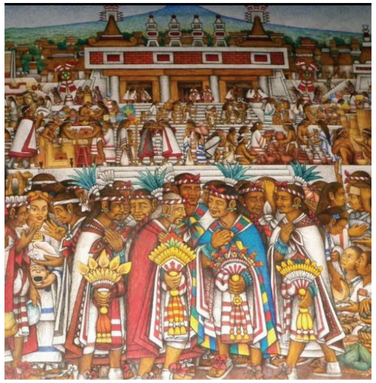
Bottomonia physics at RHIC and LHC energies

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



Topics

1. Introduction: Υ suppression in the Quark-Gluon Plasma

2. Model for bottomonium suppression

   2.1 Complex potential: Screening and damping

   2.2 Gluon-induced dissociation

   2.3 Hydrodynamic expansion

   2.4 Feed-down cascade

   2.5 Relativistic Doppler effect; p_T-dependent results vs. data

3. Comparison with centrality-dependent data

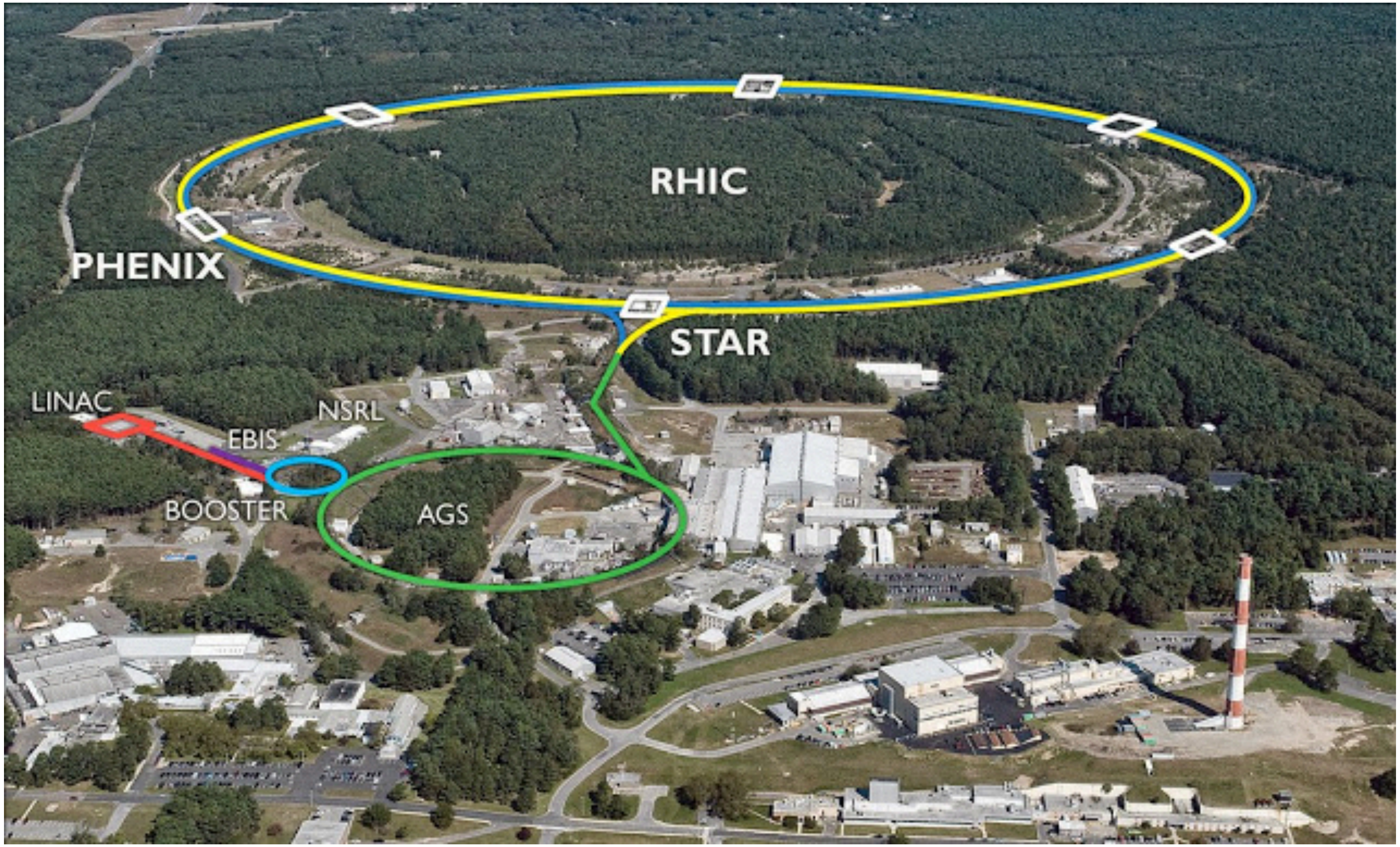
   3.1 193 GeV UU: STAR @ RHIC

   3.2 2.76 TeV PbPb: CMS and ALICE @ LHC

4. Prediction for 5.02 TeV PbPb

5. Conclusion

1. Quarkonia at the Relativistic Heavy Ion Collider, BNL



e.g. Au+Au collisions @ $\sqrt{s_{NN}}$= 200 GeV center of mass energy

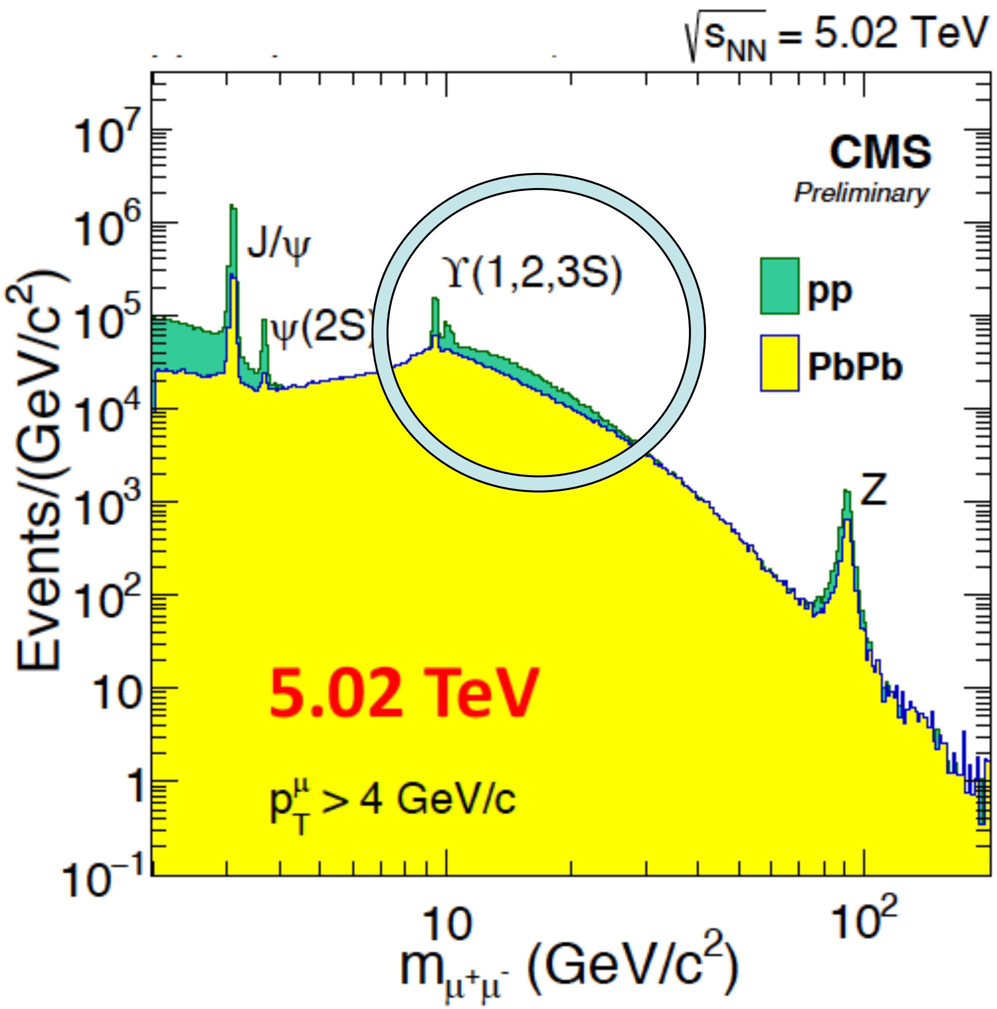
Quarkonia physics at the Large Hadron Collider, CERN

p+p @ 7,8,13,(14) TeV

p+Pb @ 5.02 TeV 2012/13
@ 5.02, 8.16 TeV 2016

Pb+Pb @ 2.76 TeV 2011/12 Run 1
@ 5.02 TeV Oct. 2015 Run 2
(design energy 5.52 TeV)

