Quarkonium Production/Suppression in Heavy-ion Collision: A Theoretical Overview

M. Mishra

Department of Physics
Birla Institute of Technology and Science - Pilani

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Motivation

- The quarkonia production/suppression: study the formation and properties of QGP in $p-p$, $p-A$ and A−A collisions.
- Since it is produced during the initial stage of hard collisions and thus have exposure of almost whole evolution period of the medium.
- Due to its large mass scale, NRQCD and other comparatively simpler non-relativistic formulations can safely be utilized.
- A precise estimate of its production in $p-p$ and $p-A$ is needed in order to use it as a potential signature for QGP formation in $A-A$ collision.
- Bottomonium suppression is thought to be cleaner probe: Very less production of secondary $b\bar{b}$ pairs are the cause of negligible regeneration of bottomonia in QGP.
- Various production (p−p collision) and suppression mechanisms (p−Pb and Pb−Pb etc.) have been proposed in the literature.

Production in p−p collision

- Both perturbative and non-perturbative aspects.
- Understanding the production $p - p$ collision helps us in understanding the medium properties formed in nucleus−nucleus collisions. Such as possible medium thermalization, interaction etc.
- Various aspects of QCD (perturbative as well as non-perturbative).
- In nucleus-nucleus collisions, open and hidden heavy-flavour productions constitute sensitive probes of the hot strongly-interacting medium.
- Effects, present in proton-nucleus collisions, can modify the production of heavy quarks in nuclear collisions with respect to proton-proton collisions without invoking the creation of a QGP. These effects are called as CNM effects.
- Theoretical approaches: Color−Singlet Model (CSM), Color−Octet Model (COM): NRQCD effective theory, Color−Evaporation Model (CEM), k_T factorization approach

- CSM, the first model, relies on assumption: quantum state of pair does not evolve during its production to hadronization.
- The partonic cross section for quarkonium production is associated to the production of a heavy−quark pair with zero relative velocity v in a colour−singlet state and in the same angular momentum and spin state as that of the to be produced quarkonium.
- NRQCD factorization approach is the most successful; in agreement with most of the inclusive production data; polarized production is still a CHALLENGE!!
- Predictions of the color-singlet model fail to describe the data

Quarkonium Production in p−Pb collisions

- Used to quantify CNM effect which is present in $p-A$ and $A-A$ collisions.
- Nuclear PDFs (Shadowing), gluon saturation in low-x regime (CGC), Cronin effect
- Parton energy loss: elastic scattering while moving through the nucleus before hard scattering.
- Nuclear absorption: Dissociation of bound states while passing through nucleus.
- Co-mover absorption: Hadrons propagating together with the quarkonium interact with it and get killed.
- Cronin effect: broadening of p_T spectra due to $N-N$ interactions in nucleus.
- Nuclear parton distribution function; npdf, pdf. ratio is $R_i(x, Q^2)$. $R_i < 1$ for $x < 10^{-2}$: shadowing; Production decreases; quarkonium suppression
- $R_i > 1$, for $10^{-2} < x < 10^{-1}$; anti-shadowing; production increases; quarkonium enhancement.

The Shadowing Effect

Bjorken x for Υ(1S)

Ballpark estimate for $g + g \rightarrow \Upsilon(1s)$

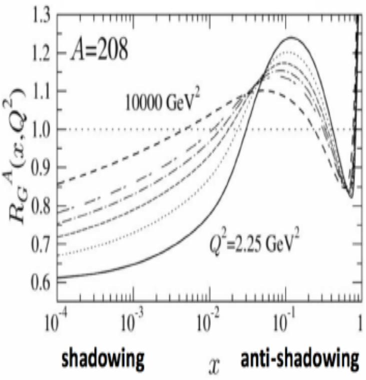
$$x_{1,2} = \frac{M}{\sqrt{s_{NN}}} e^{\pm y_{CM}}$$

