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

Georg Wolschin*

Heidelberg University

Institut für Theoretische Physik

Philosophenweg 16

D-69120 Heidelberg

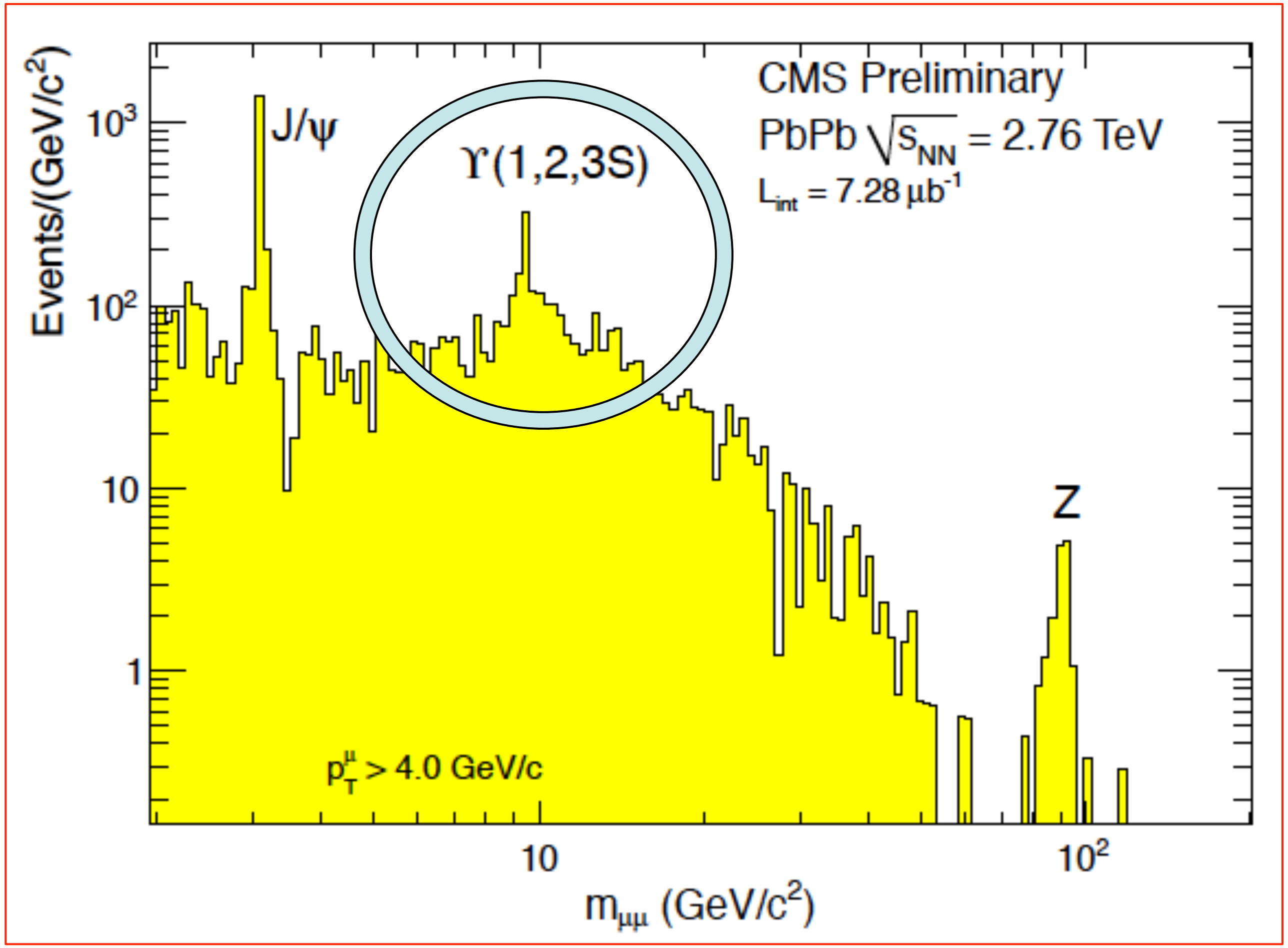
*coll. with Felix Nendzig, PhD student

Topics

1. Introduction: Υ(nS) in pp and PbPb @ LHC
2. Screening, gludissociation 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: Υ in PbPb @ LHC



