Upsilon suppression in PbPb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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Topics

1. Introduction: $\Upsilon(nS)$ in pp and PbPb @ LHC
2. Screening, gluodissociation and damping of the $\Upsilon(nS)$ and $\chi_b(nP)$ states
3. Feed-down cascade including $\chi_b(1P)$ and $\chi_b(2P)$ 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
$L_{int} = 7.28 \mu$b$^{-1}$

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

A clear QGP indicator

1. **Y(1S) ground state is suppressed in PbPb:**
   
   \[ R_{AA}[Y(1S)] = 0.62 \pm 0.11 \text{ (stat)} \pm 0.10 \text{ (sys)} \]

   \[ R_{AA} = \frac{N_{PbPb}(Q\bar{Q})}{N_{coll}N_{pp}(Q\bar{Q})} \]

2. **Y(2S, 3S) states are suppressed in PbPb:**

   \[ \frac{Y(2S + 3S)/Y(1S)}_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02 \]

   \[ \frac{Y(2S + 3S)/Y(1S)}_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02 \]

   (min. bias)

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CMS Collab., PRL 105, 252301 (2010), and this conf.
2. Screening, Gluodissociation and Collisional broadening of the Y(nS) states

- Debye screening may prevent the formation of (or dissolve the) Y states before gluodissociation occurs: Start with the consideration of screening, with initial populations estimated from pp results at the same c.m. energy: static suppression

- At LHC energies gluon-induced dissociation of the Y(1S) ground state is expected to yield a large contribution to its suppression due to the substantial thermal gluon density in the qgp at midrapidity ($\approx 16/fm^3$ at $T=400$ MeV): dynamic suppression

- 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 treated in a nonrel. potential model

Real part:

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

Screened potential: \( r_D \) Debye radius, \( \alpha_{\text{eff}} = 0.471 \) effective coupling accounting for short-range Coulomb exchange, \( \sigma \approx 0.192 \) string tension (Jacobs et al.; Karsch et al.)

\[ r_D^{-1} = T \left[ 4\pi \alpha_s (2N_c + N_f)/6 \right]^{1/2} \]

\[ E(T) = M - 2m - \frac{\sigma}{m_D(T)} + \alpha_{\text{eff}} m_D(T) \]

= \( m_D \), Debye mass

Binding energy at temperature \( T \);

\( M = \) Meson mass
Figure 1.2: Screened Cornell potential for \( \alpha_{\text{eff}} = 0.471, \sigma = 0.192 \text{ GeV}^2 \) and different values of the Debye mass \( m_D \) in units of GeV.
Radial wave functions of $Y(nS)$ states

From the numerical solution of the Schoedinger equation

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

FIG. 1. (color online) Radial wave functions of the $Y(1S), (2S), (3S)$ states (solid, dotted, dashed curves, respectively) calculated in the screened Cornell potential for temperatures $T = 0$ MeV (bottom) and 200 MeV (top) with effective coupling constant $\alpha_{\text{eff}} = 0.471$, and string tension $\sigma = 0.192$ GeV$^2$. The rms radii $<r^2>^{1/2}$ of the $2S$ and, in particular, $3S$ state are strongly dependent on temperature $T$, whereas the ground state remains nearly unchanged.

From: F. Brezinski and G. Wolschin,
Cross section for gluodissociation

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

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

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

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

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

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

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:

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

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

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

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

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

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

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

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

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

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

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

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

For 1S etc.

1S result agrees with effective field theory: Brambilla, Escobedo, Ghiglieri, Vairo 2011
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 Cornell potential for temperatures $T=200$ (solid curves) and 250 MeV (dotted curves) as functions of the gluon energy $E_g$. The thermal gluon distribution (rhs scale, with $m_g = 0$; solid for $T = 200$ MeV, dotted for 250 MeV) is used to obtain the thermally averaged cross sections through integrations over the gluon momenta.

F. Brezinski and GW, PLB 707 (2012) 534
Dynamical model for the expanding fireball with QGP lifetime $t_{\text{QGP}}$ and $Y$ formation time $t_F$ as free parameters; $v_z=0.9c$, $v_x=v_y=0.6c$
Collisional damping through imaginary potential

Calculated damping widths for $Y(1S)$ and $\chi_b$ (1P), and corresponding gluodissociation widths.

