Bottomia physics at RHIC and LHC

Georg Wolschin

Heidelberg University
Institut für Theoretische Physik
Philosophenweg 16
D-69120 Heidelberg

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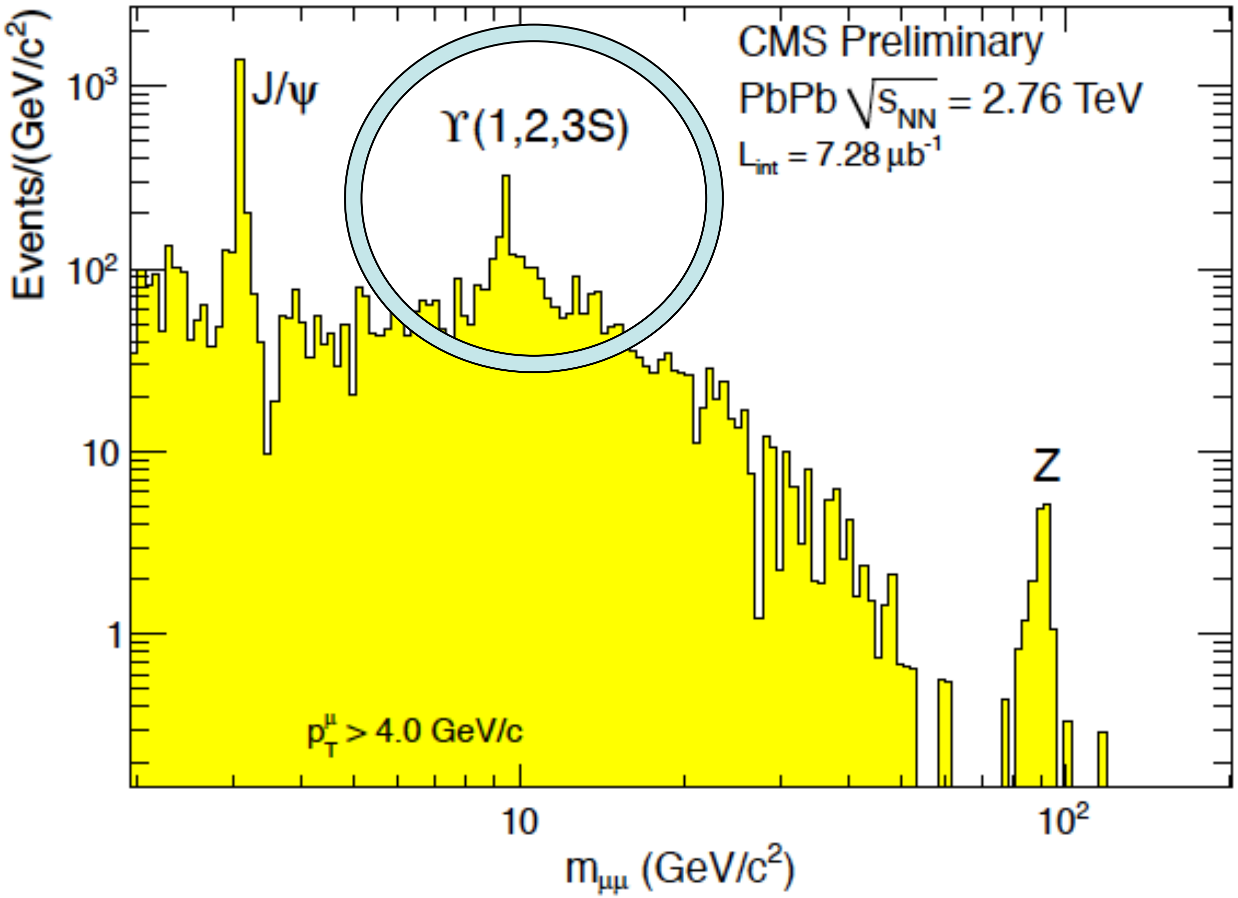
Topics

1. Introduction: Υ suppression at RHIC and LHC
2. Model for bottomium suppression
   2.1 Complex potential: Screening and damping
   2.2 Gluon-induced dissociation
   2.3 Hydrodynamic expansion
   2.4 Feed-down cascade
3. Comparison with STAR and CMS data
4. Prediction for 5.02 TeV PbPb
5. Conclusion

1. Introduction: ϒ Suppression in PbPb @ LHC



ϒ suppression as a sensitive probe for the QGP

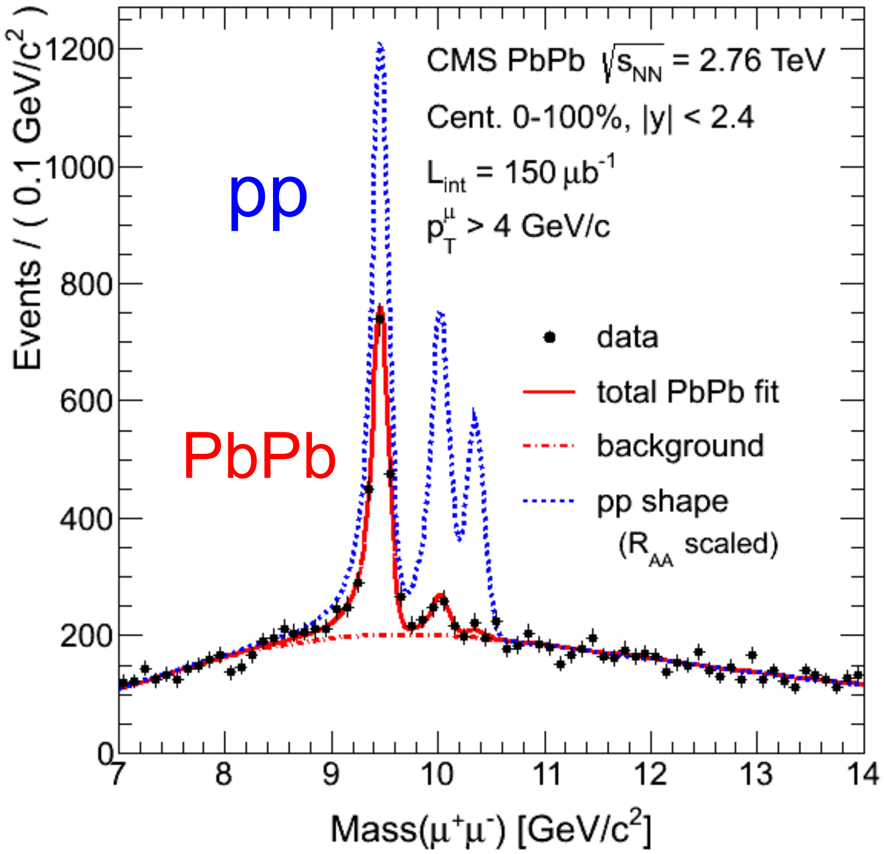
- No significant effect of regeneration
- $m_b \approx 3m_c$ ⇨ cleaner theoretical treatment
- More stable than J/ψ