p going

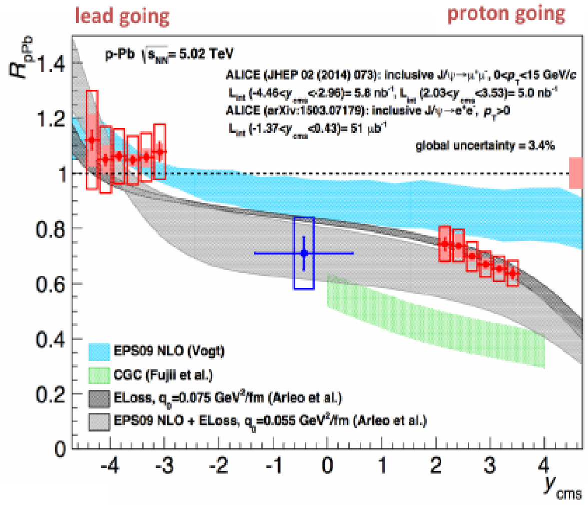
$5 \times 10^{-5} < x < 2 \times 10^{-4} \rightarrow$ shadowing

Pb going

$4 \times 10^{-2} < x < 2 \times 10^{-1} \rightarrow$ anti-shadowing



The Shadowing Effect



Quarkonium Production in $A - A$ collisions

- Why heavy quarkonia in $A - A$ collisions ?
- Ground state charmonium and bottomonium have vacuum binding energies of the order of 0.51.0 GeV implying formation times that are less than $0.5 fm/c$.
- Quarkonia are heavier than the QGP temperature; therefore, its thermal production is strongly suppressed.
- From a theoretical perspective, one can make use of heavy quark effective theory to approach the problem systematically both in vacuum as well as at finite T.

Heavy Quarkonium Suppression Mechanisms

- QGP at high temperature : Debye color screening analogous to the charged Debye screening in QED plasma.
  E. V. Shuryak, Phys. Rept. 61, 71158 (1980)
  T. Matsui, and H. Satz, Phys. Lett. B178, 416 (1986)
  F. Karsch, M. T. Mehr, and H. Satz, Z. Phys. C37, 617 (1988)
- Coulombic type plus confining part of the potential between $Q\bar{Q}$ in vacuum.
- Confining part becomes almost negligible in the presence of high temp. QGP medium.
- Coulombic part with infinite range is converted into short range Yukawa type potential in QGP.
- With range of potential which is inversely proportional to the temperature of QGP.
- Thus beyond a certain temperature heavy quarkonium would no longer exist as bound state. This temperature is the dissociation temperature, T_D.

Heavy Quarkonium Suppression Mechanisms

- Dissociation temperature of quarkonium in medium can be estimated via potential model, lattice inspired potential model and Lattice QCD calculation.
- In potential model calculation, Schrodinger equation is solved with phenomenological potential or lattice inspired potential and energy eigen values are determined.
- Above energy eigen values are used to determine binding energies of the quarkonium as a function of temperature.
  S. Ganesh and M. Mishra, Phys. Rev. C 91, 034901 (2015)
- Temperature corresponding to zero binding energy would give us dissociation temperature.
- Lattice QCD physicists determine the same using spectral function/correlation function approach.

Heavy Quarkonium Suppression Mechanisms

- Laine et al., had employed thermal field theory approach to determine the potential between $Q\bar{Q}$ located inside QGP medium using Wilson loop technique.
- They found a complex potential where imaginary part of the potential give rise to the collisional or Landau damping.
- Real part of the potential is used in Schrodinger equation to determine dissociation temperature.
  $-\frac{1}{2\mu}\frac{\partial^{\psi}}{\partial r^2} + V(r, m_D)\psi + \frac{l(l+1)}{2\mu r^2}\psi = E_T(n, l)\psi$ gives the eigen value.
  Binding energy $E_{bind}(T) = E_T(n, l) - V[r = \infty, m_D(T)]$.
- survival probability of (or equivalently nuclear modification factor) of quarkonium is determined either by using Chu and Matsui framework or by using approach used in ref. []

Suppression due to Colour Screening: modified Chu and Matsui approach

- The colour screening model used in the present work is based on pressure profile in the transverse plane and cooling law for pressure based on QPM EOS for QGP.
  The cooling law for pressure is given by:

- $p(\tau, r) = A + \frac{B}{\tau^q} + \frac{C}{\tau} + \frac{D}{\tau^{c_s^2}}$;

  where $A = -c_1$, $B = c_2 c_s^2$, $C = \frac{4\eta q}{3(c_s^2 - 1)}$ and $D = c_3$.