Medium contributions from hard thermal loop approx., to 1st order

$$H_{1/8} = -\frac{\Delta R}{4M} - \frac{\Delta r}{M} + V_{1/8}(r)$$

⇒ Complex potentials:

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

$$\phi(x) = \int_0^\infty dz \frac{2z}{(1 + z^2)^2} \left[ 1 - \frac{\sin(xz)}{xz} \right]$$

Laine et al. 2007; Beraudo et al. 2008

$C_1 = -\alpha_{\text{eff}}$

$C_8 = +\alpha_s/(2N_c)$
3. Feed-down cascade including $\chi_{1P}$ and $\chi_{2P}$ states

Initial populations in pp computed using an inverted cascade from the final populations measured by CMS and CDF ($\chi b$) [$N_{\text{final}}(1S) = 1$]

$N_{\text{initial}}$

3S: 0.387

2S: 0.371

1S: 0.458

2P: 0.976

1P: 1.29
Feed-down cascade for hadronic and radiative transitions

Decay matrix for the five states involved

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

with

\[
\begin{align*}
M_{X \leftrightarrow 3S} &= M_{2P \leftrightarrow 3S} + M_{2S \leftrightarrow 3S} + M_{1P \leftrightarrow 3S} + M_{1S \leftrightarrow 3S} \\
M_{X \leftrightarrow 2P} &= M_{2S \leftrightarrow 2P} + M_{1P \leftrightarrow 2P} + M_{1S \leftrightarrow 2P} \\
M_{X \leftrightarrow 2S} &= M_{1P \leftrightarrow 2S} + M_{1S \leftrightarrow 2S} \\
M_{X \leftrightarrow 1P} &= M_{1S \leftrightarrow 1P} \\
M_{X \leftrightarrow 1S} &= 0.
\end{align*}
\]

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

Calculate final from initial population vector

\[
\vec{P}_{\text{final}} = \mathcal{C} \vec{P}_{\text{initial}}.
\]
4. Comparison with CMS data

Suppression factor:

\[ R_{AA}^{CMS}(1S) = 0.62 \pm 0.11 \text{(stat)} \pm 0.10 \text{(sys)} , \min \text{ bias (0-100\%)} \]

Model result for

\[ t_F=0.1 \text{ fm/c}, \ t_{QGP}=8 \text{ fm/c}: \ R_{AA}^{th}(1S)=0.60 \]
\[ t_F=0.5 \text{ fm/c}, \ t_{QGP}=8 \text{ fm/c}: \ R_{AA}^{th}(1S)=0.71 \]

Ratio of yields:

\[ \frac{Y(2S+3S)}{Y(1S)}|_{pp} = 0.78 \pm 0.16 \pm 0.02 \]
\[ \frac{Y(2S+3S)}{Y(1S)}|_{PbPb} = 0.24 \pm 0.13 \pm 0.02 \]

CMS data

Model result for

\[ t_F=0.1 \text{ fm/c}, \ t_{QGP}=8 \text{ fm/c}: (2S+3S)/1S=0.46 \pm 0.26/-0.08 \]

( theoretical uncertainties from error bars in the input data)

Leaves room for additional suppression mechanisms

\[ t_F: \ Y \ formation \ time \]
\[ t_{QGP}: \ QGP \ lifetime \]
Theoretical vs. exp. Suppression factors

Consider

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

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

$Y(1S)$

$Y(2S+3S)/Y(1S)$

$t_F$: $Y$ formation time
$t_{QGP}$: QGP lifetime
$T_{max} @ t_F$: 200-800 MeV

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5. Conclusion

- The suppression of the $\Upsilon(1S)$ ground state in PbPb collisions at LHC energies through screening, gluodissociation, damping and reduced feed-down has been calculated, and is found to be in good agreement with the CMS result.

- The enhanced suppression of the $\Upsilon(2S+3S)$ 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 sufficiently small $\Upsilon$ formation times. There is room for additional suppression mechanisms.

- Need data with better statistics for a detailed comparison: expected from the Nov/Dec 2011 LHC run for 2.76 TeV PbPb. New CMS data: 20x more $\Upsilon$ events - see this conference!