Υ suppression in PbPb @ LHC



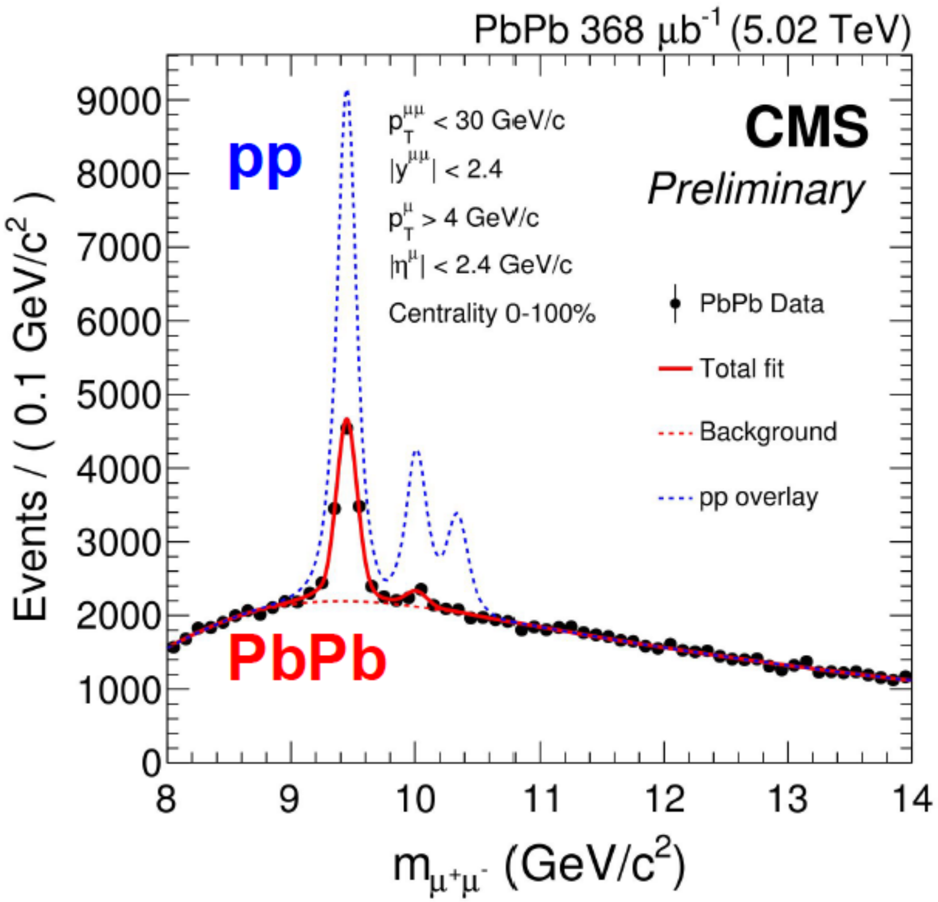
Υ suppression as a sensitive probe for the QGP

- 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., Hard Probes Wuhan (2016); CMS-PAS-HIN-16-023 (2016)

Υ(nS) suppression in 5.02 TeV PbPb @ LHC:



A clear QGP indicator

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

R_{AA} (Υ(1S)) = 0.36 ± 0.014 ± 0.048, min. bias

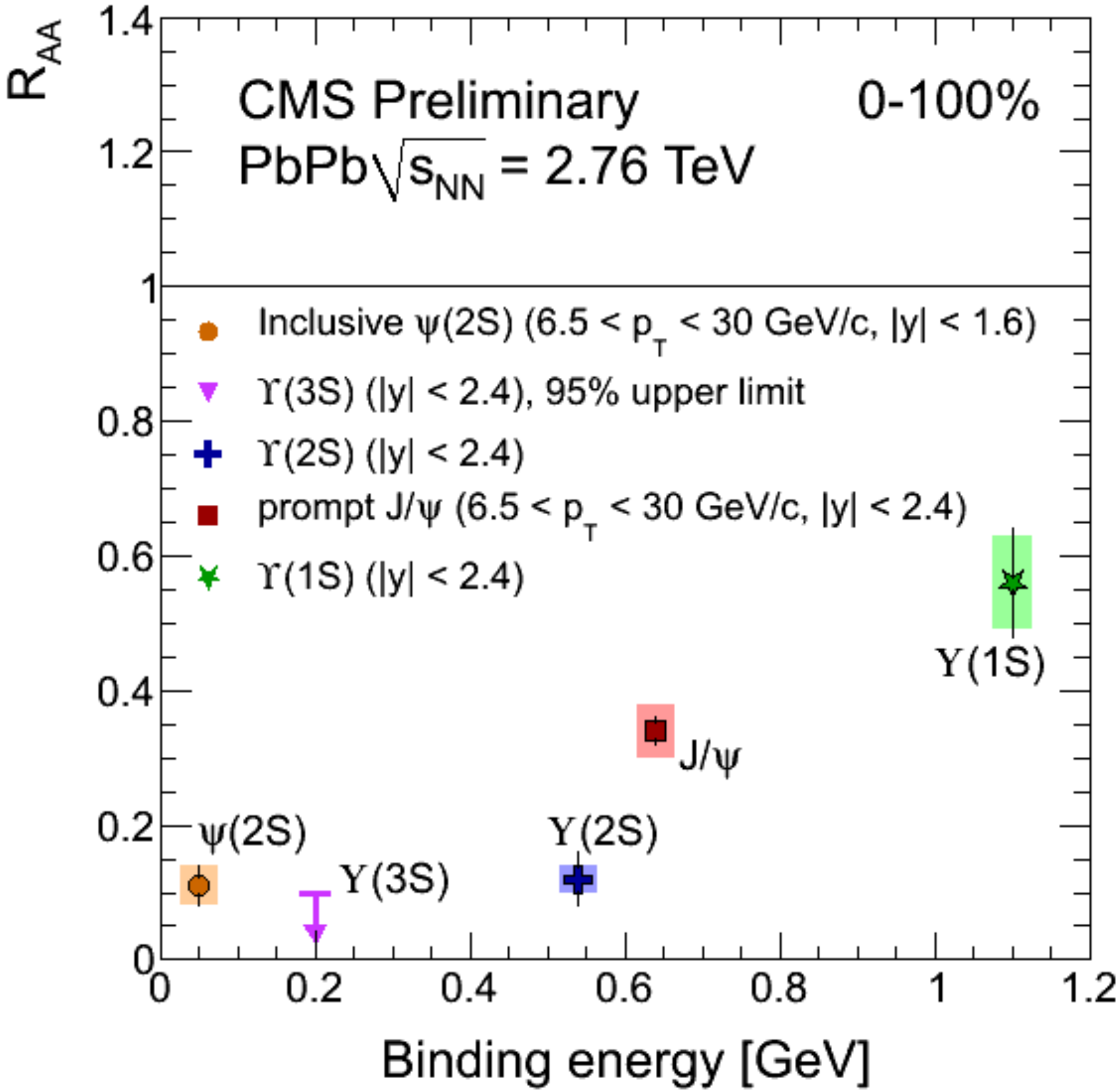
2. Υ(2S, 3S) states are >3 times stronger suppressed in PbPb than Υ(1S)

R_{AA}(Υ(2S)) = 0.104 ± 0.021 (stat.) ± 0.014
R_{AA}(Υ(3S)) < 0.071 at 95 % CL

CMS-PAS-HIN-16-023 (2016)

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

Sequential suppression of Υ(nS) and J/ψ states (2.76 TeV)