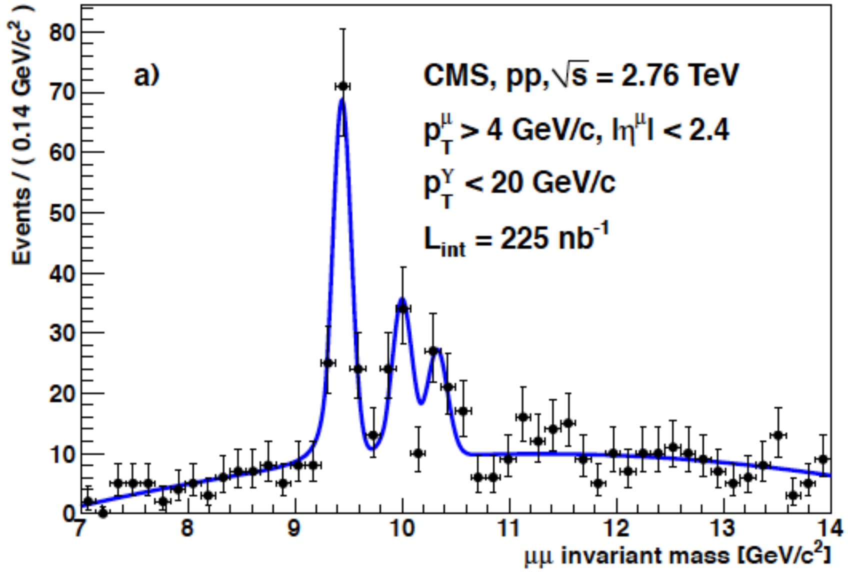
CMS Collab., CMS-PAS-HIN-10-006 (2011)

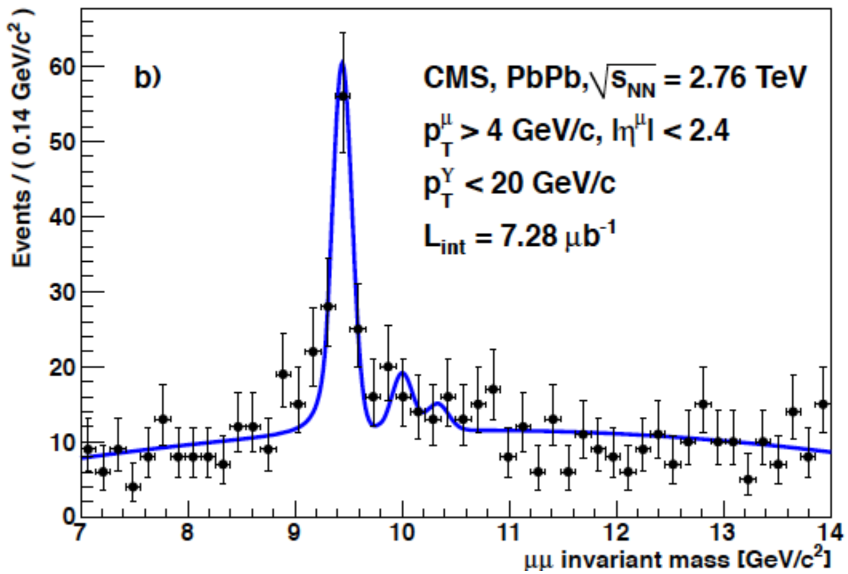
Υ suppression as a sensitive probe for the QGP

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

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

Υ(nS) states are suppressed in PbPb @ LHC:





A clear QGP indicator

1. Υ(1S) ground state is suppressed in PbPb:

R_{AA}[Υ(1S)]: 0.62 ± 0.11 (stat) ± 0.10 (sys)

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

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

$$\begin{aligned} \Upsilon(2S+3S)/\Upsilon(1S)|_{pp} &= 0.78^{+0.16}_{-0.14} \pm 0.02 \\ \Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb} &= 0.24^{+0.13}_{-0.12} \pm 0.02 \end{aligned}$$

(min. bias)

CMS Collab., PRL 105, 252301 (2010), and this conf.