- $c_1 = -c_2 \tau'^{-q} - \frac{4\eta}{3 c_s^2 \tau'}$; $c_2 = \frac{\epsilon_0 - \frac{4\eta}{3c_s^2}\left(\frac{1}{\tau_0} - \frac{1}{\tau'}\right)}{\tau_0^{-q} - \tau'^{-q}}$;

- $c_3 = (p_0 + c_1)\,\tau_0^{c_s^2} - c_2 c_s^2 \tau_0^{-1} - \frac{4\eta}{3}\left(\frac{q}{c_s^2 - 1}\right)\tau_0^{(c_s^2 - 1)}$

Suppression due to Colour Screening: Modified Chu and Matsui approach

- Using above cooling laws, we determine the screening radius (r).
- Survival of quarkonia due around screening radius (r) is obtained in the form of survival probability;

$$S_c(p_T, N_{part}) = \frac{2(\alpha+1)}{\pi R_T^2} \int_0^{R_T} dr\, r\, \phi_{max}(r) \left\{ 1 - \frac{r^2}{R_T^2} \right\}^{\alpha},$$

where $\alpha = 0.5$, R_T and ϕ_{max} (which is a function of p_t and r_s).

P. K. Srivastava, M. Mishra and C. P. Singh, Phys. Rev. C 87, 034903 (2013).

- Until the mid-2000s, Debye screening was thought to be the only possible mechanism for the anomalous suppression of charmonium and bottomonium in a QGP medium.
- The lower suppression at mid-rapidity than forward rapidity observed at the RHIC and also at LHC is in contradiction to the color-screening scenario.
- Because color screening predicts a larger suppression at a higher-density region of plasma which is actually the mid-rapidity: Hints other suppression mechanisms to play role
- The same amount of charmonium suppression at SPS and RHIC energies for the same number of participants. Although the available energy spans over two orders of magnitude in moving from the CERN SPS to the LHC: Hints for recombination
- In $d - Au$ collision at RHIC, suppression is observed at forward rapidity (in the d-going direction) and an enhancement at backward rapidity (in the Au-going direction)
- All above experimental observations suggest that the charmonium suppression in QCD plasma is not the result of a single mechanism but is a complex interplay of various physical processes.

- The imaginary part of the potential between $Q\bar{Q}$, in the limit of $t \to \infty$, represents the thermal decay width induced by Landau damping of the low-frequency gauge fields that mediate interactions between two heavy quarks.
  M. Laine, O. Philipsen, P. Romatschke, and M. Tassler, JHEP 03 (2007) 054.
- Collisional or Landau damping.
- The corresponding decay rate, Λ_{damp} is determined by using the imaginary part of the potential between $Q\bar{Q}$ and quarkonium singlet wave function.

Collisional Damping

- The singlet potential, we are using for quarkonia is given by:

$$V(r, m_D) = \frac{\sigma}{m_D}(1 - e^{-m_D\, r}) - \alpha_{eff}\left(m_D + \frac{e^{-m_D\, r}}{r}\right)$$
$$-i\alpha_{eff}\, T \int_0^\infty \frac{2\,z\,dz}{(1+z^2)^2}\left(1 - \frac{\sin(m_D\, r\, z)}{m_D\, r\, z}\right)$$

- Here, $m_D = T\sqrt{4\pi\alpha_s^T\left(\frac{N_c}{3} + \frac{N_f}{6}\right)}$; $\alpha_{eff} = \frac{4\alpha}{3} = (4/3) \times 0.22$; $N_f = 3$; $\alpha_s^T = 0.47$; $\sigma = 0.192\ GeV^2$.
- The collisional damping dissociation time constant is $\Gamma_{damp} = \int [g_{nl}(r)^\dagger\, [Im(V)]\, g_{nl}(r)] dr$.

