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

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Outline

- Introduction to QGP and Heavy-Ion collisions
- Quarkonia in QGP
- Decoupling the rates of Dissociation and recombination reaction
- 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 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.

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

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

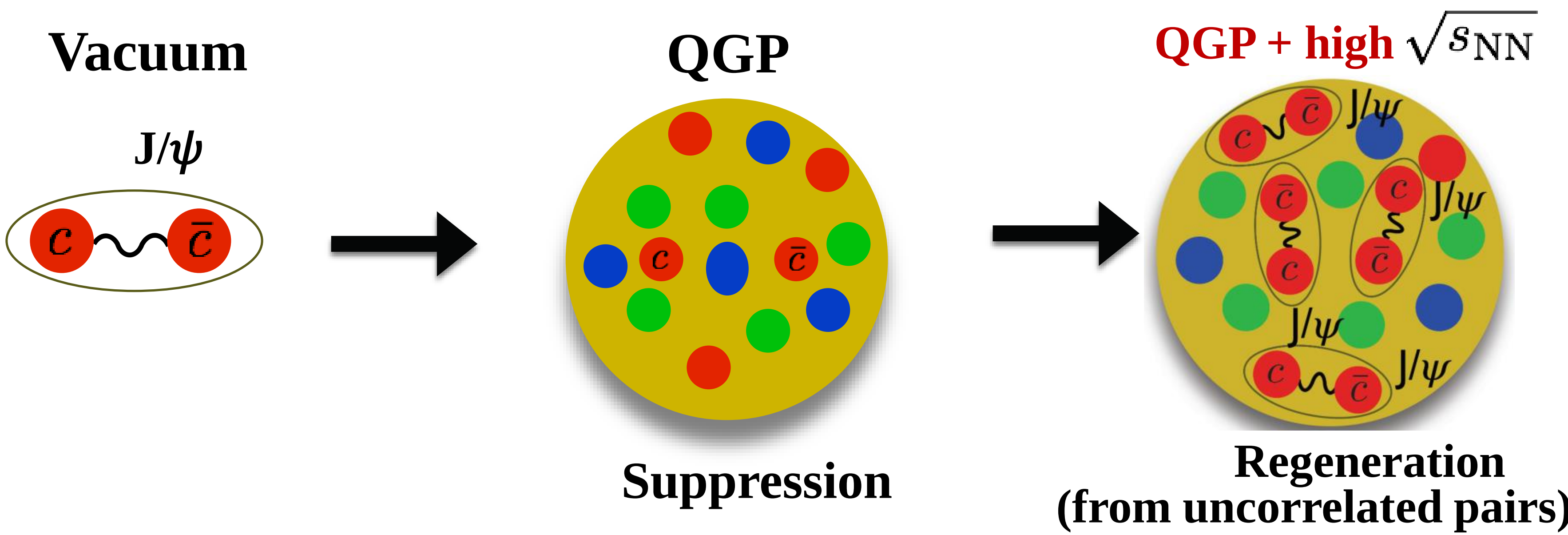
https://arxiv.org/pdf/0807.2470.pdf

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)



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.

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

Decoupling dissociation and recombination

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

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

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

- 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.

Dissociation Model

- 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.
  - ✓ To evaluate the dissociation of newly formed quarkonium states.

❖ This new approach makes the calculations simple and help to assess the effect of individual reaction.

❖ 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 and compared with experimental results.

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

Quarkonia-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 $|\mathbf{r} + \frac{\tau_F \mathbf{p_T}}{M}| > r_D$, quarkonium formation will be suppressed due to color screening. τ_F is formation time and $\boldsymbol{r_D}$ is is the boundary of the suppression region.

- The survival probability of quarkonia 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 Φ for which the 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 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 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:

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

Decoupling dissociation and recombination

- ✓ The 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 $\Lambda_D = \int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau$.

$$N_{c\bar{c}}(Tot) = \sigma_{c\bar{c}}^{NN}\, T_{AA}(\tau_0, b) + N_{\psi}(0) \int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau$$

- ✓ To get the total number of charmonium 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 survival

- 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 quarkonium due to all effects.

