Upsilon 1S and 2S suppression in p–Pb and Pb–Pb collisions at LHC: Centrality and Transverse Momentum Dependence

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Motivation

- The quarkonia suppression is a key signature to study the formation of QGP in A–A collisions.

- Bottomonium suppression is thought to be cleaner probe: Very less production of secondary $b\bar{b}$ pairs are the cause of negligible regeneration of bottomona in QGP.

- However, a precise estimate of bottomonium suppression needs to incorporate recombination due to correlated $b – \bar{b}$ pairs.

- Old predictions and observations; no QGP in p–A collisions, thought to be an important probe to explain CNM effects. But recent p–Pb collisions data at LHC show “collectivity”, a probable QGP.

- Present work, is based on the our research work: Captain R. Singh et al., arXiv:1802.09918v2.
Bottomonium Transport in QGP Medium

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

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

• This transport equation is solvable analytically under the assumption of \( N_{\Upsilon(nl)} < N_{b\bar{b}} \) at \( \tau_0 \):

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

Collisional Damping

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

\[ V(r, m_D) = \frac{\sigma}{m_D} (1 - e^{-m_D r}) - \alpha_{\text{eff}} \left( m_D + \frac{e^{-m_D r}}{r} \right) \]

\[ -i \alpha_{\text{eff}} T \int_0^\infty \frac{2 z dz}{(1 + z^2)^2} \left( 1 - \frac{\sin(m_D r z)}{m_D r z} \right) \]

- Here, \( m_D = T \sqrt{4\pi \alpha_s^T \left( \frac{N_c}{3} + \frac{N_f}{6} \right)} \); \( \alpha_{\text{eff}} = \frac{4\alpha_s}{3} = (4/3) \times 0.22 \); \( N_f = 3 \); \( \alpha_s^T = 0.47 \); \( \sigma = 0.192 \text{ GeV}^2 \).

- The collisional damping dissociation time constant is

\[ \Gamma_{\text{damp}} = \int [\psi^\dagger [\text{Im}(V)] \psi] dr. \]
Gluonic Dissociation

- Gluonic dissociation cross section is given as:

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

where, \( \alpha_s^u = 0.59 \); and \( J^{q,l'}_{nl} = \int_0^\infty dr r g^*_{nl}(r) h_{ql'}(r) \).

- Using the gluonic dissociation cross section, the dissociation time constant \( \Gamma_{\text{gdiss},nl} \) can be written as:

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

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

Regeneration due to Gluonic De-excitation

- **Regeneration:** $\Rightarrow$ Formation of $\Upsilon$ due to correlated $q\bar{q}$ pair transition from color octet to color singlet state.

- Recombination factor, $\Gamma_{F,nl}$:

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

- 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 $\Gamma_D$ Vs $T_{\text{eff}}$ and Regeneration Factor $\Gamma_F$ Vs $p_T$

$p_T < 30$ GeV

$|y| < 2.4$

$\Gamma_D$ for $\Upsilon(1S)$

$\Gamma_D$ for $\Upsilon(2S)$

$\Gamma_D$ for $\Upsilon(1S)$

$\Gamma_D$ for $\Upsilon(2S)$

$\Gamma_F$ at 400 MeV

$\Gamma_F$ at 200 MeV

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Suppression due to Colour Screening

- 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 \( D = c_3 \).

- \( c_1 = -c_2 \tau' - q - \frac{4\eta q}{3c_s^2 \tau'} \); \( c_2 = \frac{c_0 - \frac{4\eta q}{3c_s^2}}{\frac{1}{\tau_0} - \frac{1}{\tau'}} \);

- \( c_3 = (p_0 + c_1) \tau_0 c_s^2 - c_2 c_s^2 \tau_0^{-1} - \frac{4\eta q}{3} \left( \frac{q}{c_s^2 - 1} \right) \tau_0 (c_s^2 - 1) \)
Suppression due to Colour Screening

- 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 \( \phi_{\max} \) (which is a function of \( p_t \) and \( r_s \)).

We use the EPS09 parametrization to obtain the shadowing $S_i(A, x, \mu)$ for nucleus with mass $A$, momentum fraction $x$ and scale $\mu$.

