Upsilon suppression in heavy-ion collisions at LHC energies

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Topics

1. Introduction: Υ(nS) in pp and PbPb @ LHC
2. Screening, gluodissociation and damping of the Υ(nS) and χ_b(nP) states
3. Feed-down cascade including χ_b(1P) and χ_b(2P) states
4. Comparison with CMS data
5. Conclusion
1. Introduction: Y in PbPb @ LHC

Y suppression as a sensitive probe for the QGP

- No significant effect of regeneration
- $m_b \approx 3m_c$ cleaner theoretical treatment
- More stable than $J/\psi$

$E_B(Y_{1S}) \approx 1.10$ GeV
$E_B(J/\psi) \approx 0.64$ GeV

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 2.76$ TeV
$\mathcal{L}_{int} = 7.28 \mu b^{-1}$


Quark_Confinement_2012
**Y(nS) states are suppressed in PbPb @ LHC:**

A clear QGP indicator

1. \(Y(1S)\) ground state is suppressed in PbPb:
   \[ R_{AA}(1S) \approx 0.56 \text{ in min. bias} \]

2. \(Y(2S, 3S)\) states are > 4 times stronger suppressed in PbPb than \(Y(1S)\)

\[ R_{AA}(Y(2S)) = 0.12 \pm 0.04 \text{ (stat.)} \pm 0.02 \text{ (syst.)} \]

\[ R_{AA}(Y(3S)) = 0.03 \pm 0.04 \text{ (stat.)} \pm 0.01 \text{ (syst.)} \]

CMS Collab., submitted to PRL; arXiv:1208.2826
[Plot from CERN Courier 52 No 7 (2012) 24]
Y and J/Psi suppression as function of centrality

G. Roland, CMS, QM 2012

Suppression anticorrelates with binding energy
2. Screening, Gluodissociation and Collisional broadening of the Y(nS) states

- Debye screening of all states involved: Static suppression

- Gluon-induced dissociation: dynamic suppression, in particular of the Y(1S) ground state due to the large thermal gluon density

- The imaginary part of the potential (effect of collisions) contributes to the broadening of the Y(nS) states: damping

- Feed-down from the excited Y states to the ground state substantially modifies the populations: indirect suppression
Screening and damping treated in a nonrel. potential model

\[ V(r, T) = \sigma r_D \left[ 1 - e^{-r/r_D} \right] - \frac{4\alpha_s^s}{3} \left[ \frac{1}{r_D} + \frac{1}{r} e^{-r/r_D} \right] \]

\[ -i \frac{4\alpha_s^s}{3} T \int_0^\infty dz \frac{2z}{(1 + z^2)^2} \left[ 1 - \frac{\sin(rz/r_D)}{(rz/r_D)} \right] \]

Screened potential: \( r_D \) Debye radius, \( \alpha_s^s \approx 0.37 \) the strong coupling constant at the soft scale \( \alpha_s^s = \alpha_s(m_b\alpha_s) \)
accounting for short-range Coulomb exchange,
\( \sigma \approx 0.192 \) the string tension (Jacobs et al.; Karsch et al.)

Imaginary part: Collisional damping (Laine et al. 2007, Beraudo et al. 2008)

\[ r_D^{-1} = T \left[ 4\pi \alpha_s (2N_c + N_f) / 6 \right]^{1/2} = m_D, \text{ Debye mass} \]
Radial wave functions of $\Upsilon(nS)$ states

From the numerical solution of the Schrödinger equation with complex potential $V(r)$

$$\left[2m - \frac{\Delta}{2\mu} + V(r) - M\right] \psi(\vec{r}) = 0$$

$\Upsilon(1S)$ groundstate very stable against screening for $T < 4.1 T_C$

Figure 1: (color online) Radial wave functions of the $\Upsilon(1S), (2S), (3S)$ states (solid, dotted, dashed curves, respectively) calculated in the complex screened potential eq.(1) for temperatures $T = 0$ MeV (bottom) and 170 MeV (top) with effective coupling constant $\alpha_{eff} \approx (4/3)\alpha_s = 0.49$, and string tension $\sigma = 0.192$ GeV$^2$. The rms radii $<r^2>^{1/2}$ of the $2S$ and, in particular, $3S$ state strongly depend on temperature $T$, whereas the ground state remains nearly unchanged.