2. Screening, Gluodissociation and Collisional broadening of the Υ(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 (≈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, α_{eff} = 0.471 effective coupling accounting for short-range Coulomb exchange, $\sigma \approx$ 0.192 string tension (Jacobs et al.; Karsch et al.)

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

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

Binding energy at temperature T;

M=Meson mass

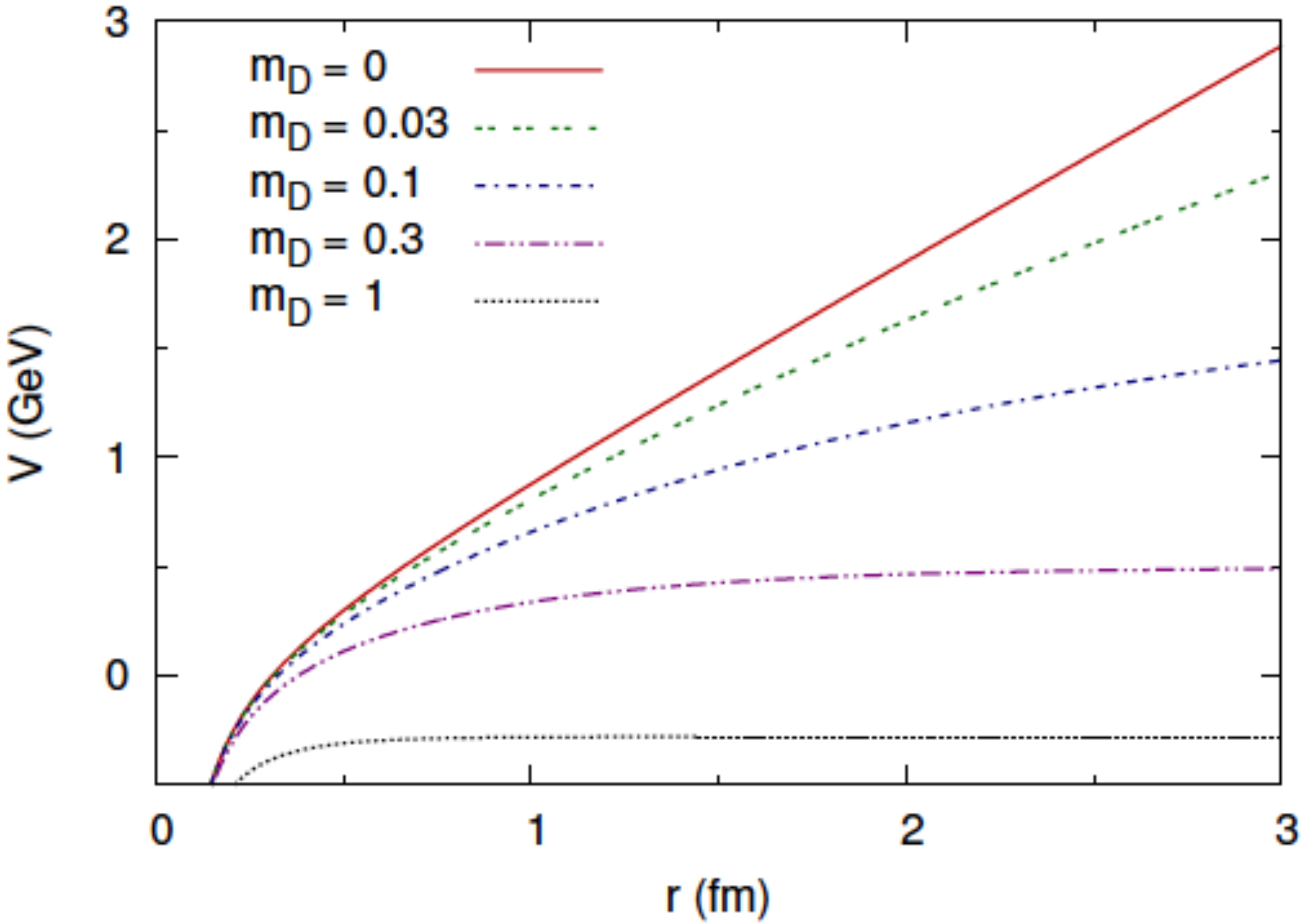
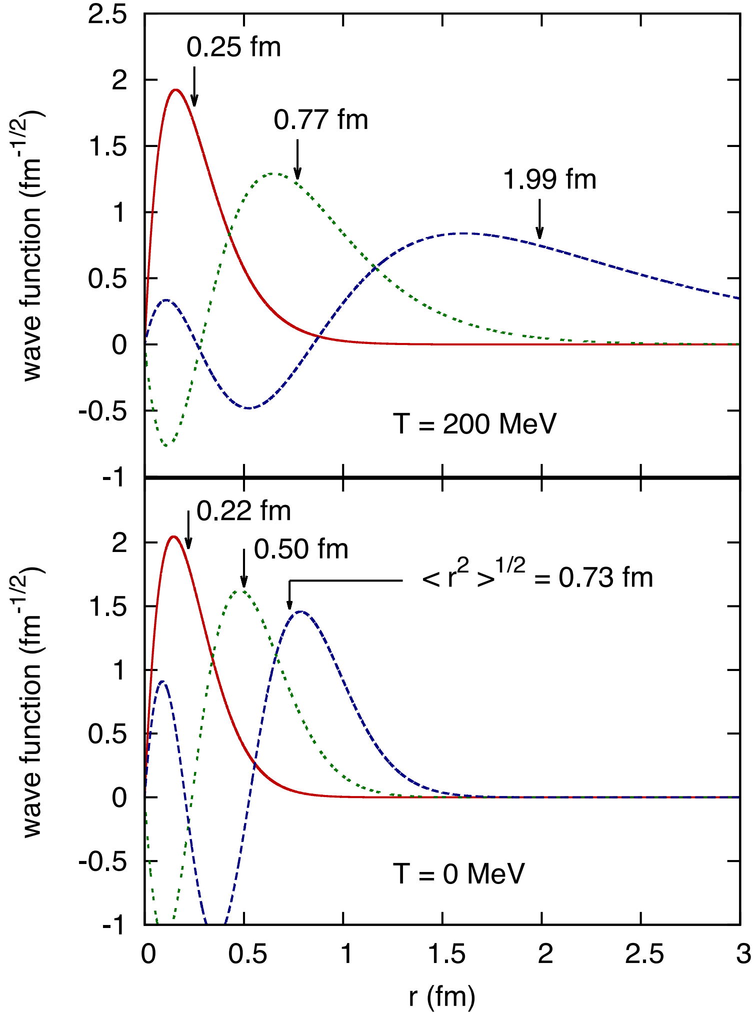