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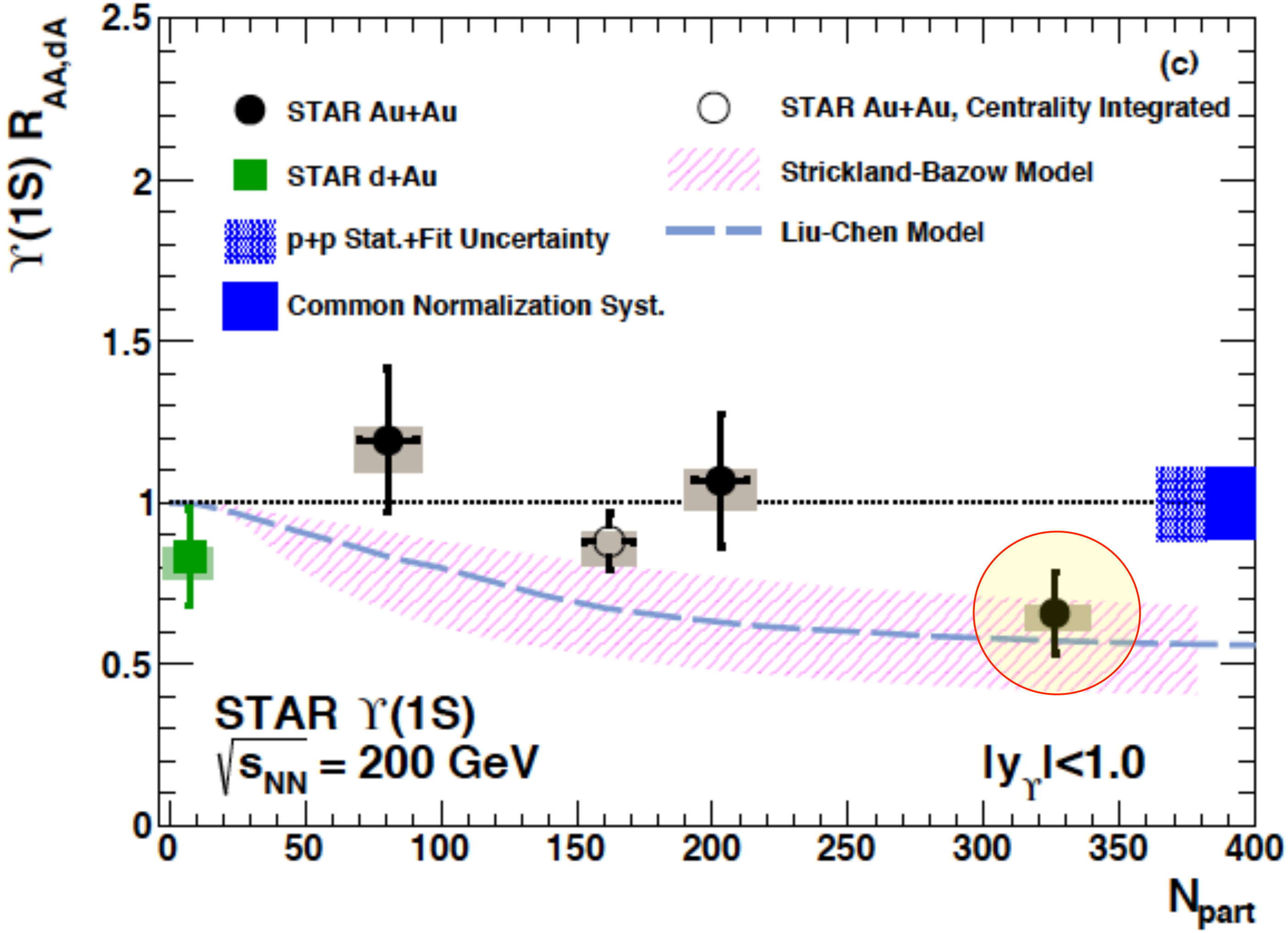
Υ(nS) states are suppressed in 200 GeV AuAu @ RHIC



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

2. The model: Screening, Gluodissociation 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

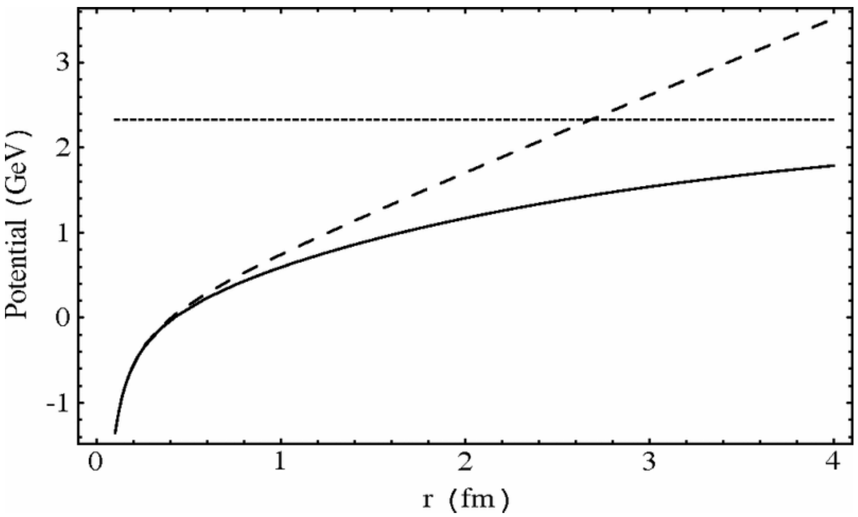
- Gluon-induced dissociation: dynamic suppression, in particular of the Υ(1S) ground state due to the large thermal gluon density

- 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, to be publ.
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)

Screening in a nonrelativistic potential model

Proposal Matsui&Satz 1986: At high temperatures in the Quark-Gluon medium, the Cornell-type real quark-antiquark potential is 'color-screened', analogously to the Debye screening in an electromagnetic plasma



$$V_{\mathrm{Cornell}}(r) = (\sigma r - \kappa / r)$$

$$V_{\mathrm{screened}}(r) = -\frac{\kappa}{r} e^{-r/\lambda_D} + \sigma \lambda_D (1 - e^{-r/\lambda_D})$$

σ string tension, $\kappa = (4\alpha_s/3)$ Coulomb-parameter

$$\lambda_{\mathrm{D}}(T) = \frac{1}{T}\sqrt{\frac{6}{2N_c + N_f}\frac{1}{4\pi\alpha_s}}$$

Debye length

⇒ Heavy mesons can "melt" in the hot medium,

⇒ But there are the important effects of damping, gluodissociation and reduced feed-down

2.1 Screening and damping treated in a nonrelativistic potential model

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

$$\phi(x) = \int_0^\infty \frac{dz\,2z}{(1+z^2)^2}\left(1-\frac{\sin xz}{xz}\right),\; m_D(T) = \lambda^{-1}(T)$$

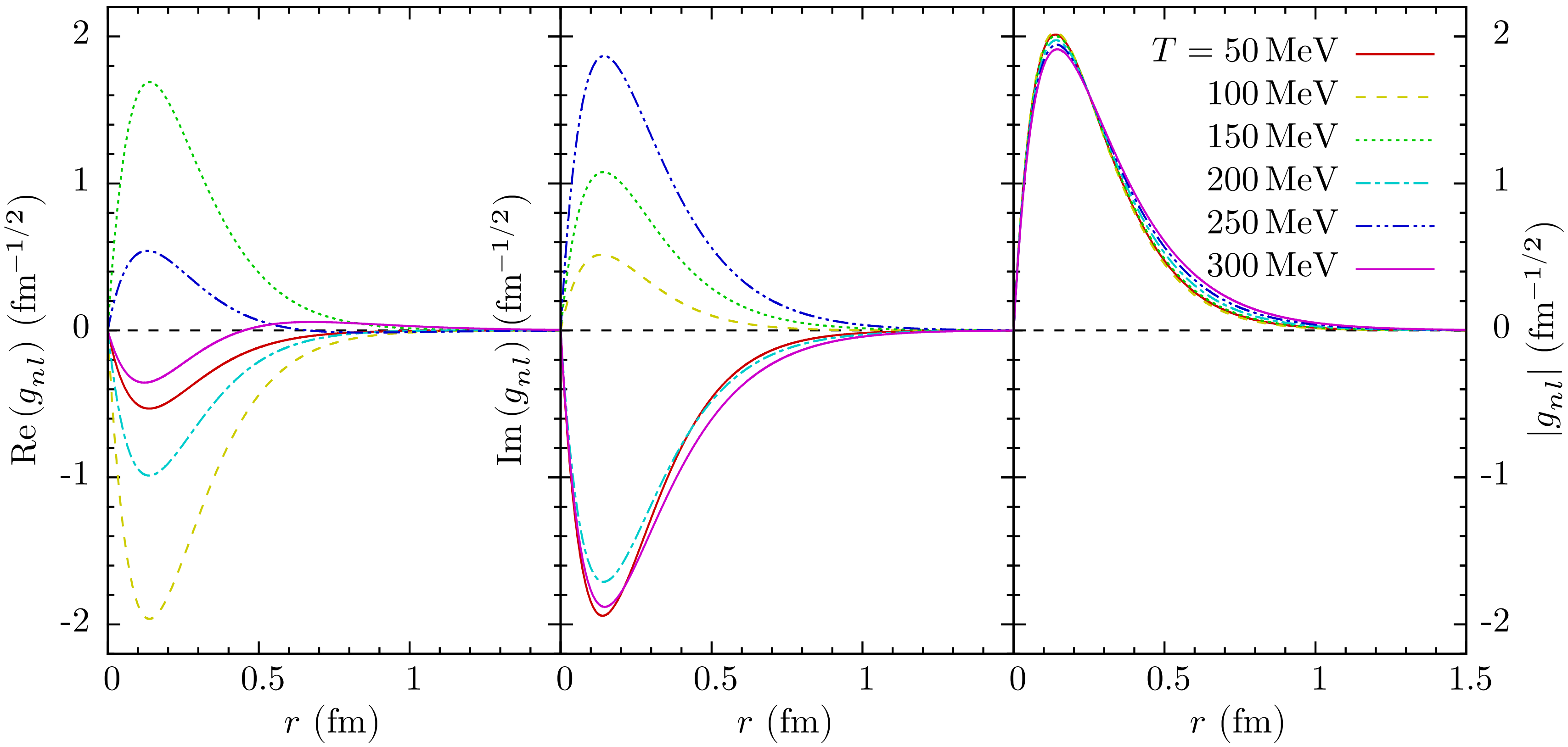
Screened potential: m_D = Debye mass,
α_{nl}(T): the strong coupling constant α_s at $\langle 1/r\rangle_{nl}$ (T)
$C_F = (N_c^2 - 1) / (2N_c)$
$\sigma \approx 0.192\text{GeV}^2$ the string tension(Jacobs et al.; Karsch et al.)