Heavy Quarkonium Suppression Mechanisms: Gluonic Dissociation

- Brambilla et al.: thermal width can also originates from singlet-to-octet transition of heavy meson resonance due to gluonic interaction apart from the imaginary part of the gluon self-energy. N. Brambilla, J. Ghiglieri, A. Vairo, and P. Petreczky, Phys. Rev. D 78, 014017 (2008).
- A singlet quarkonium absorbs a soft gluon and converted into color octet.
- Octet state then emits gluons and converted into unbound/dissociated $Q\bar{Q}$ pairs.
- Schrodinger equation is solved with the real part of the potential and octet potential.
- This gives singlet and octet wave functions.

- Gluonic dissociation cross-section is given as;

$$\sigma_{diss,nl}(E_g) = \frac{\pi^2 \alpha_s^u E_g}{N_c^2} \sqrt{\frac{m}{E_g + E_{nl}}} \left(\frac{l |J_{nl}^{q,l-1}|^2 + (l+1)|J_{nl}^{q,l+1}|^2}{2l+1} \right),$$

where, $\alpha_s^u = 0.59$; and $J_{nl}^{ql'} = \int_0^\infty dr r g_{nl}^*(r) h_{ql'}(r)$.

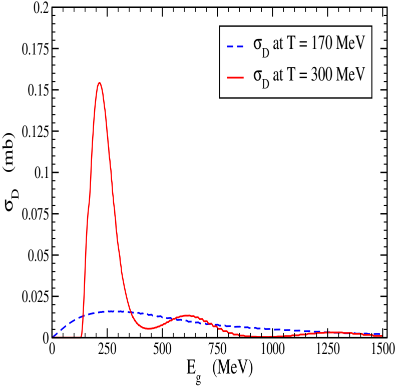
- Using the gluonic dissociation cross-section, the dissociation time constant $\Gamma_{gdiss,nl}$ can be written as;

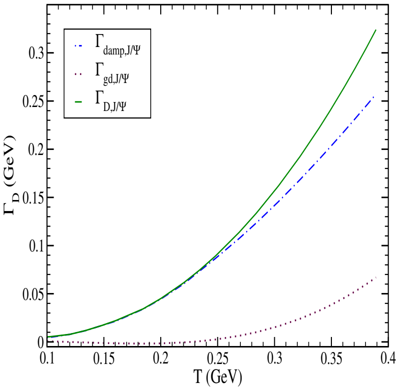
$$\Gamma_{gdiss,nl} = \frac{g_d}{2\pi^2} \int_0^\infty \frac{dp_g \, p_g^2 \sigma_{diss,nl}(E_g)}{e^{E_g/T} - 1} \; ; \; g_d = 16$$

- The total decay rate employing gluonic dissociation and collisional damping is $\Gamma_D = \Gamma_{damp} + \Gamma_{gdiss}$.

G. Wolschin et al., Phys. Rev. C 87, 024911 (2013).

Dissociation Factor Γ_D





Regeneration due to Gluonic De-excitation: regeneration due to correlated $Q\bar{Q}$ pairs

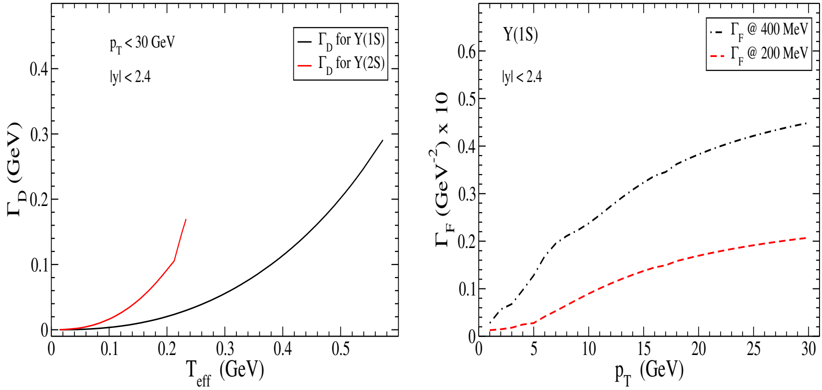
- *Regeneration:* $\Rightarrow$ Formation of Υ due to correlated $Q\bar{Q}$ pair transition from color octet to color singlet state.
- Recombination factor, $\Gamma_{F,nl}$;