- The survival probability of the charmonium in the medium

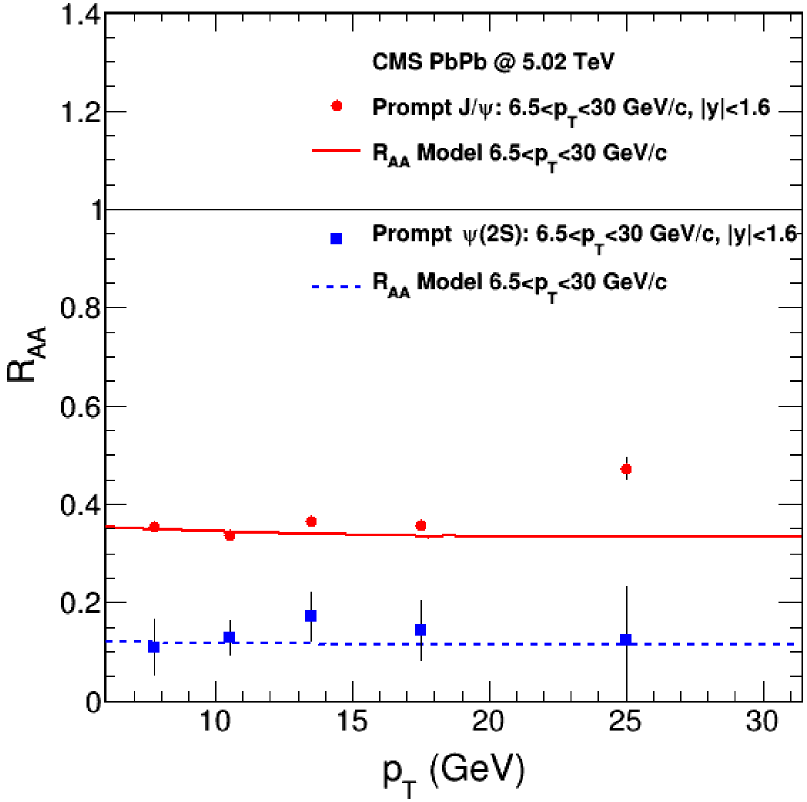
$$S(p_T, R(N_{part})) = \frac{1}{N_{\psi}(0) + N_{c\bar{c}}(Tot)} \int_0^R dr\, r\, \rho(r)\, \phi(r, p_T)$$
$$\left(\frac{\Lambda_F}{\Lambda_D - \Lambda_F} N_{c\bar{c}}(Tot)[e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_F N_{c\bar{c}}^2(Tot)[V(\tau)]^{-1} d\tau} - e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g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

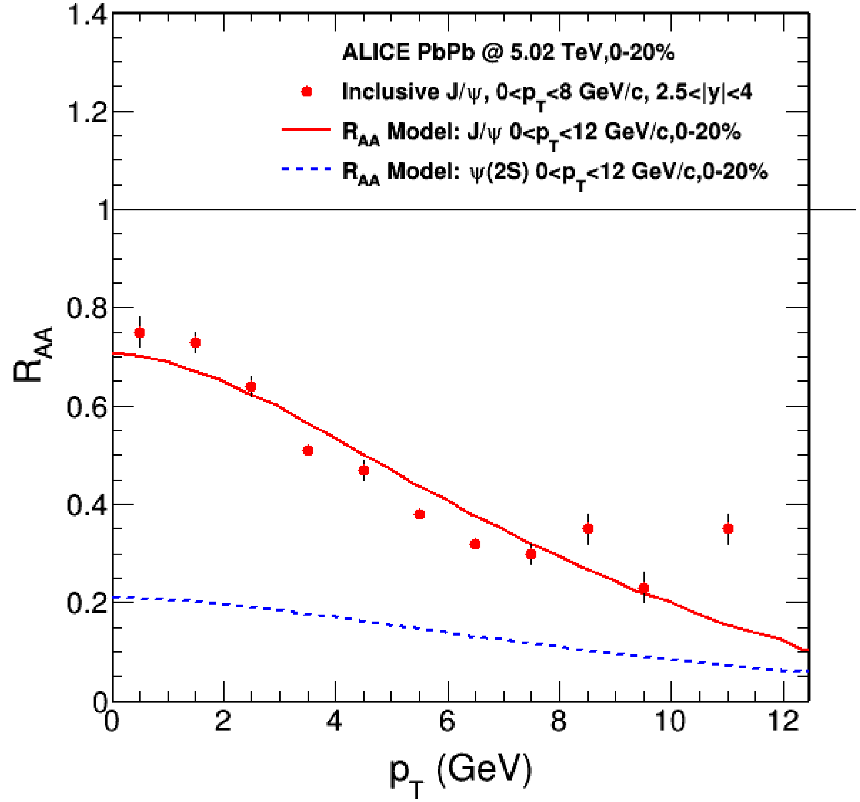
- The total survival probability of the charmonium in the medium is the combined effect of all mechanisms.