Cross section for gluodissociation

Born amplitude for the interaction of gluon clusters according to Bhanot & Peskin in dipole approximation / Operator product expansion

\[ \mathcal{M} = \frac{14 \pi \alpha_s}{2} \frac{E^2}{3} \left( \frac{1}{H_8 + \epsilon - E} + \frac{1}{H_8 + \epsilon + E} \right) \bar{r} |\psi\rangle \]

The cross section is obtained via the optical theorem from the forward scattering amplitude

\[ \Im \mathcal{M}(t = 0) = E \sigma \]

\[ \sigma = \frac{1}{E} \cdot \frac{14 \pi \alpha_s}{2} \frac{E^2}{3} \langle \psi | \bar{r} \pi \delta (H_8 + \epsilon - E) \bar{r} |\psi\rangle \]

\[ = \frac{2 \pi^2 \alpha_s E}{9} \langle \psi | \bar{r} \delta (H_8 + \epsilon - E) \bar{r} |\psi\rangle. \]

Gluodissociation cross section in leading order, with coulombic wfct
Insert a complete set of eigenstates \( |\chi_k\rangle \) of the adjoint repulsive (octet) Hamiltonian with eigenvalues \( k^2/m \) to consider also the string part of the potential:

\[
\sigma = \frac{2\pi^2\alpha_s E}{9} \int_0^\infty dk \delta \left( \frac{k^2}{m} + \epsilon - E \right) \left| \int d^3x \bar{\psi}(\vec{r}) \chi_k(\vec{r}) \right|^2
\]

which yields an expression that can be extended to include the screened rather than the coulombic eigenfunctions

\[
\sigma_{diss}^{nS}(E) = \frac{2\pi^2\alpha_s E}{9} \int_0^\infty dk \delta \left( \frac{k^2}{m_b} + \epsilon_n - E \right) |w^{nS}(k)|^2
\]

\[
w^{nS}(k) = \int_0^\infty dr \ r \ g_{n0}^s(r) g_{k1}^a(r)
\]

for the Gluodissociation cross section.
Cross section results singlet to octet, coulombic wfct

\[
\sigma_{1S} = \frac{289\pi^2}{12} \sqrt{\frac{m}{\epsilon}} \frac{1}{m^2} \frac{q_1^2 + \frac{1}{64}}{(1 + q_1^2)^5} \exp\left[\arctan(q_1)/(2q_1)\right] \exp\left[\pi/(4q_1)\right] - 1
\]

\[
q_n = \sqrt{\frac{E}{\epsilon_n} - 1}
\]

\[
\sigma_{2S} = \frac{6889\pi^2}{6} \sqrt{\frac{m}{\epsilon}} \frac{1}{m^2} \frac{q_2^2 + \frac{1}{16}}{(1 + q_2^2)^7} \left(1 - \frac{34}{83} q_2^2\right)^2 \exp\left[\arctan(q_2)/q_2\right] \exp\left[\pi/(2q_2)\right] - 1
\]

\[
\sigma_{3S} = \left(\frac{7743\pi}{16}\right)^2 \sqrt{\frac{m}{\epsilon}} \frac{1}{m^2} \frac{q_3^2 + \frac{9}{64}}{(1 + q_3^2)^9} \left(1 - \frac{2996}{2581} q_3^2 + \frac{408}{2581} q_3^4\right)^2 \exp\left[3\arctan(q_3)/(2q_3)\right] \exp\left[3\pi/(4q_3)\right] - 1
\]

\[
z_n = \frac{n}{4q_n}
\]

For \(z_n \rightarrow 0\) the expression by Bhanot&Peskin results

\[
\sigma_P = \frac{256\pi}{3} \sqrt{\frac{m}{\epsilon}} \frac{1}{m^2} \frac{q_1^3}{(1 + q_1^2)^5}
\]

For 1S etc.