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 Gluon-induced dissociation

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)

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

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

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

Gludissociation cross section

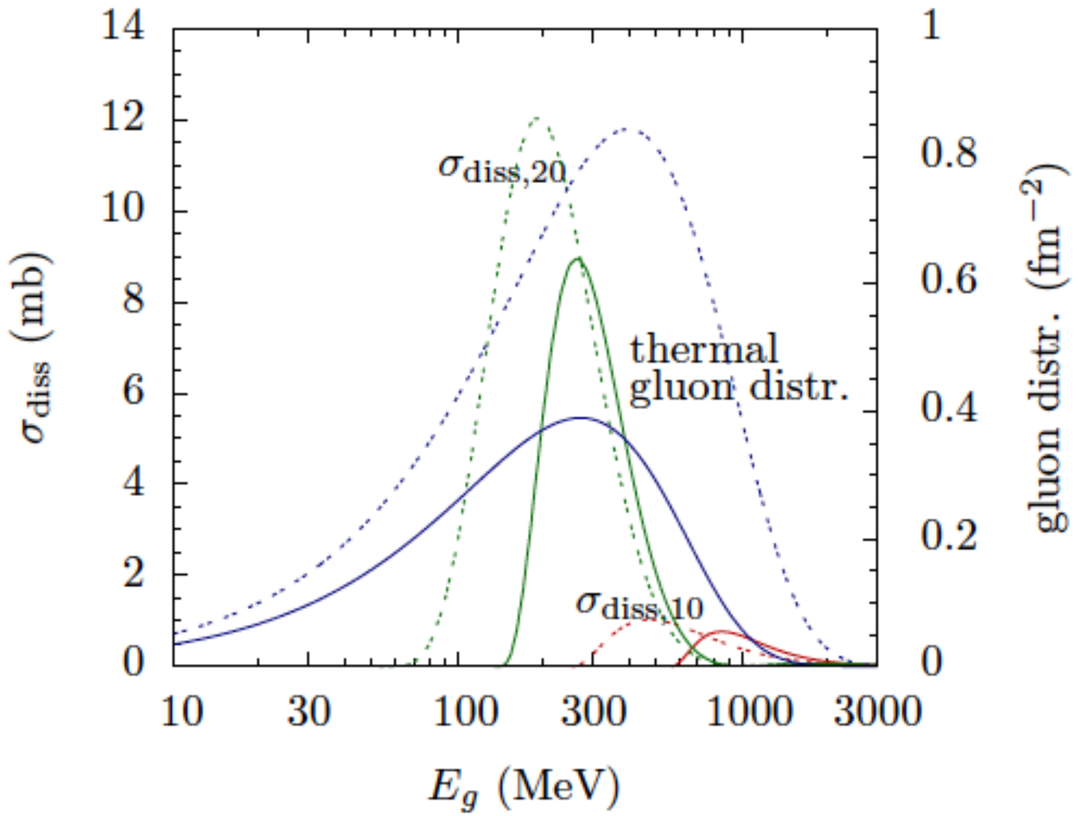


Figure 3. Gludissociation cross section σ_{diss} (left scale) of the $\Upsilon(1S)$ and $\Upsilon(2S)$ and the thermal gluon distribution (right scale) plotted for temperature $T = 170$ (solid curves) and 250 MeV (dotted curves) as functions of the gluon energy E_g.

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

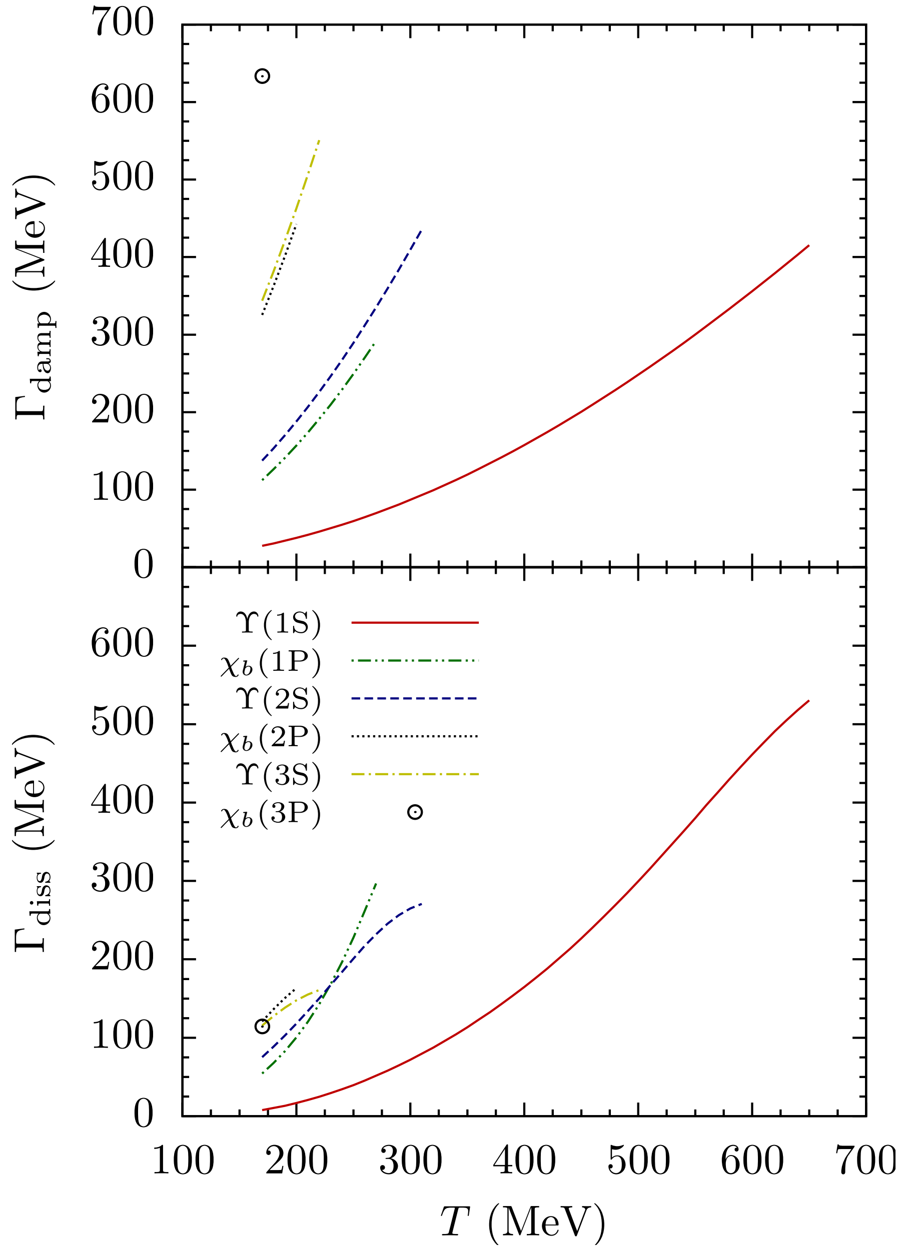
$$\Gamma_{\mathrm{diss},\,nl}(T) \equiv \frac{g_d}{2\pi^2} \int_0^\infty \frac{\mathrm{d}E_g\, E_g^2\, \sigma_{\mathrm{diss},\,nl}\left(E_g\right)}{\mathrm{e}^{E_g/T} - 1}$$

($g_d = 16$)