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

Nuclear Modification Factor- R_{AA}

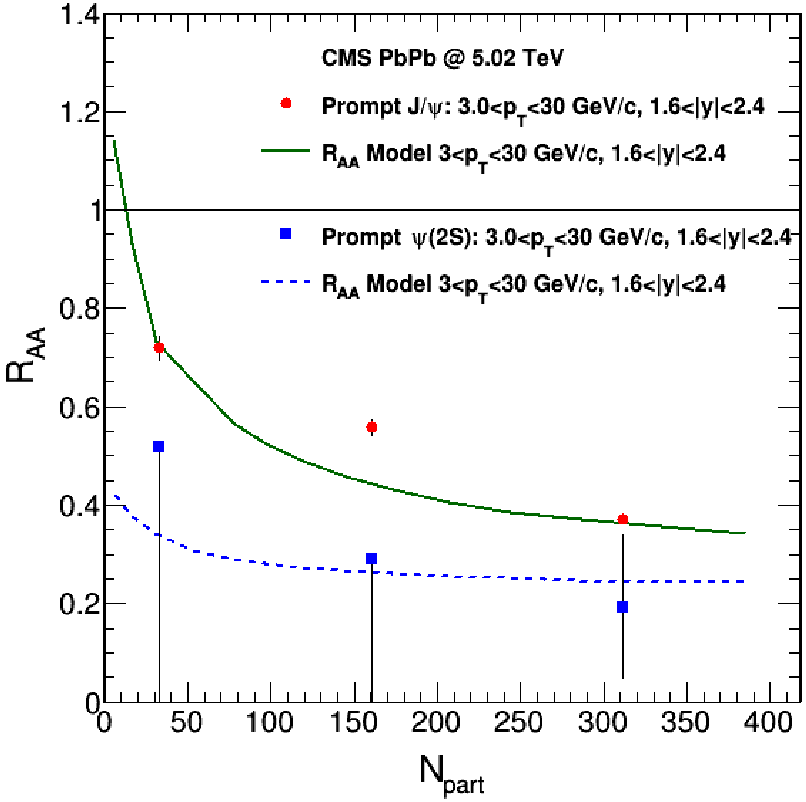
- The nuclear modification factor is obtained from survival probability taking into account the feed-down corrections