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

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

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

CMS



A clear QGP indicator

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

R_{AA} (Υ(1S)) = 0.56 ± 0.08 ± 0.07 in min. bias

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

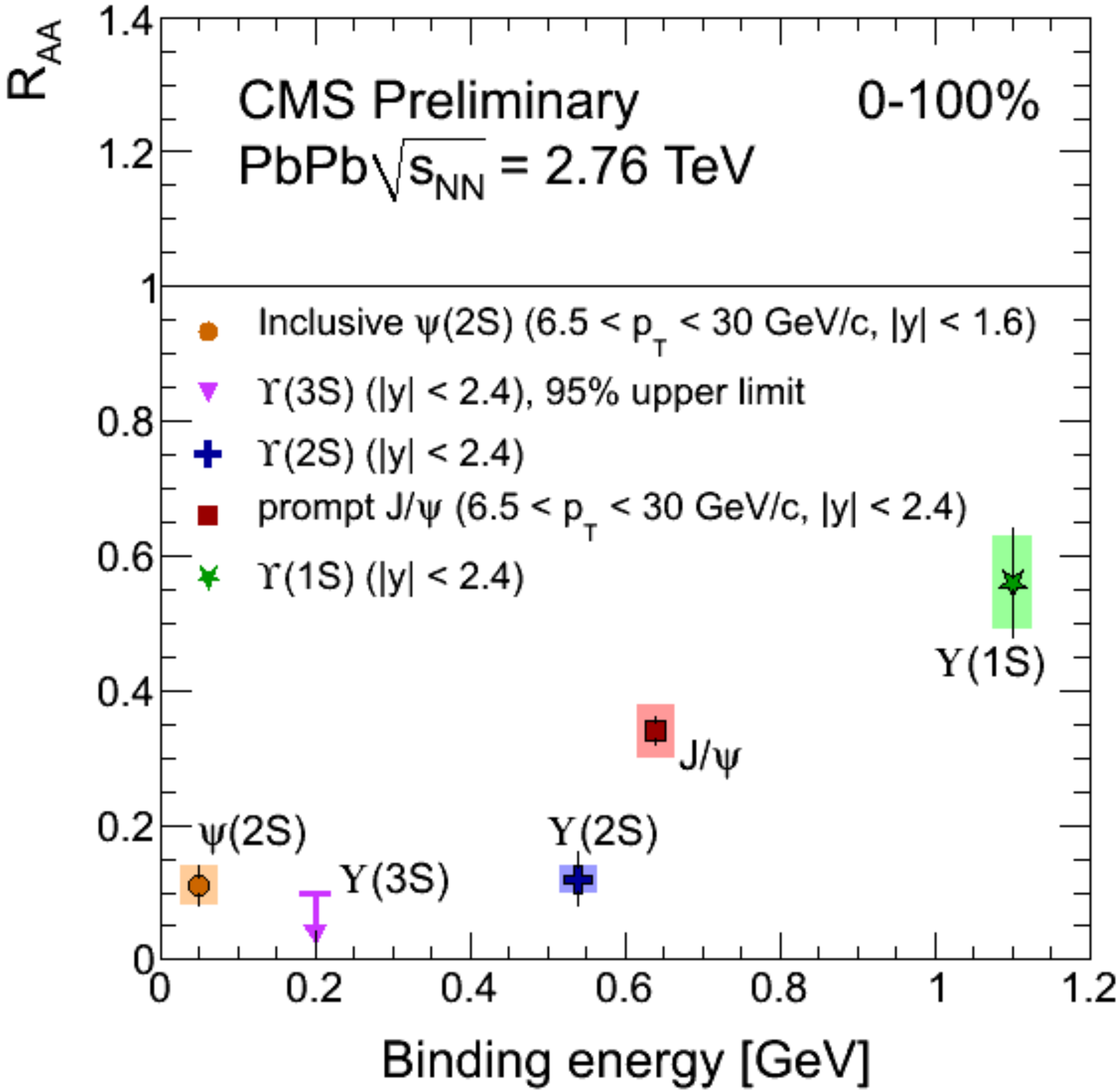
R_{AA}(Υ(2S)) = 0.12 ± 0.04 (stat.) ± 0.02 (syst.)

R_{AA}(Υ(3S)) = 0.03 ± 0.04 (stat.) ± 0.01 (syst.)

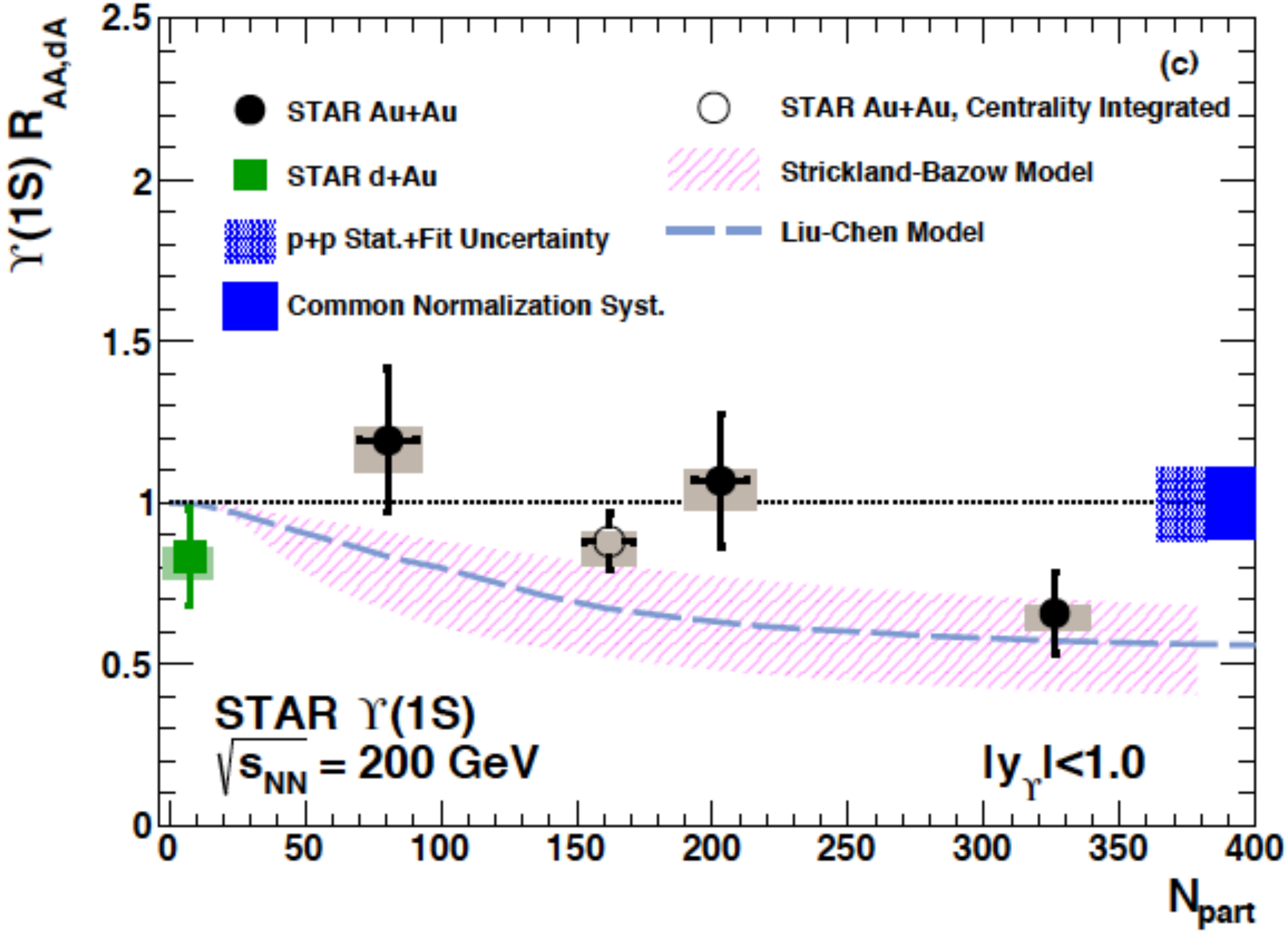
$$R_{AA} = \frac{N_{PbPb}(Q\bar{Q})}{N_{coll} N_{pp}(Q\bar{Q})}$$