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

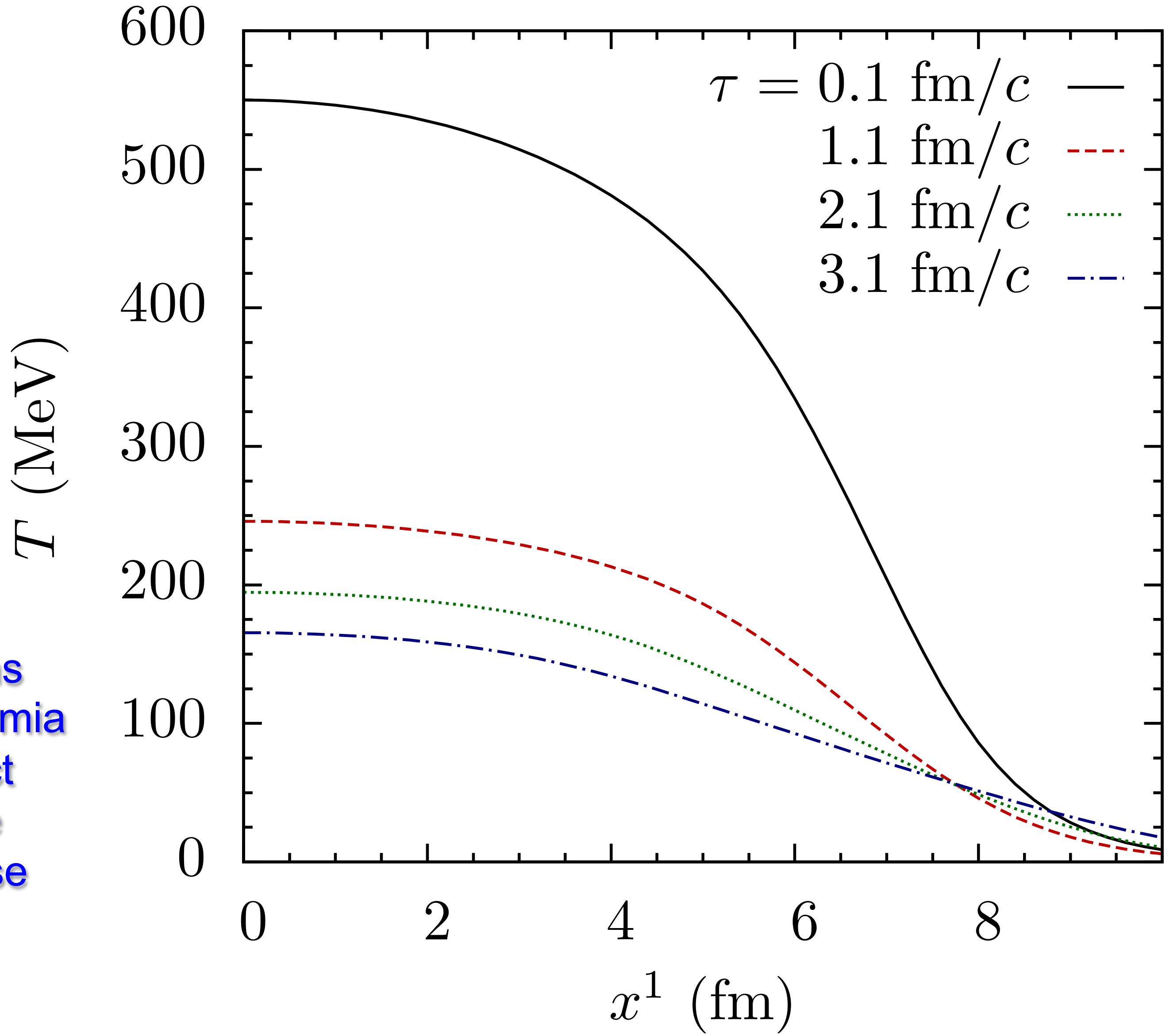
$$\Gamma_{tot}(T) = \Gamma_{damp}(T) + \Gamma_{diss}(T)$$



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

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

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

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

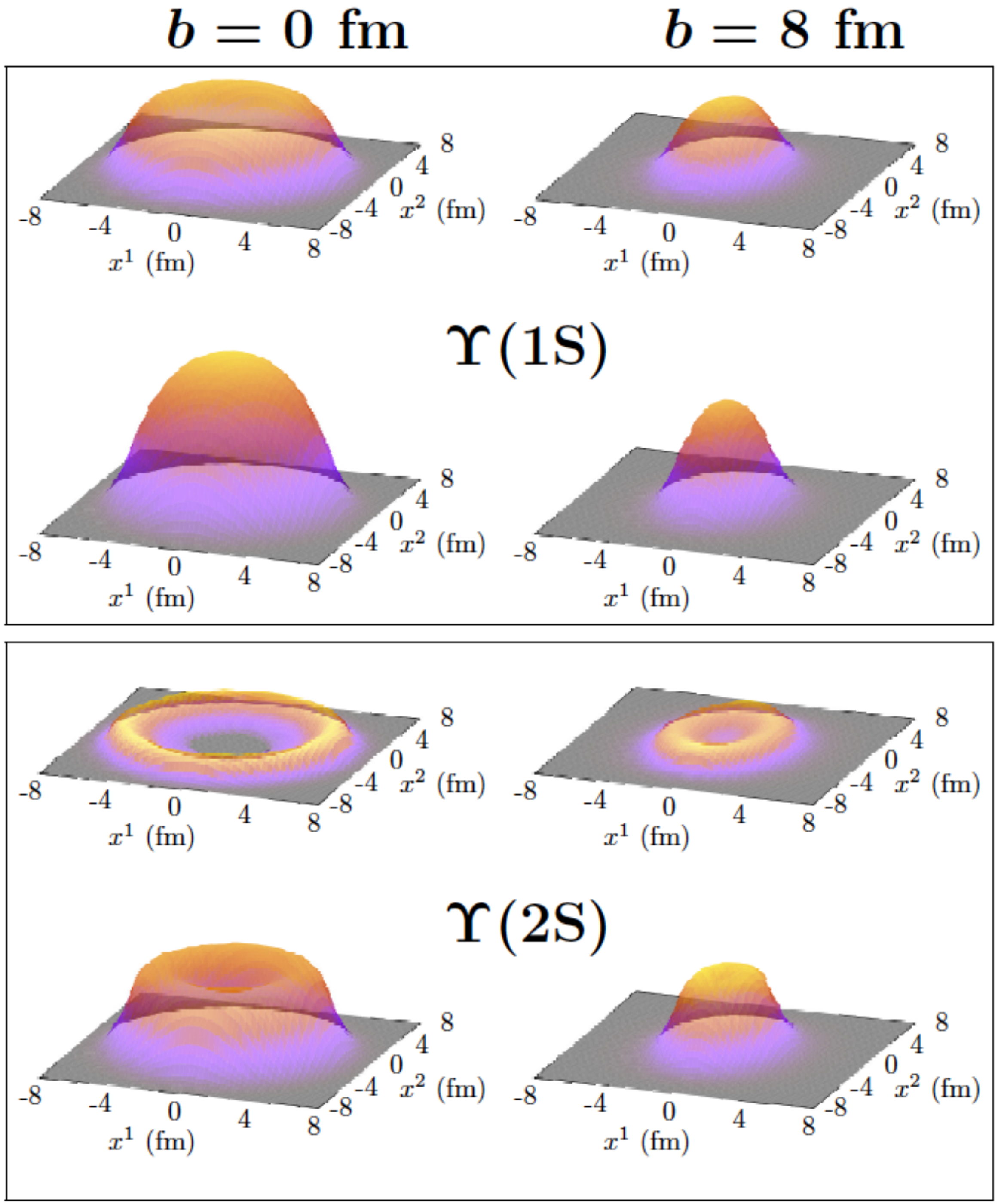
The number of produced $b\bar{b}$-pairs is proportional to the number of binary collision, and the nuclear overlap

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

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

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

Integrand in the transverse plane



p_T = 0

p_T = 12 GeV/c

p_T = 0

p_T = 12 GeV/c

J. Phys. G41, 095003 (2014)

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).