$$\Gamma_{F,nl} = \frac{\int_{p_{b,min}}^{p_{b,max}} \int_{p_{\bar{b},min}}^{p_{\bar{b},max}} dp_b \; dp_{\bar{b}} \; p_b^2 \; p_{\bar{b}}^2 \; f_b \; f_{\bar{b}} \; \sigma_{f,nl} \; v_{rel}}{\int_{p_{b,min}}^{p_{b,max}} \int_{p_{\bar{b},min}}^{p_{\bar{b},max}} dp_b \; dp_{\bar{b}} \; p_b^2 \; p_{\bar{b}}^2 \; f_b \; f_{\bar{b}}}$$

- The recombination cross section $\sigma_{f,nl}$:

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

Dissociation Factor Γ_D Vs T_{eff} and Regeneration Factor Γ_F Vs p_T



Regeneration: regeneration due to uncorrelated $Q\bar{Q}$ pairs

- If the population of $Q\bar{Q}$ is high enough, then it is possible for quarkonia to be regenerated through recombination of $Q\bar{Q}$ pairs. There can also be local re-formation of an individual bound state due to medium interactions.
- Reliable $p - p$ reference: Experimental measurements rely on R_{AA}, which is defined relative to the $p - p$ cross-section; therefore, we need reliable $p - p$ reference data and a firm theoretical understanding of open and closed charm/bottom production in $p - p$ collisions.

Quarkonium Transport in QGP Medium

- We model suppression and recombination processes using the rate equations;

$$\frac{dN_{\Upsilon(nl)}}{d\tau} = \Gamma_{F,nl} N_b \; N_{\bar{b}} \; [V(\tau)]^{-1} - \Gamma_{D,nl} N_{\Upsilon(nl)}$$

- This transport equation is solvable analytically under the assumption of $N_{\Upsilon}(nl) < N_{b\bar{b}}$ at τ_0:

$$N_{\Upsilon(nl)} \; = \; \epsilon(\tau_{QGP}) \left[N_{\Upsilon(nl)}(\tau_0) + N_{b\bar{b}}^2 \int_{\tau_0}^{\tau_{QGP}} \Gamma_{F,nl}(\tau) [V(\tau)\epsilon(\tau)]^{-1} d\tau \right]$$

Captain R. Singh et al., Phy. Rev. C 92, 034916 (2015).

CNM Effect

- We use the *EPS09* parametrization to obtain the shadowing $S^i(A, x, \mu)$ for nucleus with mass A, momentum fraction x and scale μ.

$$S^i_\rho(A, x, \mu, \vec{r}) = 1 + N_\rho(S^i(A, x, \mu) - 1)\frac{\int dz \rho_A(\vec{r}, z)}{\int dz \rho_A(0, z)}$$

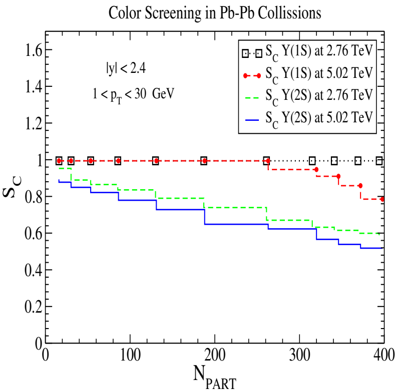
where N_ρ is determined by the following normalization condition:
$\frac{1}{A}\int d^2 r dz \rho_A(s) S^i_\rho(A, x, \mu, \vec{r}) = S^i(A, x, \mu)$

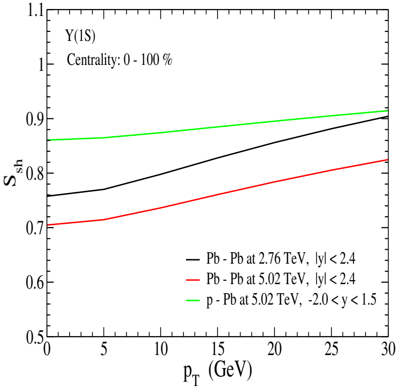
- The suppression factor due to CNM effect is thus determined by,

$$S_{sh} = R_{AB}(N_{part}; b) = \frac{d\sigma_{AB}/dy}{T_{AB}(b) d\sigma_{pp}/dy}$$