CMS Collab., PRL 109, 222301 (2012)
[Plot from CMS database]

Sequential suppression of Υ(nS) and J/ψ states



Υ(nS) states are suppressed in AuAu @ RHIC



R. Vértesi, Nucl. Part. Phys. Proc. 276 (2016) 269

2. The model: Screening, Gludissociation and Collisional broadening of the Υ(nS) states

- Debye screening of all states involved: Static suppression

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

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

- Reduced feed-down from the excited Υ/χ_b states to Υ(1S) substantially modifies the populations: indirect suppression

F. Vaccaro, F. Nendzig and GW, Europhys.Lett. 102, 42001 (2013); J. Hoelck and GW, unpublished
F. Nendzig and GW, Phys. Rev. C 87, 024911 (2013); J. Phys. G41, 095003 (2014)
F. Brezinski and GW, Phys. Lett.B 70, 534 (2012)

2.1 Screening and damping treated in a nonrelativistic potential model

$$V_{nl}(r,T) = -\frac{\sigma}{m_D(T)} e^{-m_D(T)r} - C_F \alpha_{nl}(T) \left(\frac{e^{-m_D(T)r}}{r} + iT\phi(m_D(T)r) \right)$$

$$\phi(x) = \int_0^\infty \frac{dz\, 2z}{(1+z^2)^2} \left(1 - \frac{\sin xz}{xz} \right), m_D(T) = T\sqrt{4\pi\alpha_s(2\pi T)\frac{2N_c + N_f}{6}}$$

From the literature

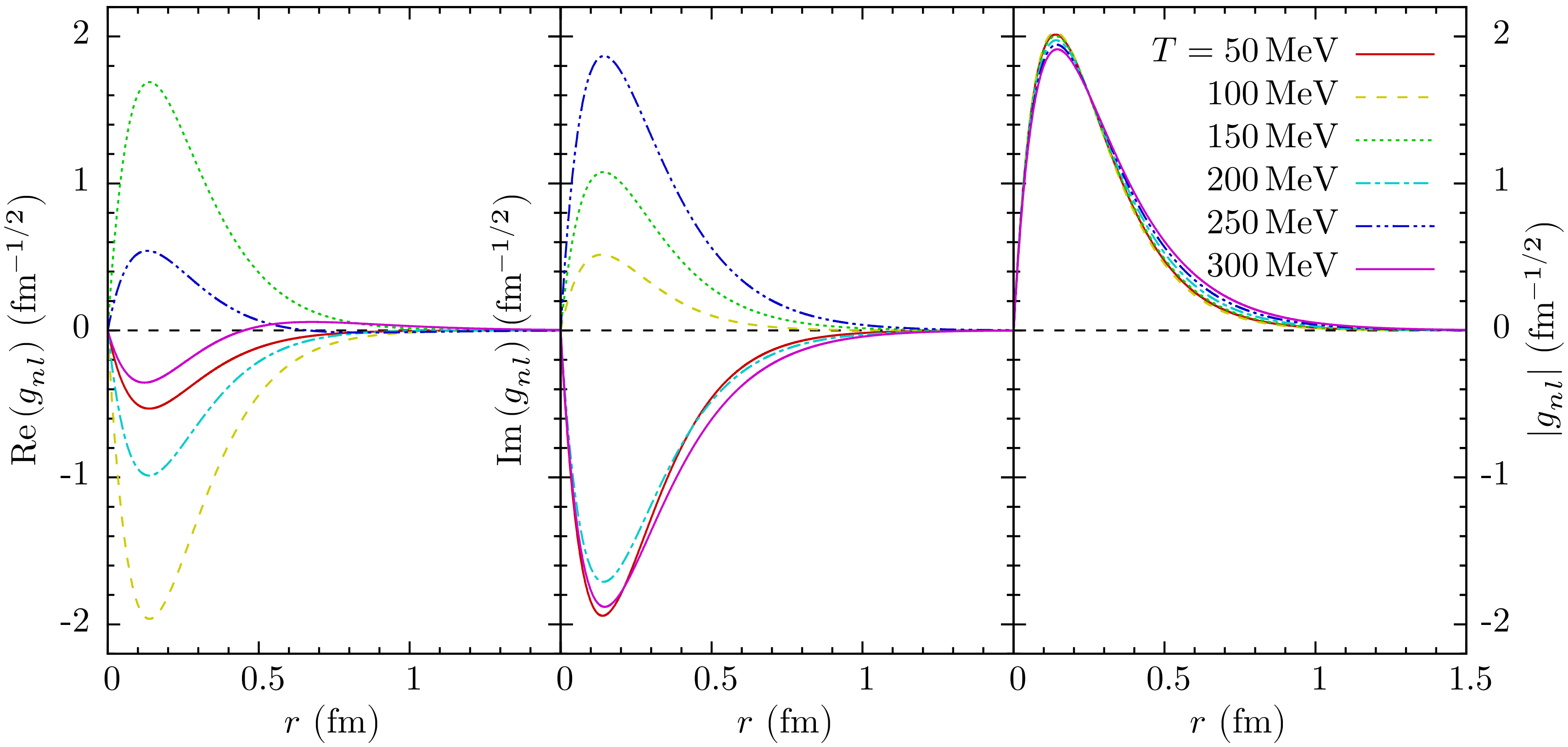
Screened potential: m_D = Debye mass,
$\alpha_{nl}(T)$ the strong coupling constant;
$C_F = (N_c^2 - 1) / (2N_c)$
$\sigma \approx 0.192$ the string tension (Jacobs et al.; Karsch et al.)

Imaginary part: Collisional damping (Laine et al. 2007, Beraudo et al. 2008, Brambilla et al. 2008) for $2\pi T \gg \langle 1/r \rangle$; different form for $2\pi T \ll \langle 1/r \rangle$.