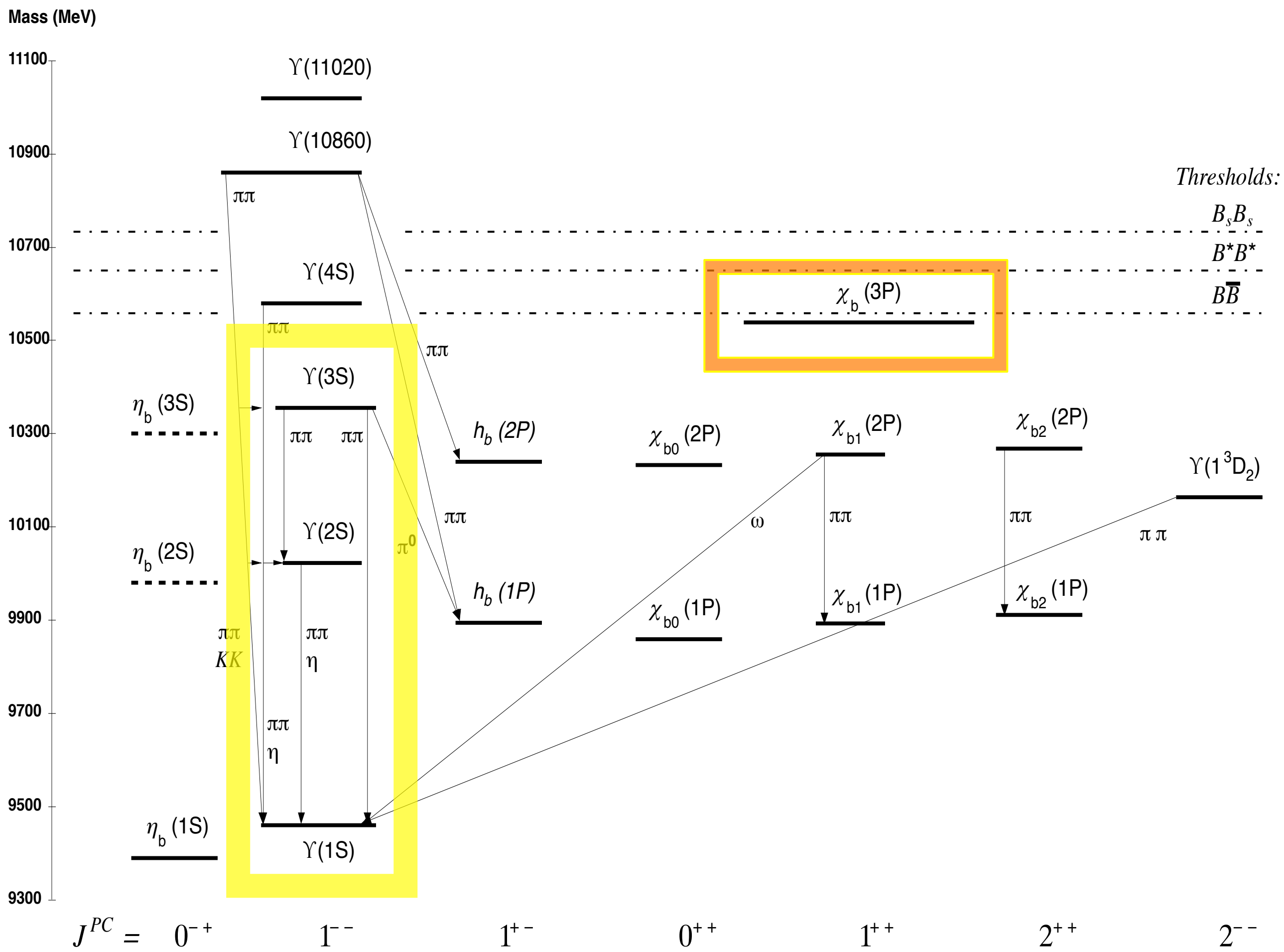
Feed-down is reduced if excited states are screened or depopulated

N$_{initial}$

3S: 0.324

2S: 0.367

1S: 0.373

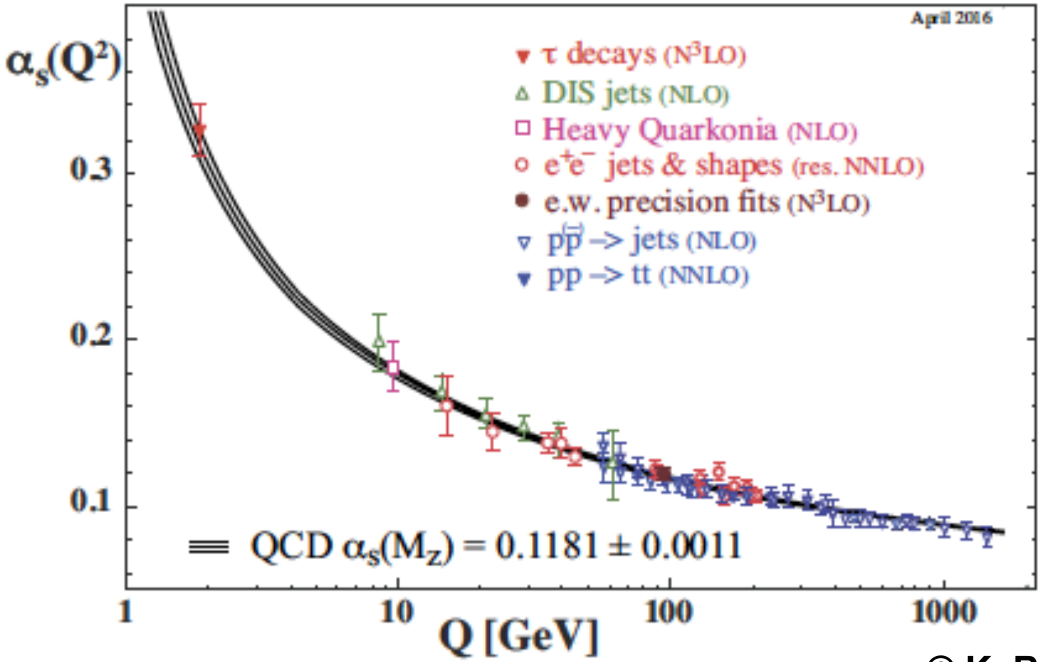


N$_{initial}$

2P: 0.881

1P: 1.084

More model ingredients



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- Consider running of the coupling
- Transverse momentum distribution of the ϒ included, $\langle p_T \rangle \approx 6$ GeV/c
- Relativistic Doppler effect included
- T_c = 160 MeV

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

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

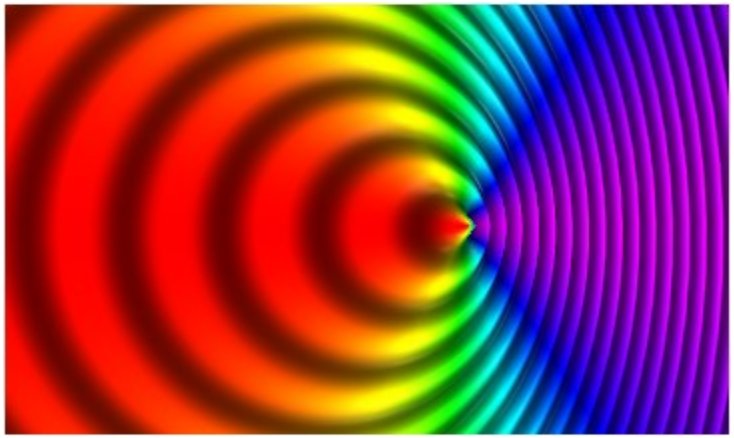
$\alpha_{nl}(T)$ depends on the solution $g_{nl}(r,T)$ of the Schrödinger eq.: Iterative solution

Relativistic Doppler effect

For a finite relative velocity between the expanding QGP and the bottomium states the relativistic Doppler shift results in an angle-dependent effective temperature

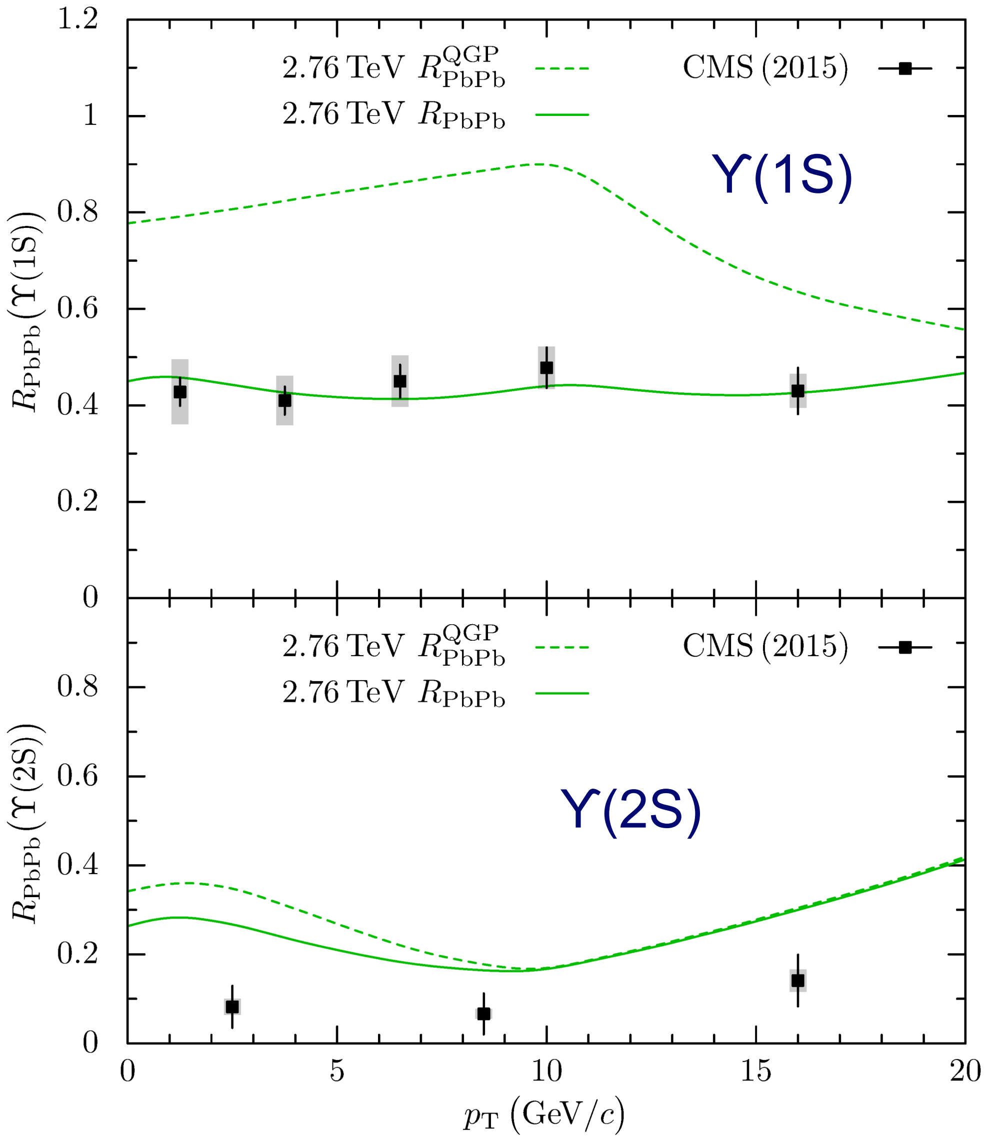
$$T_{\text{eff}}(T, \boldsymbol{u}) = T \frac{\sqrt{1 - |\boldsymbol{u}|^2}}{1 - |\boldsymbol{u}| \cos\theta}$$