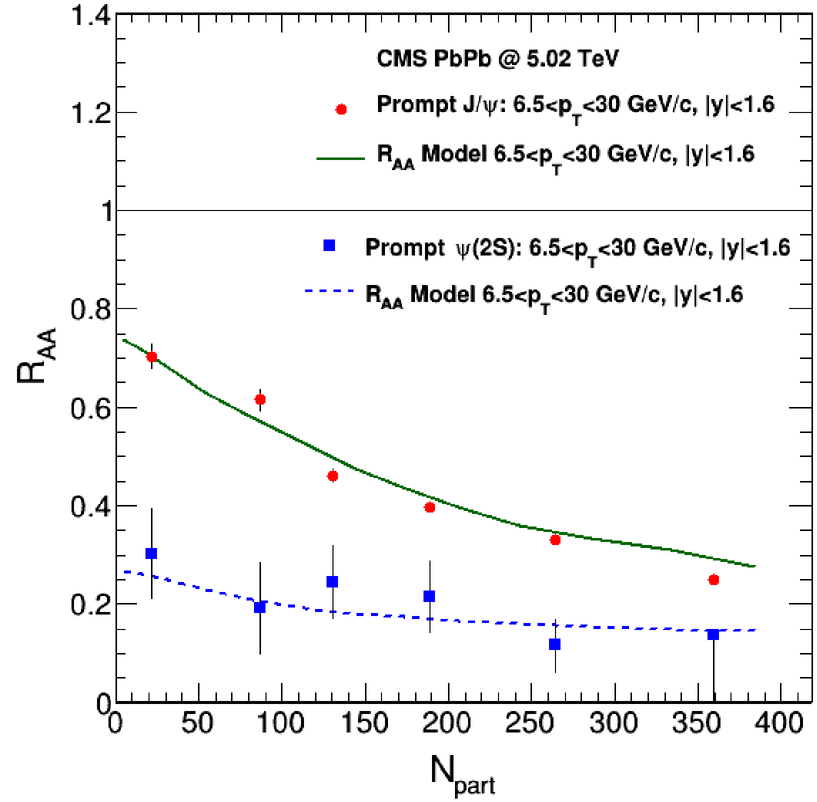




- The solid and dashed lines are the model calculations for in the respective pT regions.
- The model replicates the measured R_{AA} (Left-CMS, Right-ALICE) except in last bin, may be because of less energy loss of high pT charmonia.

Nuclear Modification Factor- R_{AA}



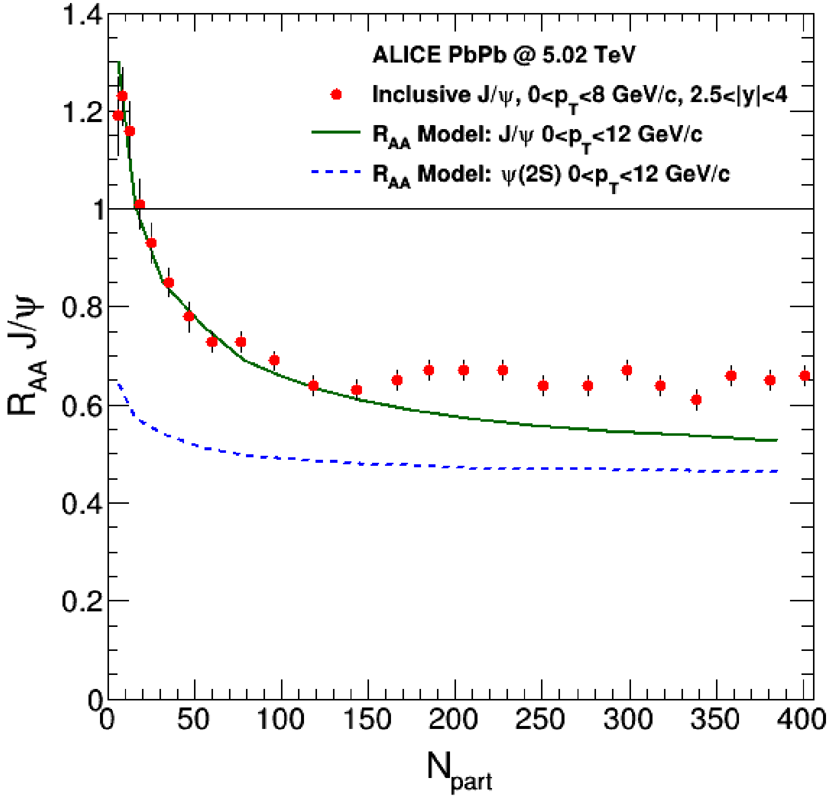


The model reproduces well the measured nuclear modification factors (CMS Experiment) of both J/ψ and ψ(2S)in all centralities.

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.

Summary

- ✓ We have studied Quarkonia 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.

- ✓ In this presentation, only the results from Charmonium measurements are discussed.

- ✓ The study on Bottomonium suppression is underway.

Thank you

This study is published in NPA:

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

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:

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

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

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

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