Radial wave function of Υ(1S) at temperatures T

Solutions of the Schoedinger equation with complex potential $V(r,T,\alpha_s)$ for the radial wave functions $g_{nl}(r,T)$,

$$[H(r,T,\alpha_s) - E + i\Gamma/2]g(r) = 0$$



From: J. Hoelck and GW, unpublished

2.2 Cross section for gluodissociation

Born amplitude for the interaction of gluon clusters according to Bhanot&Peskin in dipole approximation / Operator product expansion, extended to include the screened coulombic + string eigenfunctions as outlined in Brezinski and Wolschin, PLB 70, 534 (2012)

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

$$w^{nS}(k) = \int_0^\infty dr\, r\, g^s_{n0}(r) g^a_{k1}(r)$$

for the Gluodissociation cross section of the Y(nS) states, and correspondingly for the χ_b(nP) states.

Gludissociation cross section

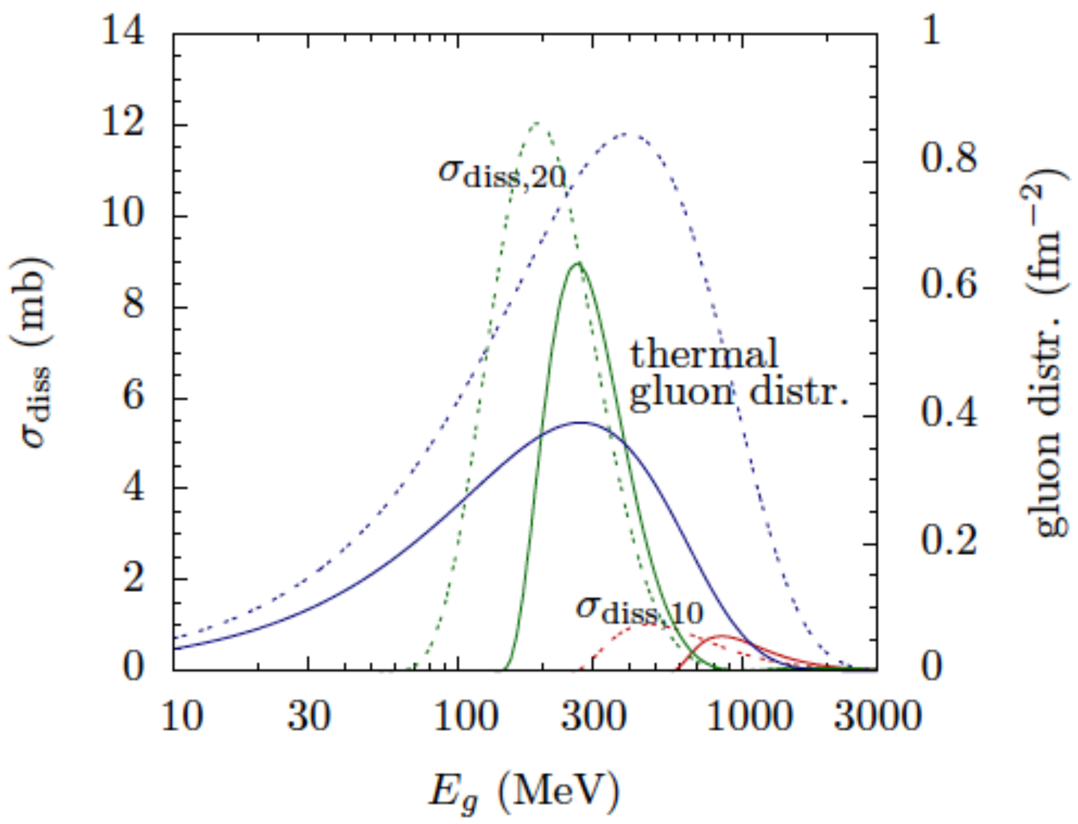


Figure 3. Gludissociation cross section σ_{diss} (left scale) of the $\Upsilon(1S)$ and $\Upsilon(2S)$ and the thermal gluon distribution (right scale) plotted for temperature $T = 170$ (solid curves) and 250 MeV (dotted curves) as functions of the gluon energy E_g.

F. Nendzig and GW, J. Phys. G41, 095003 (2014)

Thermal gluodissociation cross section

Average the gluodissociation cross section over the Bose-Einstein distribution of the thermal gluons in the QGP to obtain the dissociation width at temperature T for each of the six bottomia states involved

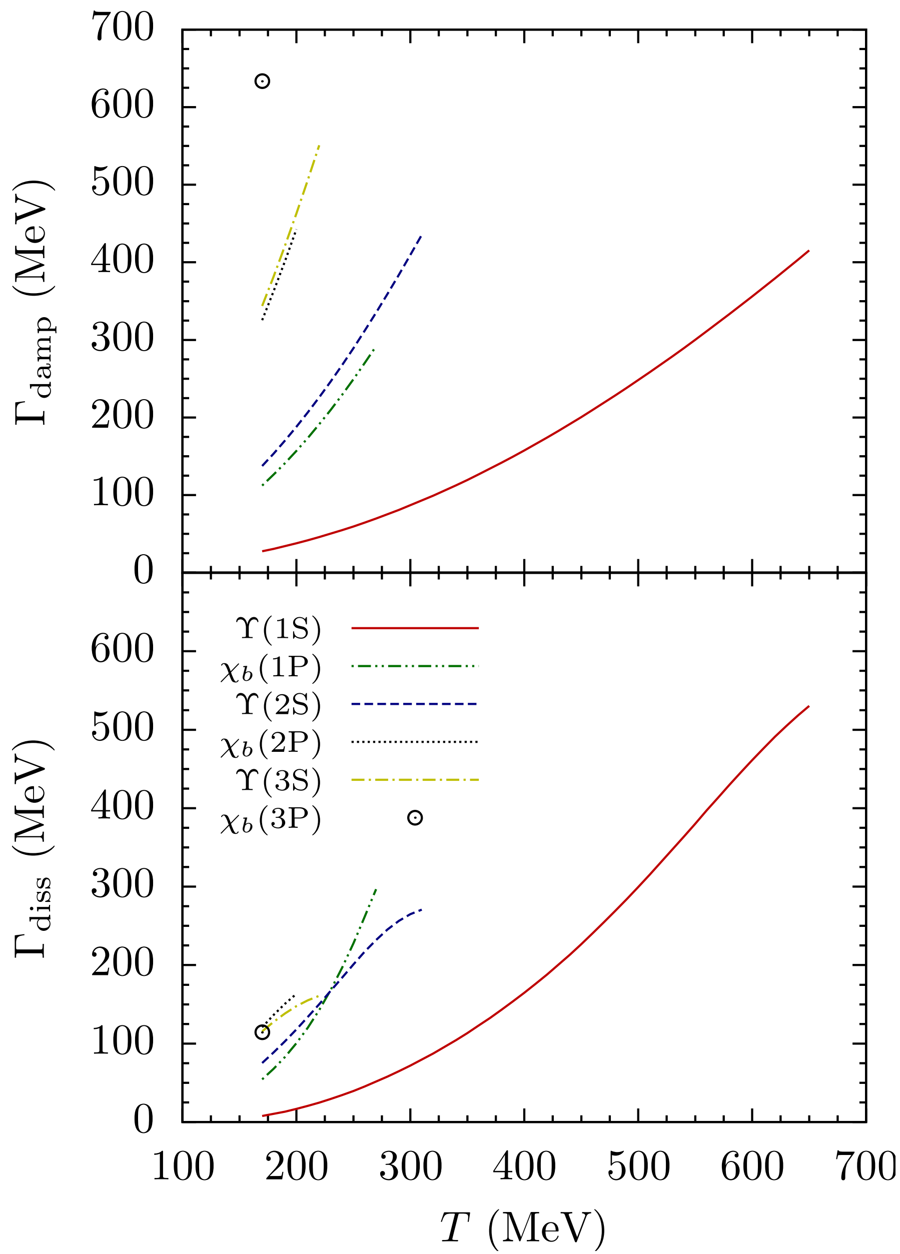
$$\Gamma_{\mathrm{diss},\, nl}(T) \equiv \frac{g_d}{2\pi^2} \int_0^\infty \frac{\mathrm{d}E_g\, E_g^2\, \sigma_{\mathrm{diss},\, nl}\left(E_g\right)}{\mathrm{e}^{E_g/T} - 1}$$