\(Y(1S)\) result agrees with effective field theory: Brambilla, Escobedo, Ghiglieri, Vairo

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Figure 2: (color online) Gluodissociation cross sections $\sigma_{diss}(nS)$ in mb (lhs scale) of the $\Upsilon(1S)$ and $\Upsilon(2S)$ states calculated using the screened wave functions calculated from the complex potential eq. (1) for temperatures $T = 170$ (solid curves) and 250 MeV (dotted curves) as functions of the gluon energy $E_g$. The thermal gluon distribution (rhs scale, solid curve for $T = 170$ MeV, dotted for 250 MeV) is used to obtain the thermally averaged gluodissociation cross sections.

Thermally averaged gluodissociation cross sections

\[
< \sigma_{diss}^{nS} > = \frac{g_d}{2\pi^2 n_g} \int_0^\infty \sigma_{diss}^{nS}(E) \frac{p^2 dp}{\exp [E(p)/T] - 1}
\]

Table 1: Thermally averaged cross sections \( < \sigma_{diss}(nS) > \) in mb for the gluodissociation of the \( Y(1S), (2S), (3S) \) states at four different temperatures \( T \) and \( m_g = 0 \) in 2.76 TeV PbPb. The values include screening as described in the text; \( 2S \) and \( 3S \) states are screened completely at high \( T \).

<table>
<thead>
<tr>
<th>( T ) (MeV)</th>
<th>( &lt; \sigma_{diss}(1S) &gt; ) (mb)</th>
<th>( &lt; \sigma_{diss}(2S) &gt; ) (mb)</th>
<th>( &lt; \sigma_{diss}(3S) &gt; ) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>0.094</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>300</td>
<td>0.141</td>
<td>0.041</td>
<td>–</td>
</tr>
<tr>
<td>200</td>
<td>0.124</td>
<td>0.465</td>
<td>0.152</td>
</tr>
<tr>
<td>170</td>
<td>0.080</td>
<td>0.783</td>
<td>0.604</td>
</tr>
</tbody>
</table>

Gluodissociation width of the \( Y(nS) \) states: Cross section x gluon density
Collisional damping through imaginary potential

Due to the imaginary part in the complex Hamiltonian

\[ H_{1/8} = -\frac{\Delta_R}{4M} - \frac{\Delta r}{M} + V_{1/8}(r) \]

\[ V_{1/8} = C_{1/8}\left[ m_D + \frac{\exp(-m_D r)}{r} - iT\phi(m_D r) \right] \]

\[ \phi(x) = \int_{0}^{\infty} dz \frac{2z}{(1 + z^2)^2}\left[1 - \frac{\sin(xz)}{xz}\right] \]

the energy eigenvalues acquire a width \( \Gamma \)

\[ E_{n,l} \rightarrow E_{n,l} - \frac{i\Gamma_{n,l}}{2} \]

Laine et al. 2007; Beraudo et al. 2008
Collisional damping through imaginary potential

The energy eigenvalues acquire a width $\Gamma$ (MeV)

\[ E_{n,l} \rightarrow E_{n,l} - \frac{i\Gamma_{n,l}}{2} \]

J. Wahner, BSc thesis Heidelberg (2012)
Damping and gluodissociation width of the Y(nS) and $\chi_b(nP)$ states

- Gluodissociation and Collisional (damping) width are of the same order of magnitude
- Damping becomes dominant at $T \geq 300$ MeV
- Since the excited states melt due to screening at high T, damping and gluodissociation are relevant for these states only at low temperature.