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

where $N_{\rho}$ is determined by the following normalization condition:

$$\frac{1}{A} \int d^2 rdz \rho_A(s) S_i^\rho(A, x, \mu, \vec{r}) = S_i(A, x, \mu)$$

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

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

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 $\Upsilon$s includes hot and cold nuclear matter effects.
- The initially suppressed $\Upsilon$s due to shadowing effect is given as:

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

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

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

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

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

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

$$S_P(p_T, b) = S_{gd}^\Upsilon(p_T, b) \cdot S_c^\Upsilon(p_T, b).$$
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:

$$S_f^{\Upsilon(1S)} = 0.68 \frac{N_{\Upsilon(1S)} S_P^{\Upsilon(1S)} + 0.17 N_{\chi_b(1P)} S_P^{\chi_b(1P)} + 0.086 N_{\Upsilon(2S)} S_P^{\Upsilon(2S)} + 0.051 N_{\chi_b(2P)} S_P^{\chi_b(2P)} + 0.01 N_{\Upsilon(3S)} S_P^{\Upsilon(3S)}}{0.65 N_{\Upsilon(1S)} + 0.15 N_{\chi_b(1P)} + 0.20 N_{\Upsilon(2S)} + 0.051 N_{\chi_b(2P)} + 0.01 N_{\Upsilon(3S)}}$$
$R_{AA}$ against Transverse momentum $p_T$

CMS Pb-Pb 2.76 TeV

CMS Pb-Pb 5.02 TeV

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\( R_{AA} \) against Transverse momentum \( p_T \)

**Results**

CMS Pb-Pb 5.02 TeV

- CMS Data: \( R_{AA} Y(2S) / R_{AA} Y(1S) \)
- UMQS Result: \( S_p Y(2S) / S_p Y(1S) \) w/o FD
- UMQS Result: \( S_p Y(2S) / S_p Y(1S) \) with FD

ATLAS p-Pb 5.02 TeV

- ATLAS Data: \( R_{pPb} Y(1S) \)
- UMQS Result: \( S_p Y(1S) \) w/o FD
- UMQS Result: \( S_p Y(1S) \) with FD
- UMQS Result: \( S_p Y(2S) \) w/o FD
- UMQS Result: \( S_p Y(2S) \) with FD

Centrality: 0 - 100 %

- CMS Pb-Pb: \(|y| < 2.4\)
- ATLAS p-Pb: \(-2.0 < y < 1.5\)
$R_{AA}$ against Centrality

CMS Pb-Pb 5.02 TeV

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<th>$S_p Y(2S)/Y(1S)$</th>
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CMS Data: $R_{AA} Y(2S)/R_{AA} Y(1S)$
- UMQS Result: $S_p Y(2S)/S_p Y(1S)$ w/o FD
- UMQS Result: $S_p Y(2S)/S_p Y(1S)$ with FD

$|y| < 2.4$
$p_T < 30 \text{ GeV}$

ATLAS p-Pb 5.02 TeV

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ATLAS Data: $R_{pPb} Y(2S)/R_{pPb} Y(1S)$
- UMQS Result: $S_p Y(2S)/S_p Y(1S)$ w/o FD
- UMQS Result: $S_p Y(2S)/S_p Y(1S)$ with FD

$p_T < 40 \text{ GeV}$
$-2.0 < y < 1.5$
Summary & Conclusions

- Outcomes of our model show that the bottomonium suppression is the combined effect of hot and cold nuclear matters.

- The color screening effect is almost insignificant to suppress the $\Upsilon(1S)$ production while it significantly suppressed $\Upsilon(2S)$ production in Pb–Pb and p–Pb collisions at all the LHC energies.

- The gluonic dissociation along with the collisional damping mechanisms play an important role in $\Upsilon(1S)$ and $\Upsilon(2S)$ in Pb–Pb and p–Pb collisions. Our model suggests a effective regeneration of $\Upsilon(1S)$ in Pb–Pb at $\sqrt{s_{NN}} = 2.76$ & 5.02 TeV.

- QGP formation in p–Pb collision clearly explained by $\Upsilon(1S)$ suppression are around unity with large uncertainty and no direct experimental results are available for $\Upsilon(2S)$ suppression. However, an indirect experimental information of $\Upsilon(2S)$ suppression is available in the form of double ratio. Our model predicted the $\Upsilon(2S)$ suppression in p–Pb collisions.
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