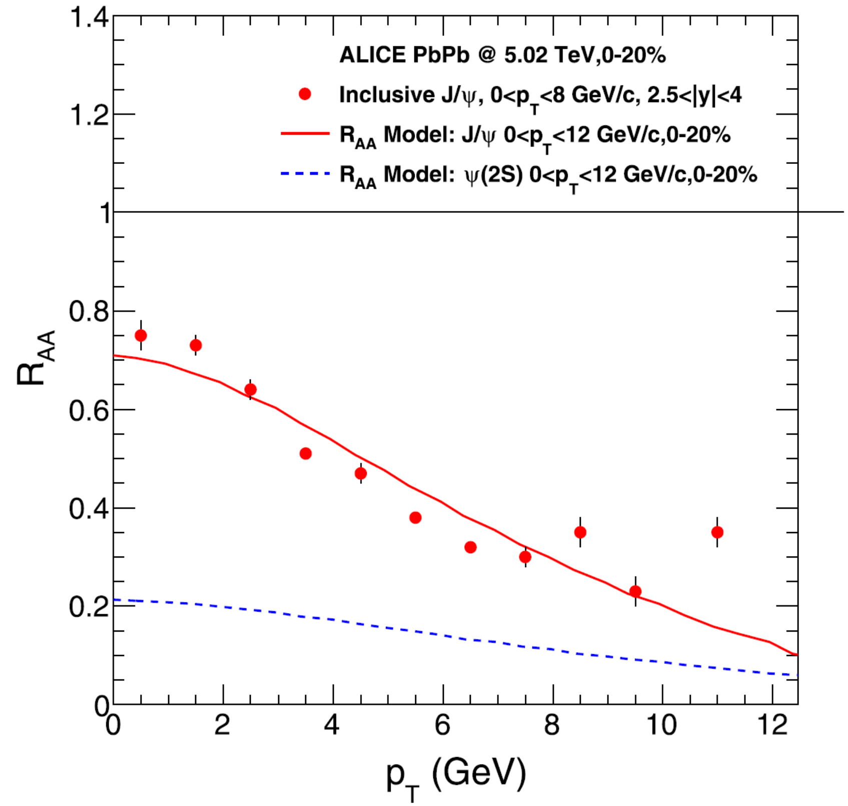
Nuclear Modification Factor- R_{AA}

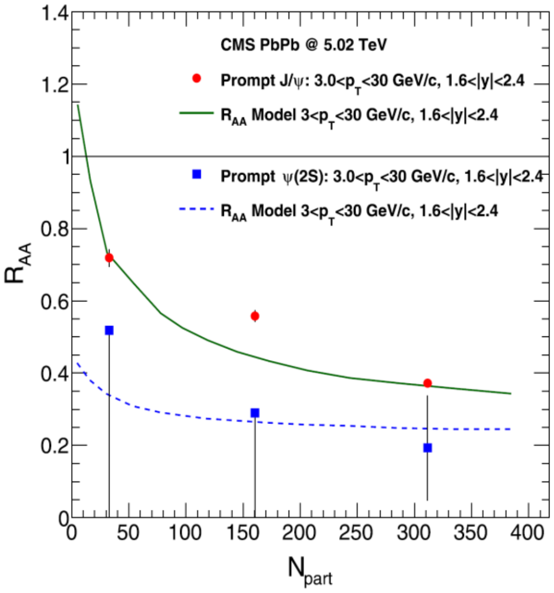
- The nuclear modification factor is obtained from survival probability taking into account the feed-down corrections

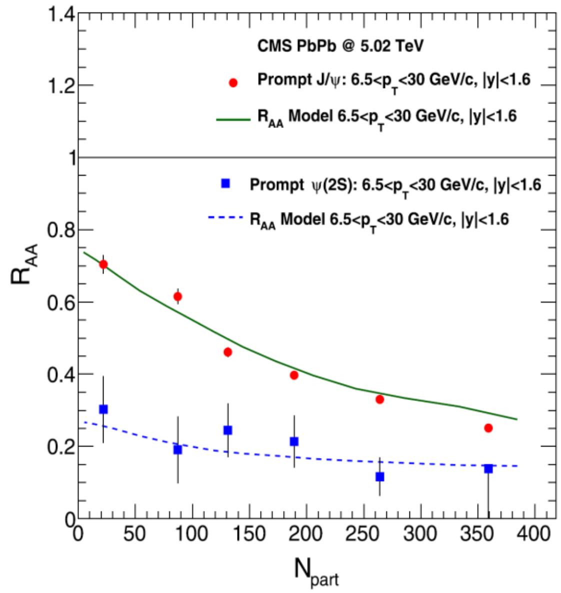


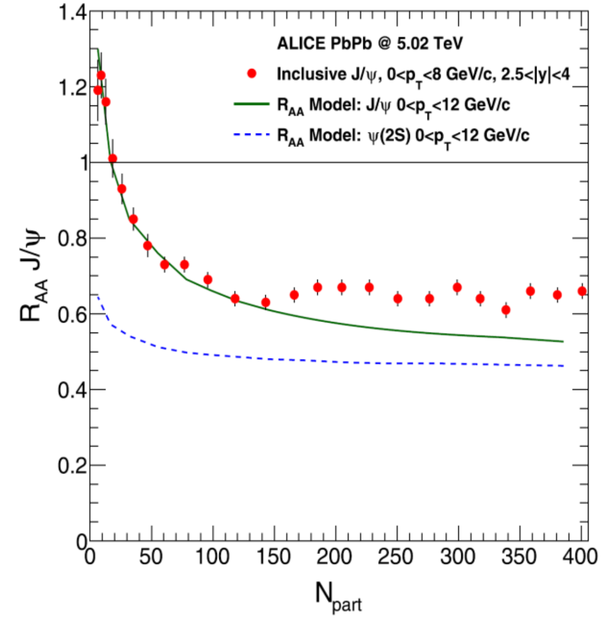


- The solid and dashed lines are the model calculations for in the respective pT regions.
- The model replicates the measured R_{AA} (Left-CMS, Right-ALICE) except in last bin, may be because of less energy loss of high pT charmonia.

Nuclear Modification Factor- R_{AA}







Right figure: 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).

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

This study is published in NPA:

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

Thank you