Y(1S) very stable wrt screening
Dynamical fireball evolution

Dependence of the local temperature $T$ on impact parameter $b$, time $t$, and transverse coordinates $x$, $y$:

$$T(b, t, x, y) = T_c \frac{T_{AA}(b, x, y)}{T_{AA}(0, 0, 0)} \left( \frac{V(0, t_{QGP})}{V(b, t)} \right)^{-1/4}$$

With the nuclear overlap (thickness function) $T_{AA}(b, x, y)$.

The number of produced $b\bar{b}$-pairs is proportional to the number of binary collision, and the nuclear overlap

$$N_{b\bar{b}}(b, x, y) \propto N_{\text{coll}}(b, x, y) \propto T_{AA}(b, x, y)$$

Preliminary suppression factor (without feed-down):

$$R_{AA}^{\text{prel}} = \frac{\int d^2b \int dx dy T_{AA}(b, x, y) e^{-\int_{t_F}^{\infty} dt \Gamma_{\text{tot}}(b, t, x, y)}}{\int d^2 b \int dx dy T_{AA}(b, x, y)}$$
Dynamical model for the expanding fireball with QGP lifetime $t_{QGP}$ and $Y$ formation time $t_F$ as free parameters; $v_z = 0.9c$, $v_x=v_y = 0.6c$

Scaled $Y(1S)$ population

Scaled $Y(2S)$ population

Maximum density

From: F. Nendzig, PhD thesis Heidelberg (forthcoming)
Relative initial populations in pp computed using an inverted cascade from the final populations measured by CMS and CDF ($\chi_b$)

$N_{\text{initial}}$ of $1S$ states:

- $\eta_b(1S)$: 0.458
- $\eta_b(2S)$: 0.371
- $\eta_b(3S)$: 0.387
- $\eta_b(4S)$: 0.976
- $\chi_{b1}(1P)$: 1.29
- $\chi_{b1}(2P)$
- $\chi_{b2}(1P)$
- $\chi_{b2}(2P)$

$N_{\text{initial}}$ of $2P$ states:

- $\gamma$: 2P: 0.976

$N_{\text{initial}}$ of $3S$ states:

- $\gamma$: 3S: 0.387

3. Feed-down cascade including $\chi_{1P}$ and $\chi_{2P}$ states
Feed-down cascade for hadronic and radiative transitions

Decay matrix for the five states involved

\[
D = \begin{pmatrix}
1 - M_{X \rightarrow 3S} & 0 & 0 & 0 & 0 \\
M_{2P \rightarrow 3S} & 1 - M_{X \rightarrow 2P} & 0 & 0 & 0 \\
M_{2S \rightarrow 3S} & M_{2S \rightarrow 2P} & 1 - M_{X \rightarrow 2S} & 0 & 0 \\
M_{1P \rightarrow 3S} & M_{1P \rightarrow 2P} & M_{1P \rightarrow 2S} & 1 - M_{X \rightarrow 1P} & 0 \\
M_{1S \rightarrow 3S} & M_{1S \rightarrow 2P} & M_{1S \rightarrow 2S} & M_{1S \rightarrow 1P} & 1 - M_{X \rightarrow 1S}
\end{pmatrix}
\]

with

\[
M_{X \rightarrow 3S} = M_{2P \rightarrow 3S} + M_{2S \rightarrow 3S} + M_{1P \rightarrow 3S} + M_{1S \rightarrow 3S},
\]

\[
M_{X \rightarrow 2P} = M_{2S \rightarrow 2P} + M_{1P \rightarrow 2P} + M_{1S \rightarrow 2P},
\]

\[
M_{X \rightarrow 2S} = M_{1P \rightarrow 2S} + M_{1S \rightarrow 2S},
\]

\[
M_{X \rightarrow 1P} = M_{1S \rightarrow 1P},
\]

\[
M_{X \rightarrow 1S} = 0.
\]

(use a cumulative decay matrix \( C \) since multiple decays may occur before detection of the states)

Calculate final from initial population vector

\[
\mathbf{P}_{\text{final}} = C \mathbf{P}_{\text{initial}}.
\]
4. Comparison with CMS min. bias data

TABLE II. Calculated minimum bias results for different $t_{\text{QGP}}$ and $t_{\text{F}}$ from Set 2 of Table I compared to the CMS results [12] with statistical and systematic error bars, respectively. While the $R_{AA}(1S)$ is in good agreement with experiment, results for the excited states allow for additional suppression mechanisms.