R. Vogt, Phys. Report. 197, 310 (1999).

Color Screening Survival Probability S_c Vs N_{PART} and Shadowing Factor S_{sh} Vs p_T





Net Survival Probability, S_P

- The net production of Υs includes hot and cold nuclear matter effects.
- The initially suppressed Υs due to shadowing effect is given as;

$$N^{i}_{\Upsilon(nl)}(\tau_0, p_T, b) = N_{\Upsilon(nl)}(\tau_0, b)\; S_{sh}(p_T, b)$$

- Now solution of transport Eq. can be written as:

$$N^{f}_{\Upsilon(nl)} = \epsilon(\tau_{QGP})\left[N^{i}_{\Upsilon(nl)}(\tau_0) + N^2_{b\bar{b}}\int_{\tau_0}^{\tau_{QGP}} \Gamma_{F,nl}(\tau)[V(\tau, b)\epsilon(\tau)]^{-1} d\tau\right]$$

- The survival probability due to shadowing, gluonic dissociation along with the collisional damping and recombination is defined as;

$$S^{\Upsilon}_{gd}(p_T, b) = \frac{N^{f}_{\Upsilon(nl)}(p_T, b)}{N_{\Upsilon(nl)}(\tau_0, b)}$$

The net yield obtained after color screening of survival probability (S_c);

$$S_P(p_T, b) = S^{\Upsilon}_{gd}(p_T, b)\; S^{\Upsilon}_{c}(p_T, b).$$

Vacuum or temperature dependent formation times of heavy flavour bound states

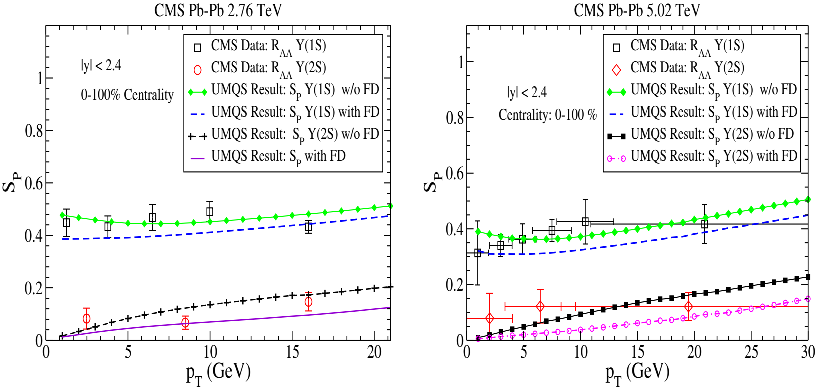
- Formation time is an important quantity used in the above calculations.
- It is time taken to form bound states from $Q\bar{Q}$ pairs formed due to initial stage hard collisions.
- Vacuum formation time (i.e., at $T = 0$) has been employed in various theoretical model calculations.
- It seems more logical to use medium temperature dependent formation time instead of vacuum formation times.
- Two methods (based on the solution of time independent and time dependent Schrodinger equation) for the same have been described in ref. S. Ganesh and M. Mishra, Phys. Rev. C 91, 034901 (2015).
- Surprisingly, these formation times are coming quite large as compared to the corresponding vacuum formation time !! need further study to reach any firm conclusion.