Figure 1.2: Screened Cornell potential for $\alpha_{\text{eff}} = 0.471$, $\sigma = 0.192$ GeV^2 and different values of the Debye mass m_D in units of GeV.

Radial wave functions of Υ(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 $\Upsilon(1S), (2S), (3S)$ 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,
Phys. Lett. B 707 (2012) 534 (arXiv:1109.0211)

Cross section for gludissociation

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

$$\mathcal{M} = \frac{1}{2}\frac{4\pi\alpha_s}{3}\frac{E^2}{3}\langle\psi|\vec{r}\left(\frac{1}{H_8+\epsilon-E}+\frac{1}{H_8+\epsilon+E}\right)\vec{r}\,|\psi\rangle$$

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

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

$$\sigma = \frac{1}{E}\cdot\frac{1}{2}\frac{4\pi\alpha_s}{3}\frac{E^2}{3}\langle\psi|\vec{r}\,\pi\delta\left(H_8+\epsilon-E\right)\vec{r}\,|\psi\rangle$$
$$= \frac{2\pi^2\alpha_s E}{9}\langle\psi|\vec{r}\,\delta\left(H_8+\epsilon-E\right)\vec{r}\,|\psi\rangle.$$

Gludissociation 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:

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

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

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

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

for the Gluodissociation cross section.

Cross section results singlet to octet, coulombic wfct

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

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

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

$$z_n = \frac{n}{4q_n}$$

For $z_n \longrightarrow 0$ 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.