<table>
<thead>
<tr>
<th>$t_{\text{QGP}}$ (fm/$c$)</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>CMS data [12]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{AA}(1S)$</td>
<td>0.56</td>
<td>0.49</td>
<td>0.43</td>
<td>0.56 ± 0.08 ± 0.07</td>
</tr>
<tr>
<td>$R_{AA}(2S)$</td>
<td>0.37</td>
<td>0.30</td>
<td>0.27</td>
<td>0.12 ± 0.04 ± 0.02</td>
</tr>
<tr>
<td>$R_{AA}(3S)$</td>
<td>0.22</td>
<td>0.18</td>
<td>0.16</td>
<td>0.03 ± 0.04 ± 0.01</td>
</tr>
<tr>
<td>$(2S/1S)_{\text{PbPb}}$</td>
<td>0.66</td>
<td>0.63</td>
<td>0.62</td>
<td>0.21 ± 0.07 ± 0.02</td>
</tr>
<tr>
<td>$(2S/1S)_{pp}$</td>
<td>0.39</td>
<td>0.37</td>
<td>0.37</td>
<td>0.06 ± 0.06 ± 0.06</td>
</tr>
</tbody>
</table>

$R_{AA}(3S)_{pp}$: $0.56\pm0.08\pm0.07$

$R_{AA}(1S)=0.56\pm0.08\pm0.07$

Leaves room for additional suppression mechanisms in the excited states

$t_{\text{F}}$: Y formation time

$t_{\text{QGP}}$: QGP lifetime

Typical QGP temperatures at $t_{\text{F}}$: 200-800 MeV, with strong time dependence

$T_C = 170$ MeV

Dependence on Upsilon formation times and qgp lifetime (fm/c)

= T_{QGP}

Preliminary suppression factors for Υ(2S)
(= before feed-down)

<table>
<thead>
<tr>
<th>t_f</th>
<th>Υ(1S)</th>
<th>χ_b(1P)</th>
<th>Υ(2S)</th>
<th>χ_b(2P)</th>
<th>Υ(3S)</th>
<th>χ_b(3P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>0.05</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.005</td>
</tr>
<tr>
<td>Set 2</td>
<td>0.1</td>
<td>0.05</td>
<td>0.05</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Set 3</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.05</td>
<td>0.05</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Theoretical vs. exp. (CMS) Suppression factors

Consider

- Screening (potential model)
- Gluodissociation (OPE with string tension included)
- Collisional damping (imaginary part of potential)
- Feed-down from excited states

\[ t_F: \text{Y formation time} \]
\[ t_{QGP}: \text{QGP lifetime} \]
\[ T_{\text{max}} @ t_F: 200-800 \text{ MeV} \]

\[ \langle N_{\text{part}} \rangle \]

Leaves room for additional suppression mechanisms in particular, for the excited states.
5. Conclusion

- The suppression of the $Y(1S)$ ground state in PbPb collisions at LHC energies through gluodissociation, damping, reduced feed-down and screening has been calculated for min. bias, and as function of centrality, and is found to be in good agreement with the CMS result. Screening is not decisive for the 1S state except for central collisions.

- The enhanced suppression of the $Y(2S, 3S)$ relative to the 1S state in PbPb as compared to pp collisions at LHC energies (CMS) is consistent with the model within the (large) error bars for central collisions. There is room for additional suppression mechanisms, in particular for peripheral collisions where discrepancies to the CMS data persist. Screening is very relevant for the excited states.