Feed-down from higher resonances

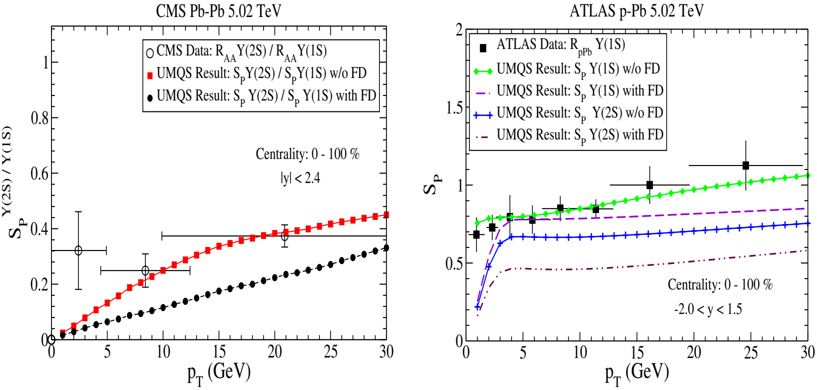
- Feed-down of $\chi_b(2P)$ and $\Upsilon(3S)$ into $\Upsilon(2S)$, effectively suppress its production. Feed-down fractions for $\Upsilon(2S)$, we have considered that $\sim$ 65% of $\Upsilon(2S)$ come up by direct production whereas $\sim$ 30% is from the decay of $\chi_b(2P)$ and $\sim$ 5% is from the decay of $\Upsilon(3S)$.
- Similarly, feed-down for $\Upsilon(1S)$ is obtained by considering that $\sim$ 68% of $\Upsilon(1S)$ come up by direct production whereas $\sim$ 17% is from the decay of $\chi_b(1P)$ and $\sim$ 9% is from the decay of $\Upsilon(2S)$. The feed-down of $\chi_b(2P)$ and $\Upsilon(3S)$ into $\Upsilon(1S)$ is taken as $\sim$ 5% and $\sim$ 1%, respectively.
- The $\Upsilon(1S)$ yield of a mixed system after incorporating feed-down correction is expressed as;

$$S_P^f = \frac{0.68\ N_{\Upsilon(1S)}\ S_P^{\Upsilon(1S)} + 0.17\ N_{\chi_b(1P)} S_P^{\chi_b(1P)} + 0.086\ N_{\Upsilon(2S)}\ S_P^{\Upsilon(2S)} + 0.051\ N_{\chi_b(2P)} S_P^{\chi_b(2P)} + 0.01\ N_{\Upsilon(3S)}\ S_P^{\Upsilon(3S)}}{0.65\ N_{\Upsilon(1S)} + 0.15\ N_{\chi_b(1P)} + 0.20\ N_{\Upsilon(2S)} + 0.051\ N_{\chi_b(2P)} + 0.01\ N_{\Upsilon(3S)}}$$

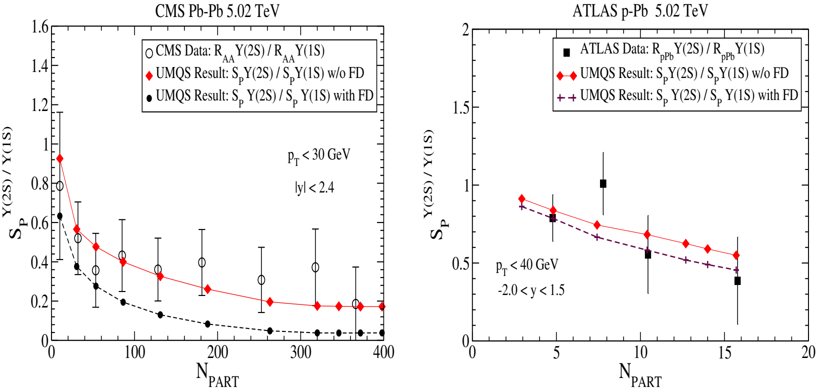
R_{AA} against Transverse momentum p_T



R_{AA} against Transverse momentum p_T



R_{AA} against Centrality



Summary & Conclusions

- Bottomonium/charmonium suppression is the combined effect of hot (QGP) and cold nuclear matters.
- Even after completing around 40 years of discovery of J/ψ (in 1974), its production mechanism is still not a closed topic.
- For charmonium, CNM effects are important in order to explain $A-A$ suppression data.
- For charmonium, at LHC energies, we find signs of regeneration for $p_T < 4-5$ GeV; to see suppression directly, we should apply $p_T > 5$ GeV.
- For $\Upsilon(1S)$, regeneration is not so important but can be included.
- For $\Upsilon(1S)$, CNM cannot generate large suppression.
- Complex screening model works reasonably well to describe suppression seen at LHC and RHIC.

Acknowledgment

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Thank you