1S result agrees with effective field theory: Brambilla, Escobedo, Ghiglieri, Vairo 2011

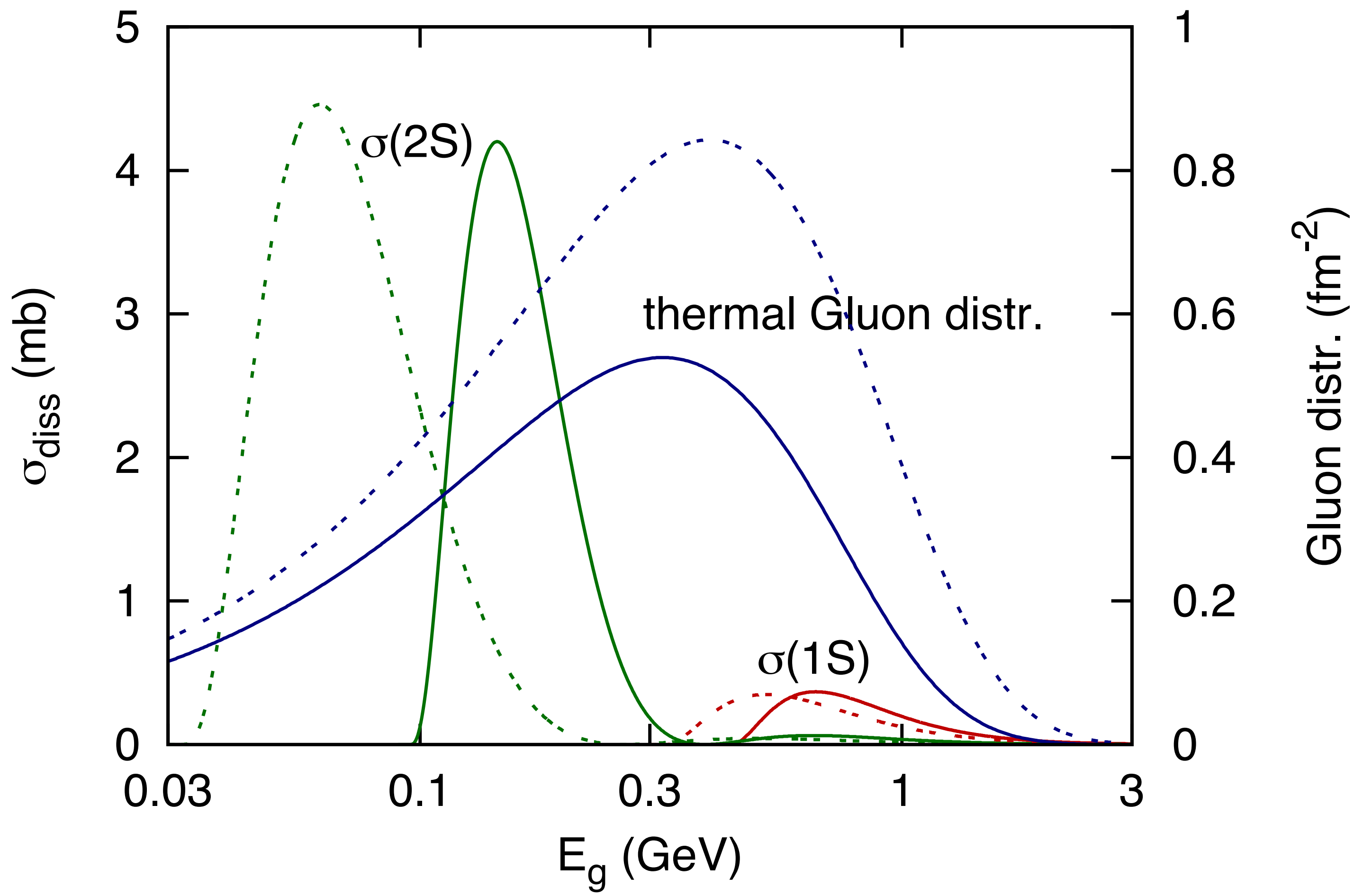


Figure 2: (color online) Gluodissociation cross sections $\sigma_{diss}(nS)$ in mb (lhs scale) of the $\Upsilon(1S)$ and $\Upsilon(2S)$ states calculated using the screened Cornell potential for temperatures T =200 (solid curves) and 250 MeV (dotted curves) as functions of the gluon energy E_g. The thermal 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