($g_d = 16$)

With rising temperature, the peak of the gluon distribution moves to larger gluon energies E_g, whereas the dissociation cross sections move to smaller E_g, giving rise to a maximum in the gluodissociation width for fixed coupling α_s.
(Larger cross sections at higher temperatures due to running coupling counteract.)

Damping and gluodissociation widths for six bottomia states

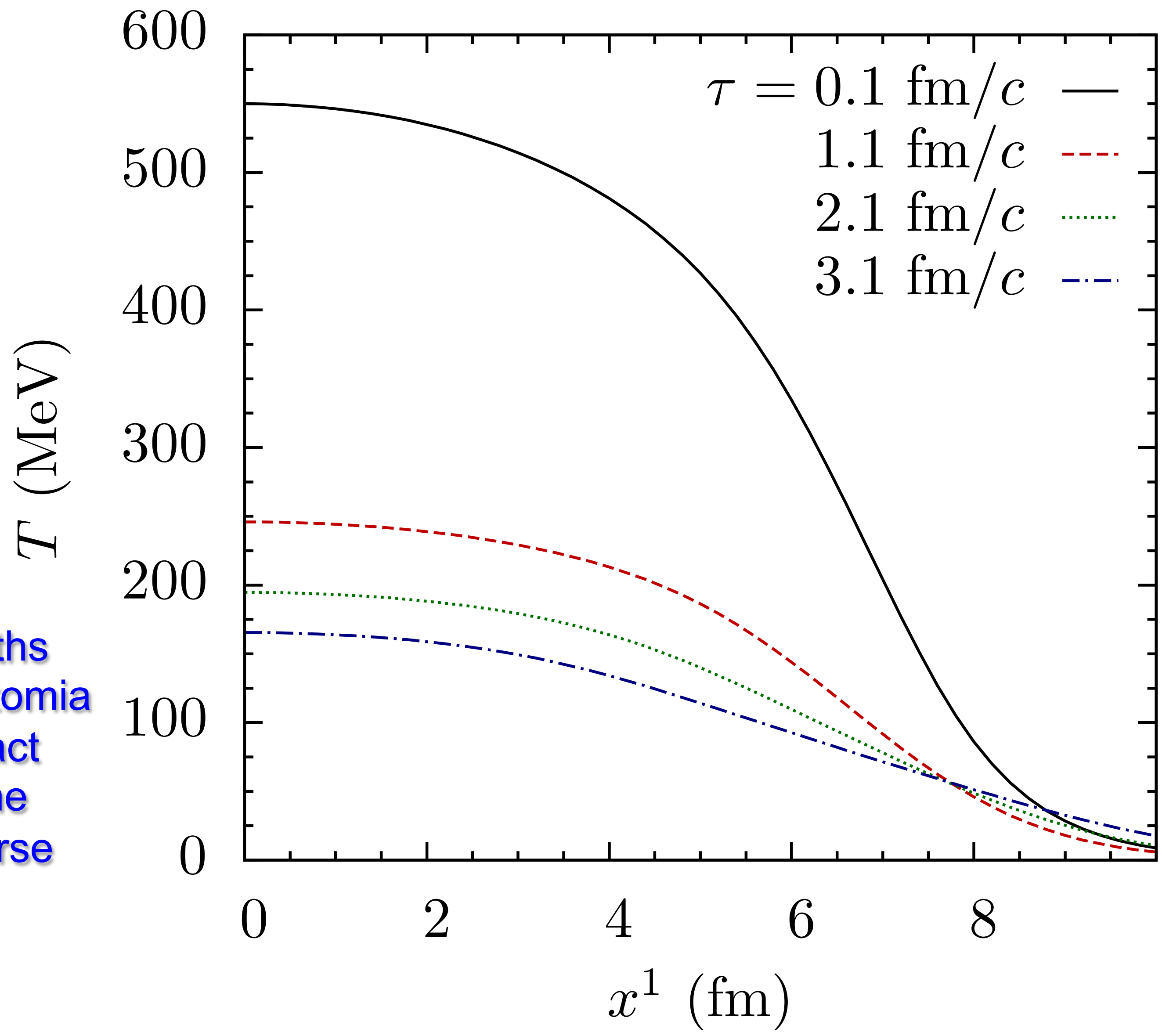
$$\Gamma_{tot}(T) = \Gamma_{damp}(T) + \Gamma_{diss}(T)$$



F. Nendzig and GW, J. Phys. G41, 095003 (2014) ; arXiv:1406.5103

2.3 Hydrodynamic expansion (ideal)

Temperature profile for central collisions at different times τ



Use total decay widths $\Gamma_{tot}(b,x,y)$ of the bottomia states for each impact parameter b and time step t in the transverse (x^1,x^2) plane