with the angle θ between the medium velocity **u** (in the bottomium restframe) and the direction of the incident light parton. This effective temperature is anisotropic: blue-shifted for θ ≈ 0°, red-shifted in the opposite direction.



This has a significant effect on the transverse momentum distributions of the Υ's: It leads to more suppression in the high-p_T region.

Transverse momentum dependence of ϒ(1S) suppression in PbPb at 2.76 TeV: Width-averaging



The ϒ(1S) suppression is mostly reduced feed-down (31% in-medium), the ϒ(2S) suppression primarily in-medium (94% in min. bias)

← In-medium suppression only

← Including reduced feed-down

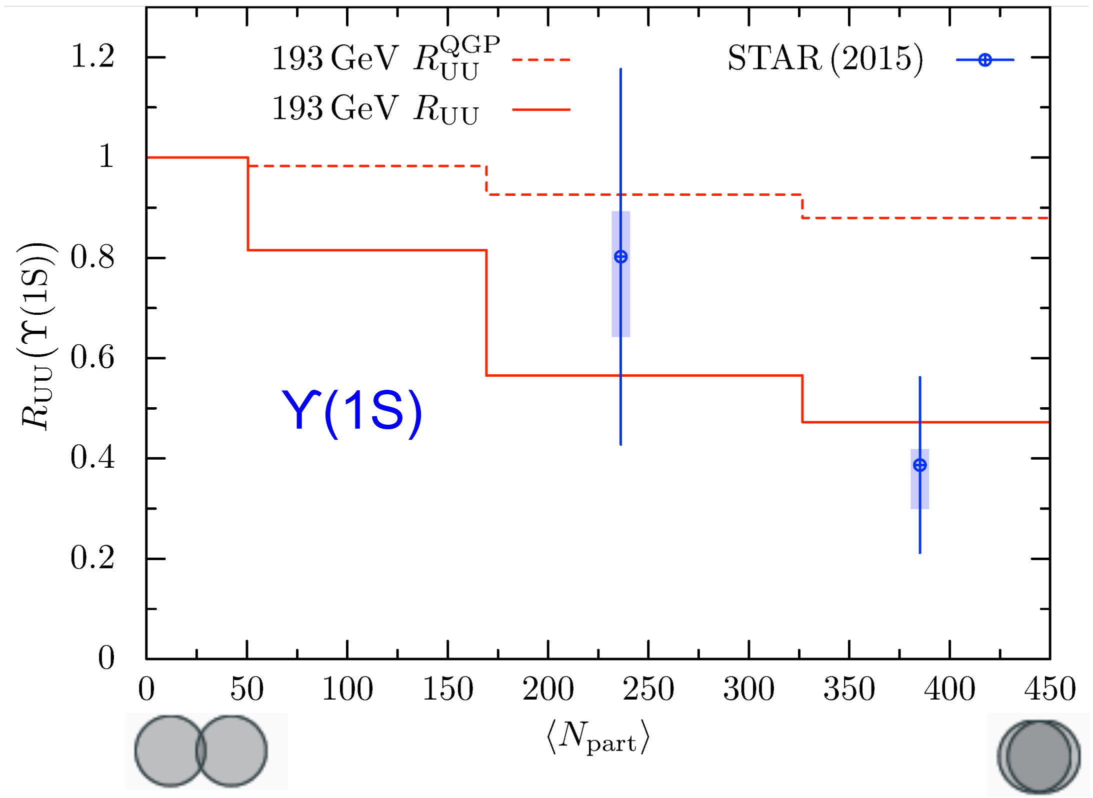
(t_F= 0.4 fm/c; prel. CMS data 2015)