Thermally averaged gludissociation cross sections

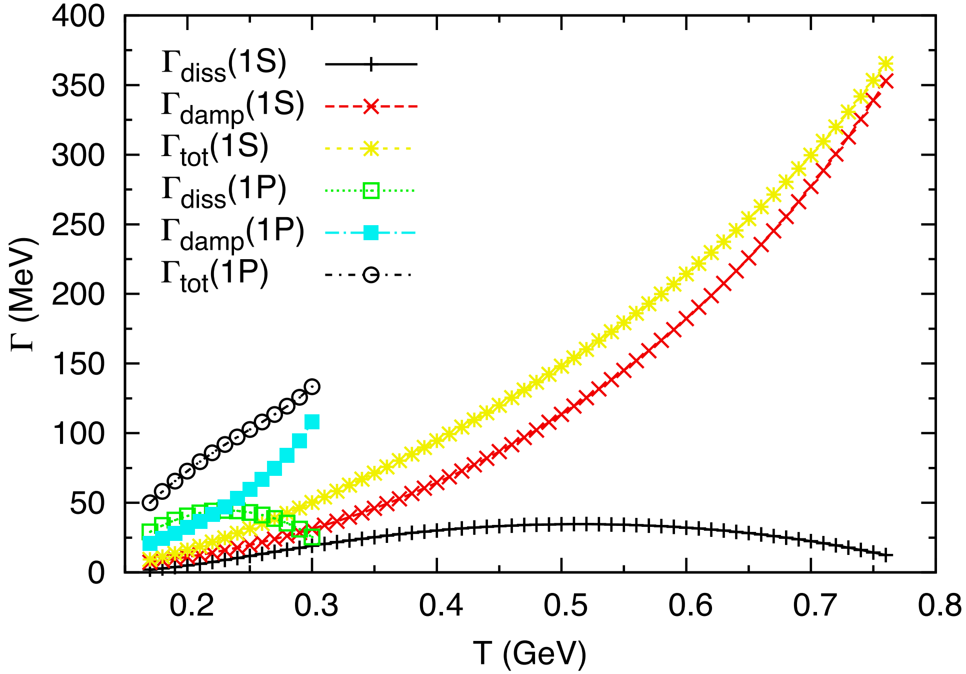
$$< \sigma_{diss}^{nS} >= \frac{g_d}{2\pi^2 n_g} \int_0^\infty \sigma_{diss}^{nS}(E) \, \frac{p^2 dp}{\exp\left[E(p)/T\right] - 1}$$

Table 1: Thermally averaged cross sections $< \sigma_{diss}(nS) >$ in mb for the gluodissociation of the $\Upsilon(1S), (2S), (3S)$ 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.

T (MeV)	$< \sigma_{diss}(1S) >$ (mb)	$< \sigma_{diss}(2S) >$ (mb)	$< \sigma_{diss}(3S) >$ (mb)
400	0.094	–	–
300	0.141	0.041	–
200	0.124	0.465	0.152
170	0.080	0.783	0.604

Dynamical model for the expanding fireball with QGP lifetime t_{QGP} and Υ 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 χ_b (1P), and corresponding gluo-dissociation 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:

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

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

$$C_1 = -\alpha_{eff}$$
$$C_8 = +\alpha_s/(2N_c)$$

Laine et al. 2007; Beraudo et al. 2008

3. Feed-down cascade including χ_{1P} and χ_{2P} states

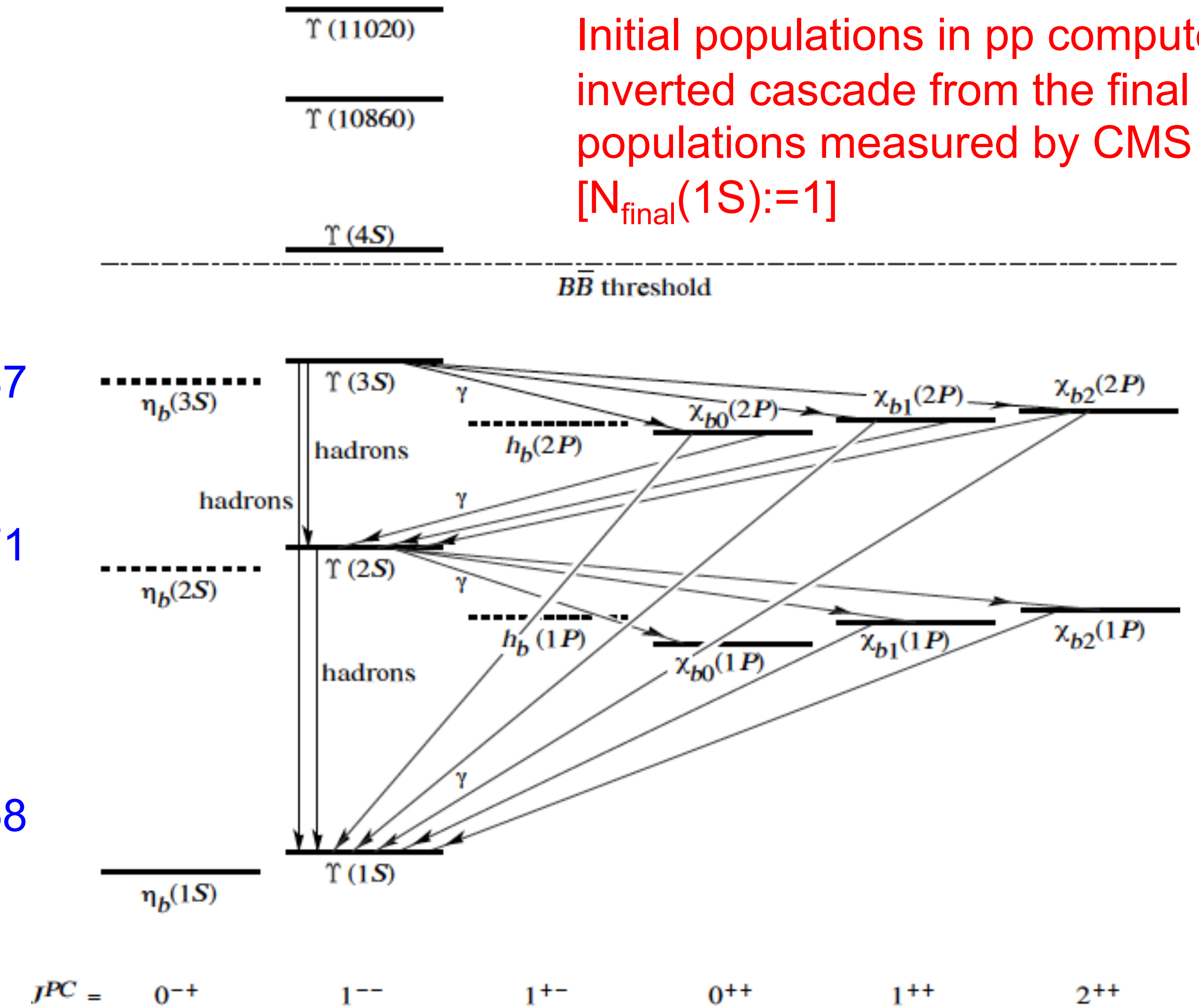
Initial populations in pp computed using an inverted cascade from the final populations measured by CMS and CDF(χ_b) [N_{final}(1S):=1]

$N_{initial}$

3S: 0.387

2S: 0.371

1S: 0.458



$N_{initial}$

2P: 0.976

1P: 1.29

Feed-down cascade for hadronic and radiative transitions

Decay matrix for the five states involved

$$\mathcal{D} = \begin{pmatrix} 1-M_{X\leftarrow 3S} & 0 & 0 & 0 & 0 \\ M_{2P\leftarrow 3S} & 1-M_{X\leftarrow 2P} & 0 & 0 & 0 \\ M_{2S\leftarrow 3S} & M_{2S\leftarrow 2P} & 1-M_{X\leftarrow 2S} & 0 & 0 \\ M_{1P\leftarrow 3S} & M_{1P\leftarrow 2P} & M_{1P\leftarrow 2S} & 1-M_{X\leftarrow 1P} & 0 \\ M_{1S\leftarrow 3S} & M_{1S\leftarrow 2P} & M_{1S\leftarrow 2S} & M_{1S\leftarrow 1P} & 1-M_{X\leftarrow 1S} \end{pmatrix}$$