Dynamical fireball evolution

Dependence of the local temperature T on impact parameter b, time t, and transverse coordinates x, y evaluated in ideal hydrodynamic calculation with transverse expansion

$$T(b, \tau_{init}, x^1, x^2) = T_0 \left(\frac{N_{mix}(b, x^1, x^2)}{N_{mix}(0,0,0)} \right)^{1/3}$$

$$N_{mix} = \frac{1-f}{2} N_{part} + f N_{coll}, \qquad f = 0.145$$

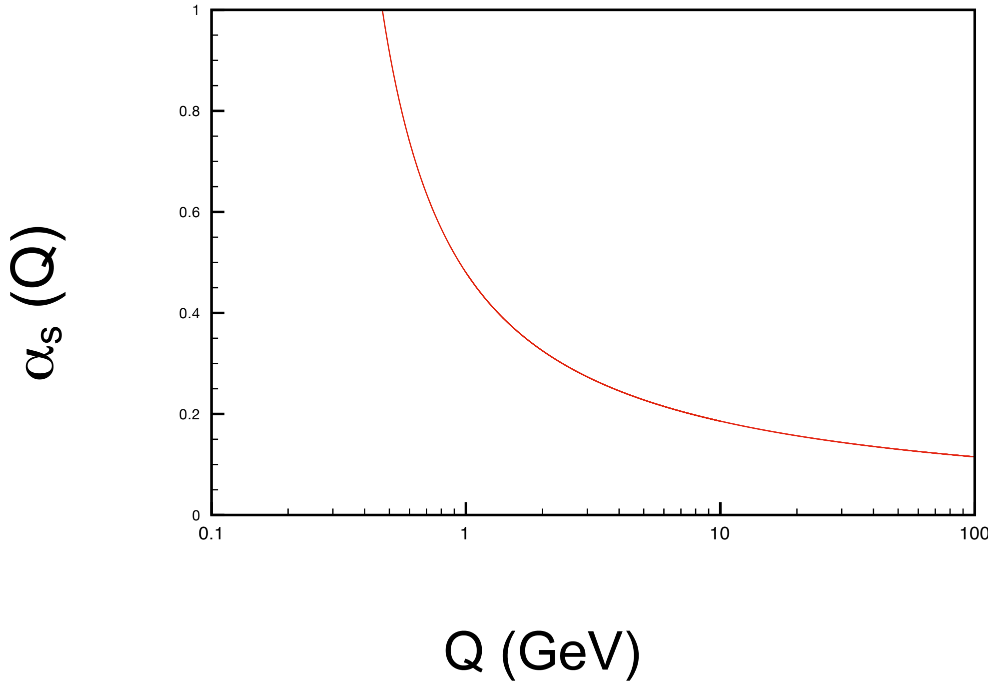
The number of produced $b\bar{b}$-pairs is proportional to the number of binary collision, and the nuclear overlap

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

QGP suppression factor (without feed-down and CNM effects):

$$R_{AA}^{QGP} = \frac{\int d^2b \int dx dy \, T_{AA}(b,x,y) \, e^{-\int_{t_F}^{\infty} dt \, \Gamma_{\rm tot}(b,t,x,y)}}{\int d^2b \int dx dy \, T_{AA}(b,x,y)}$$

Model ingredients



- Consider running of the coupling
- Transverse momentum distribution of the Υ included
- Relativistic Doppler effect included
- T_c = 160 MeV

$$\alpha_s(Q) = \frac{\alpha(\mu)}{1 + \alpha(\mu) b_0 \ln \frac{Q}{\mu}}, \quad b_0 = \frac{11N_c - 2N_f}{6\pi}$$

F. Nendzig and GW, J. Phys. G41, 095003 (2014)

$\alpha_{nl}(T)$ depends on the solution $g_{nl}(r,T)$ of the Schrödinger eq.: Iterative solution

2.4 Feed-down cascade including χ_{nP} states

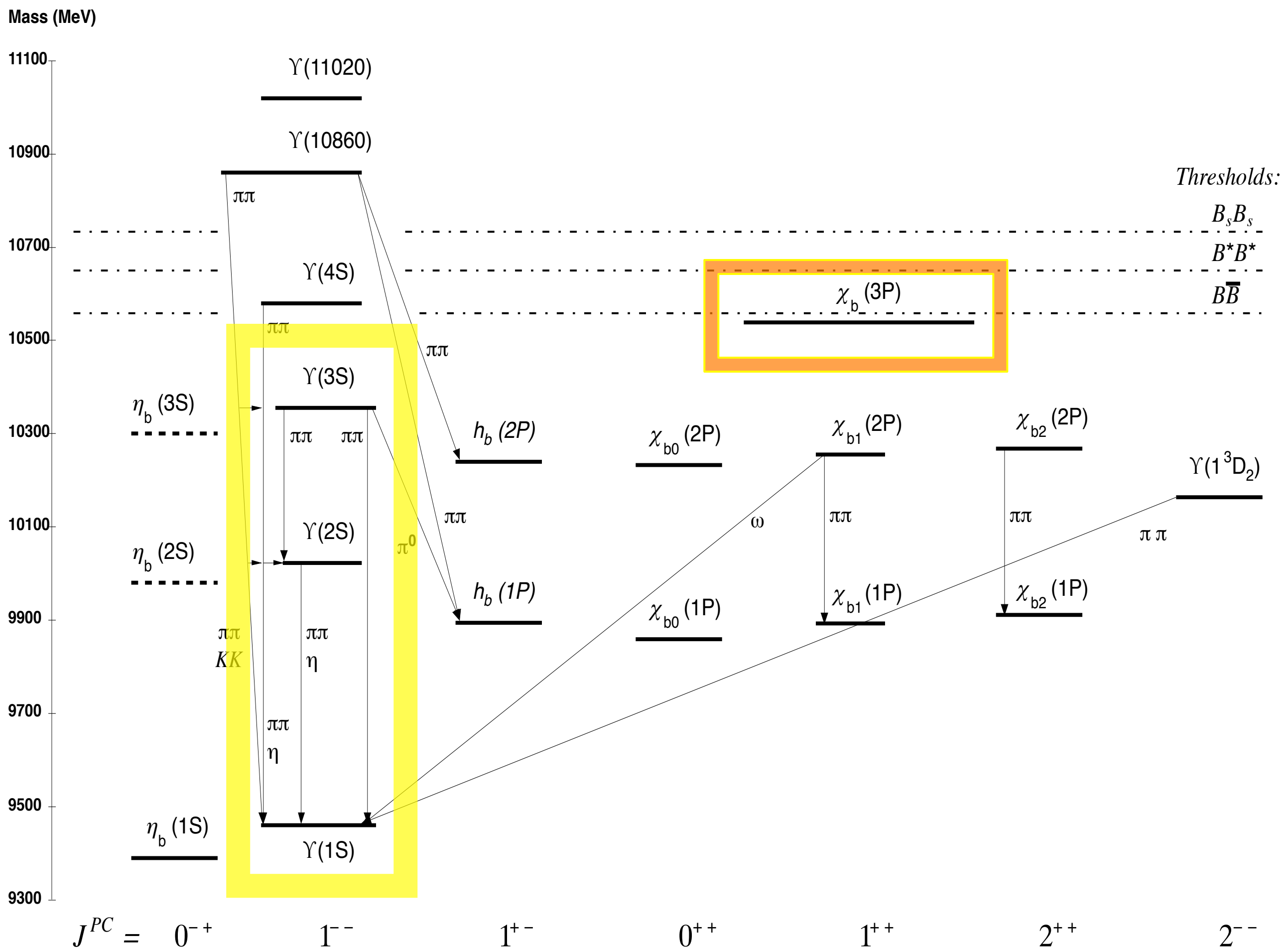
Relative initial populations in pp computed using an inverted cascade from the final populations measured by CMS and CDF(χ_b)
[N_{final}(1S):=1]

$N_{initial}$

3S: 0.387

2S: 0.371

1S: 0.458



$N_{initial}$

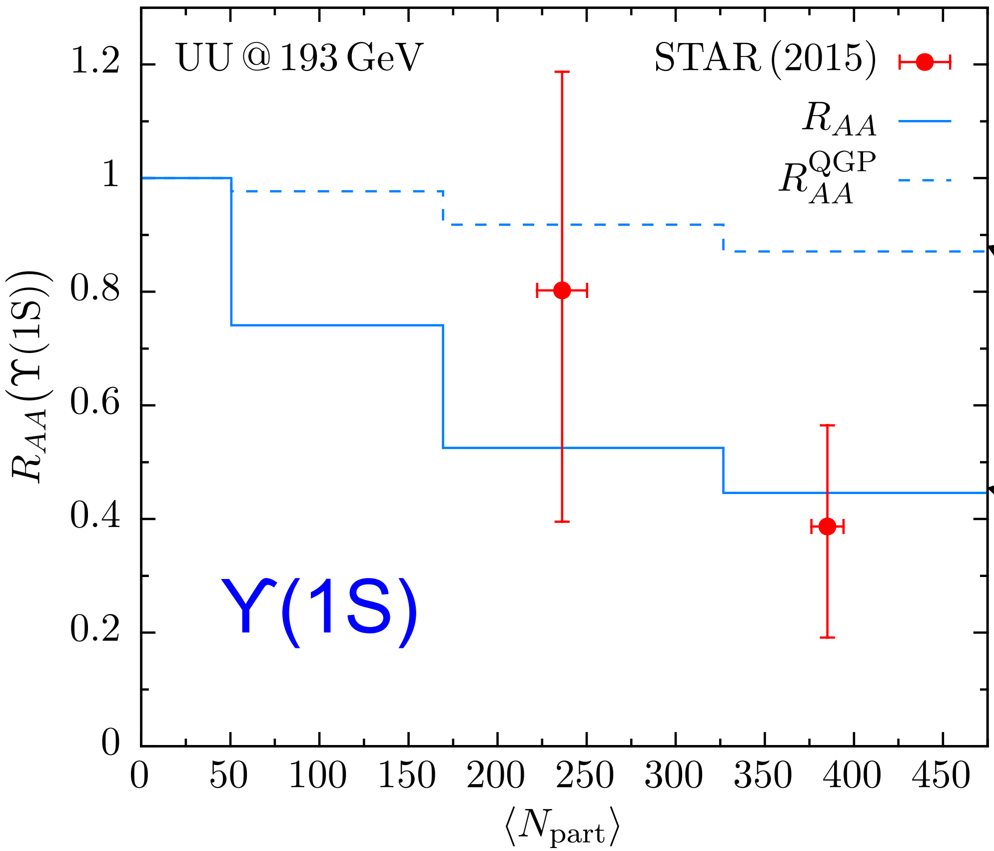
2P: 0.976

1P: 1.29

3. Theoretical vs. exp. (STAR, CMS) suppression

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

t_F: ϒ formation time
T_0 @ t_F: initial central temperature



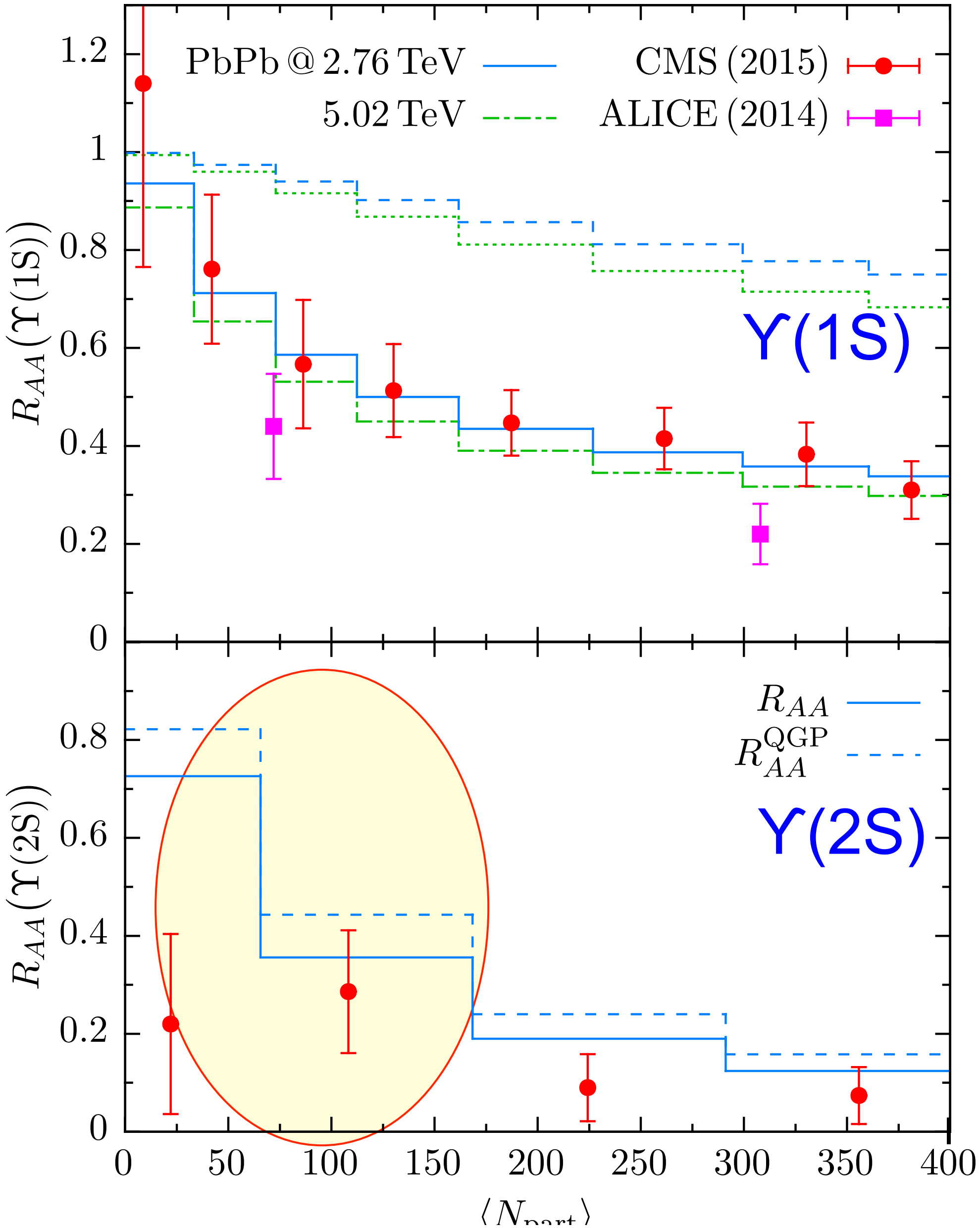
t_F= 0.4 fm/c
T_0= 417 MeV

QGP suppression only

with modified feed-down cascade

J. Hoelck, F. Nendzig and GW, arXiv:1602.00019 (2016)

Theoretical vs. exp. (CMS) suppression factors



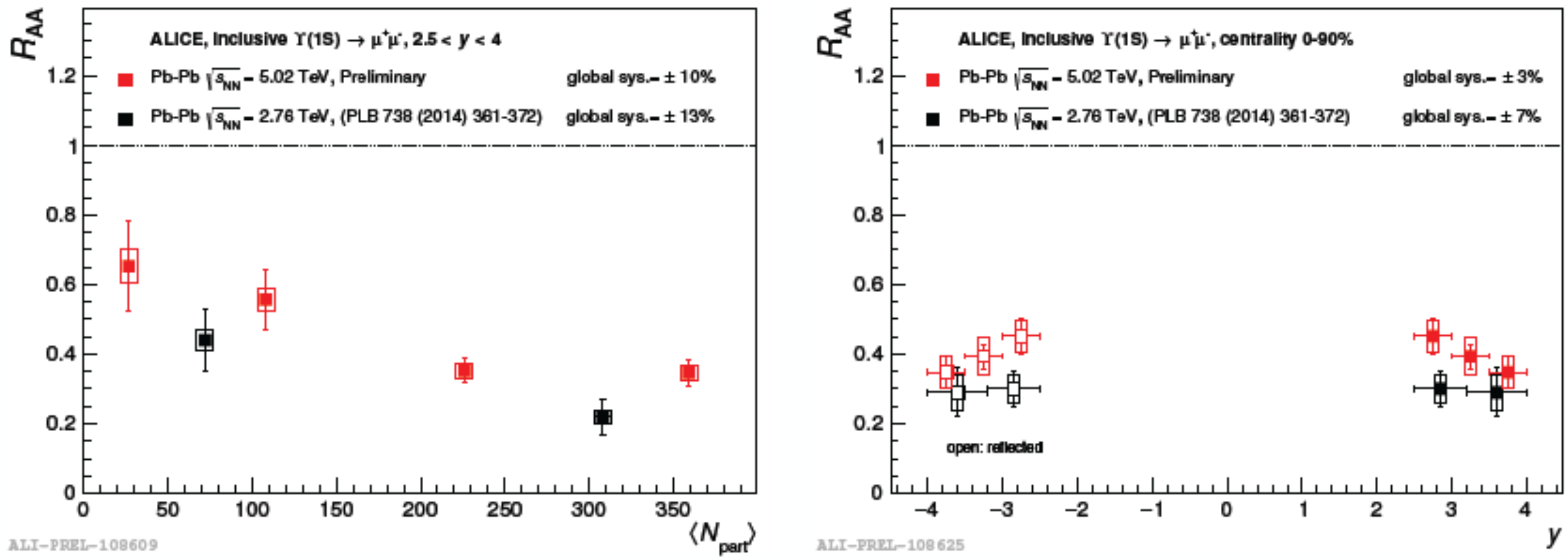
t_F= 0.4 fm/c: Υ formation time
T_0= 550 MeV: central temp.
at b = 0 and t = t_F

2.76/ 5.02 TeV PbPb

Room for additional suppression mechanisms for the excited states: Hadronic dissociation, mostly by pions, is one possibility. Thermal pions are in-sufficient; direct pions may contribute, and magnetic dissociation.

J. Hoelck, F. Nendzig and GW, arXiv:1602.00019 (2016)

Collision energy comparison: 5.02 TeV PbPb ALICE prel. data **NEW**



R_{AA} (5.02 TeV, 0-90%) = 0.40 ± 0.03 (stat.) ± 0.04 (syst.)

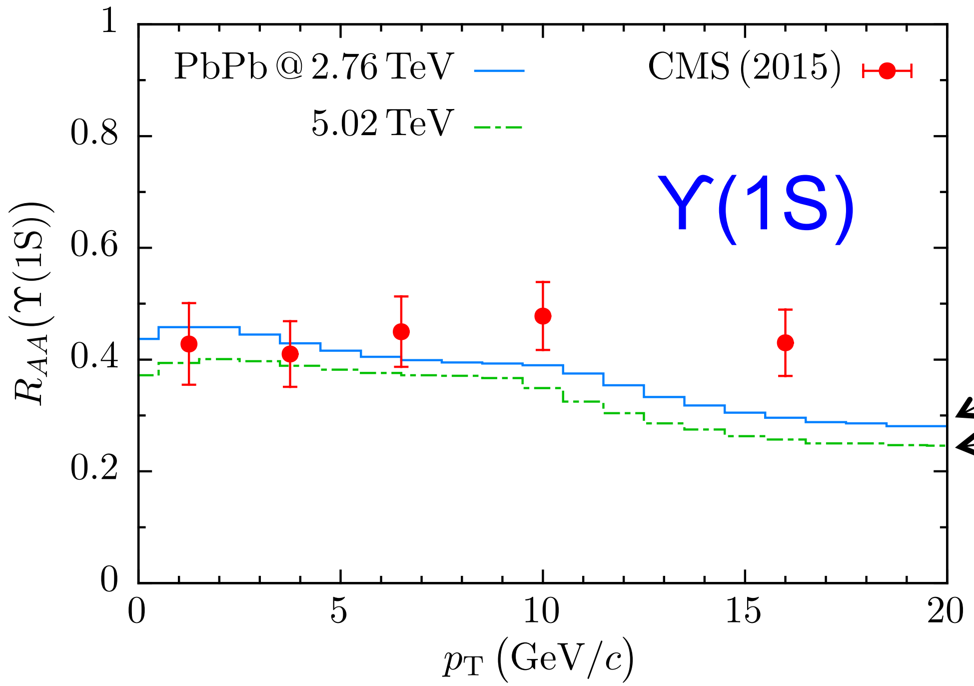
R_{AA} (2.76 TeV, 0-90%) = 0.30 ± 0.05 (stat.) ± 0.04 (syst.)