with

$$\begin{aligned} M_{X\leftarrow 3S} &= M_{2P\leftarrow 3S} + M_{2S\leftarrow 3S} + M_{1P\leftarrow 3S} + M_{1S\leftarrow 3S} \\ M_{X\leftarrow 2P} &= M_{2S\leftarrow 2P} + M_{1P\leftarrow 2P} + M_{1S\leftarrow 2P}, \\ M_{X\leftarrow 2S} &= M_{1P\leftarrow 2S} + M_{1S\leftarrow 2S}, \\ M_{X\leftarrow 1P} &= M_{1S\leftarrow 1P}, \\ M_{X\leftarrow 1S} &= 0. \end{aligned}$$

(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:

t_F: Y formation time
t_{QGP}: QGP lifetime

$R_{AA}^{CMS}(1S)$ = 0.62±0.11(stat)±0.10(sys) , min. bias (0-100%)

Model result for t_F=0.1 fm/c, t_{QGP}=8 fm/c: $R_{AA}^{th}(1S)$=0.60
for t_F=0.5 fm/c, t_{QGP}=8 fm/c: $R_{AA}^{th}(1S)$=0.71

Ratio of yields:

$$\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{pp}} = 0.78^{+0.16}_{-0.14} \pm 0.02$$
$$\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{PbPb}} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

CMS data

Model result for t_F=0.1 fm/c, t_{QGP}=8 fm/c: (2S+3S)/1S=0.46 +0.26/-0.08

(theoretical uncertainties from error bars in the input data)

⇨ Leaves room for additional suppression mechanisms

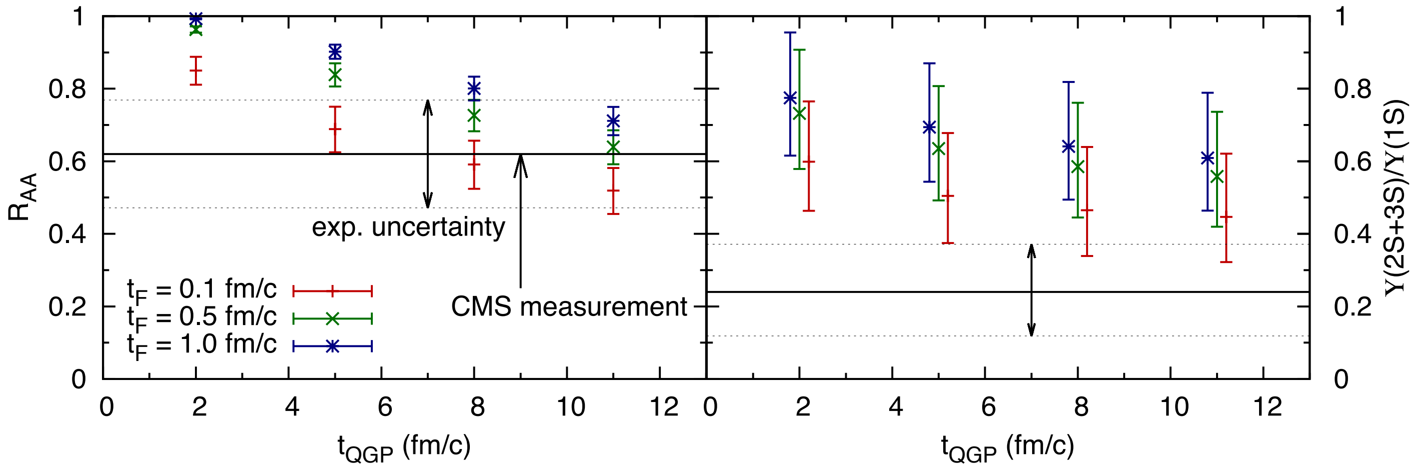
Theoretical vs. exp. Suppression factors

Consider

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

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

Υ(1S) Υ(2S+3S)/Υ(1S)



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

5. Conclusion

- The suppression of the Υ(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 Υ(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 Υ 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 Υ events - see this conference !