Larger R_{AA} values at 5.02 TeV than at 2.76 TeV but remain compatible within uncertainties.

Transverse momentum dependence of Υ(1S) suppression in PbPb at 2.76/5.02 TeV

Γ-averaging, min. bias 0-100%; Doppler shift:

$$T_{\text{eff}}(T,\boldsymbol{u}) = T\frac{\sqrt{1-|\boldsymbol{u}|^2}}{1-|\boldsymbol{u}|\cos\theta}$$



< 10% higher suppression at 5.02 TeV vs 2.76 TeV

2.76 TeV (calculation)

5.02 TeV (prediction)

(t_F= 0.4 fm/c; prel. CMS data 2015/16)

5. Conclusion ϒ at RHIC and LHC

- The suppression of the ϒ(1S) ground state in UU collisions at RHIC and PbPb at LHC energies through gluodissociation, damping, screening, and reduced feed-down 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 flat p_T dependence is understood based on the relativistic Doppler effect.

- The enhanced suppression of the ϒ(2S, 3S) relative to the 1S state in PbPb as compared to pp collisions at LHC energies (CMS) leaves room for additional suppression mechanisms, in particular for peripheral collisions where discrepancies to the CMS data persist. Hadronic and/or magnetic dissociation of the excited states may be relevant.

❖ Thank you for your attention,

and for organizing ISMD2016 !