J. Hoelck, F. Nendzig and GW, Phys. Rev. C 95, 024905 (2017)

Reduced feed-down only relevant for ϒ(1S), not for excited states

3. Comparison with centrality-dependent data

3.1 Theoretical vs. exp. (STAR) ϒ(1S)-suppression factors: Centrality dependent, p_T- integrated

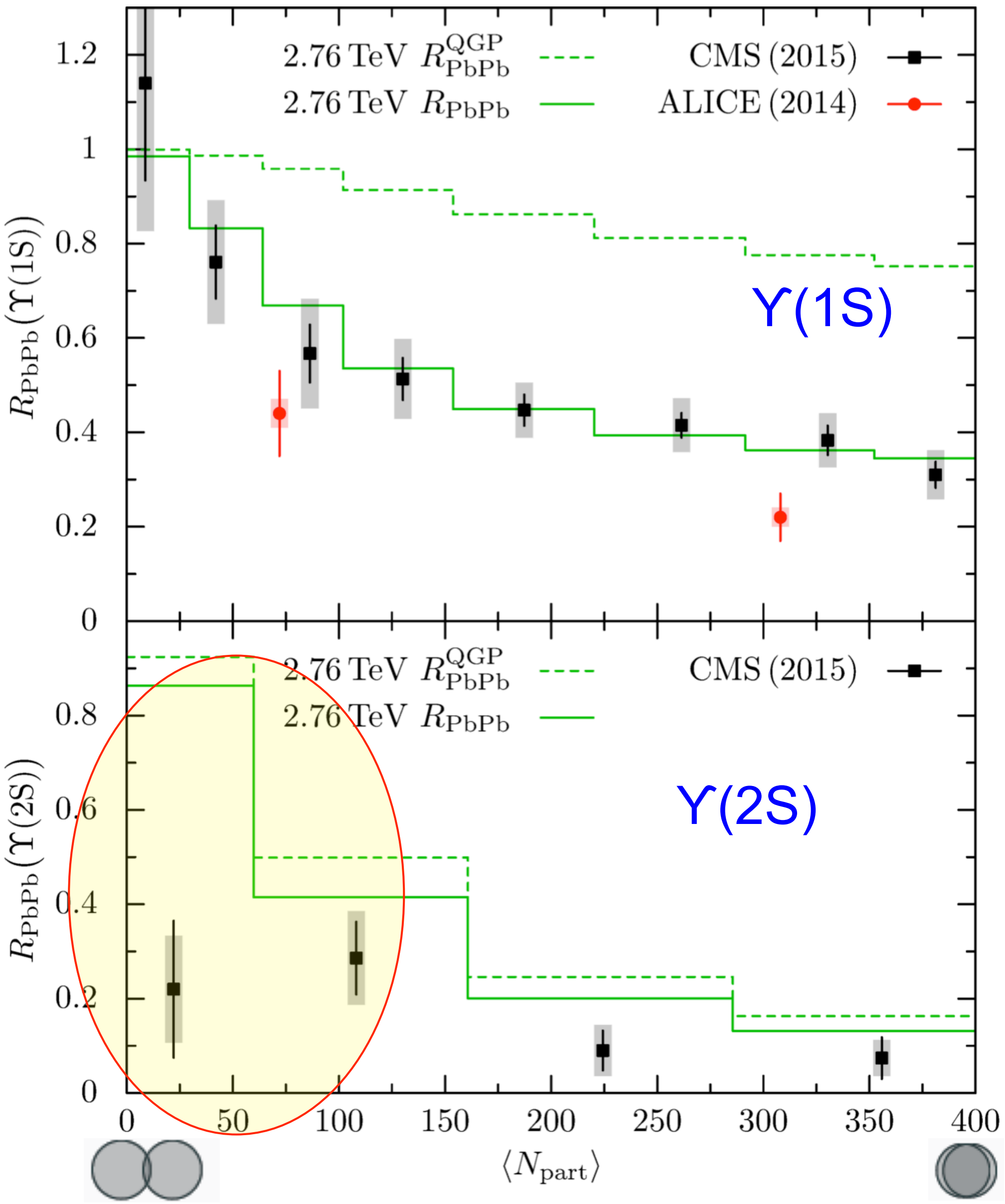


193 GeV UU RHIC

t_F= 0.4 fm/c: ϒ formation time
T_0= 417 MeV: central temp.
at b = 0 and t = t_F

J. Hoelck, F. Nendzig and GW, Phys. Rev. C 95, 024905 (2017)

3.2 2.76 TeV PbPb: CMS and ALICE



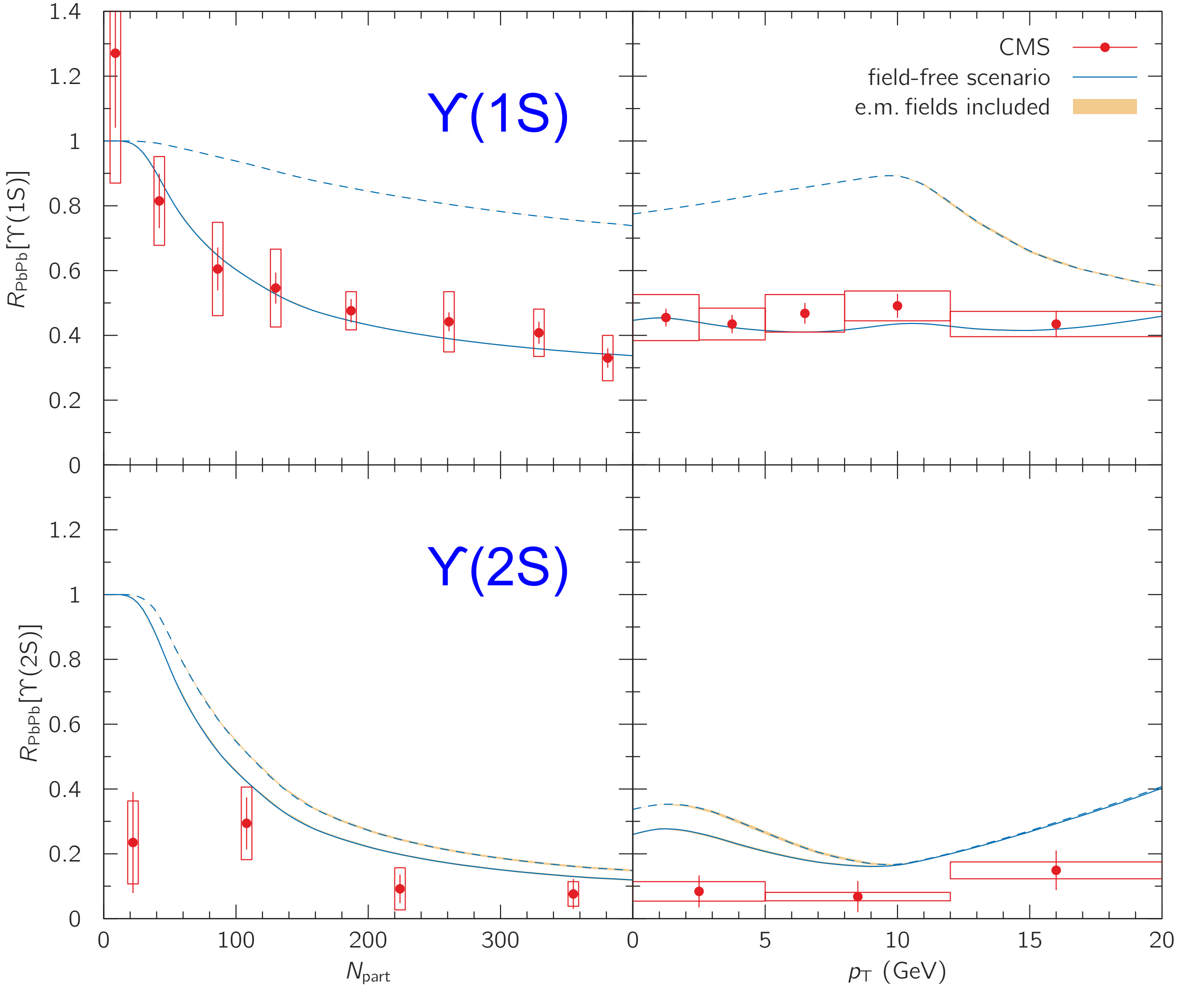
2.76 TeV PbPb LHC

t_F= 0.4 fm/c: Υ formation time
T_0= 480 MeV: central temp.
at b = 0 and t = t_F

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 electromagnetic dissociation.

J. Hoelck, F. Nendzig and GW,
Phys. Rev. C 95, 024905 (2017)

2.76 TeV PbPb: Electromagnetic field effects



t_F= 0.4 fm/c: Υ formation time
T_0= 480 MeV: central temp.
at b = 0 and t = t_F
QGP conductivity: σ = 5.8 MeV

$$\boldsymbol{B}_q = \frac{q}{4\pi} e^{-\varrho^2\sigma/4t_{\rm eff}} \frac{v\varrho\sigma}{2t_{\rm eff}^2} \boldsymbol{e}_\varphi$$

$$t_{\rm eff} = x^0 - x^3/v$$

$$\varrho = \sqrt{(x^1)^2 + (x^2)^2}$$

$$\varphi = \arctan(x^2/x^1)$$

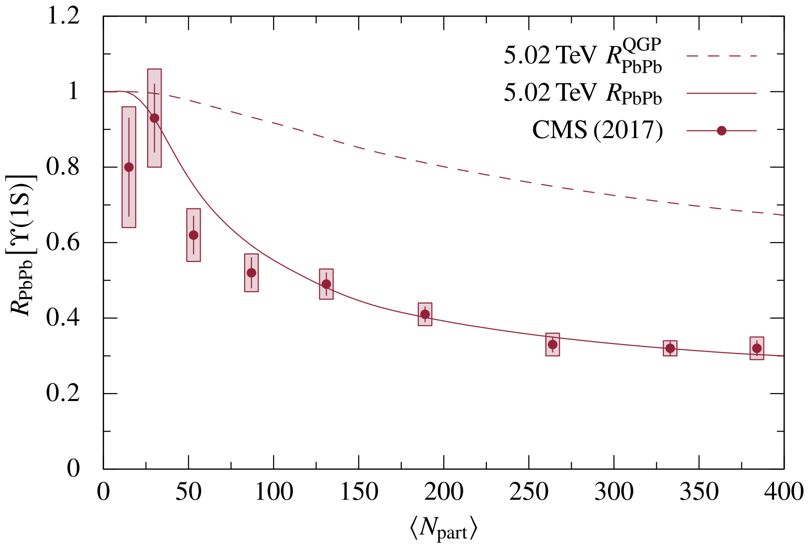
No significant em. field effects:

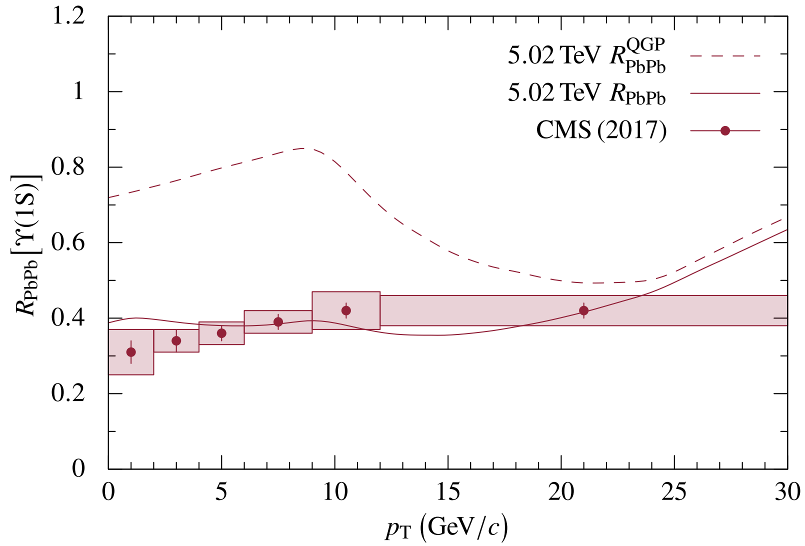
Although the field decays in the medium on a time scale that is larger than t_F, the magnitude is considerably reduced such that it can not produce additional suppression

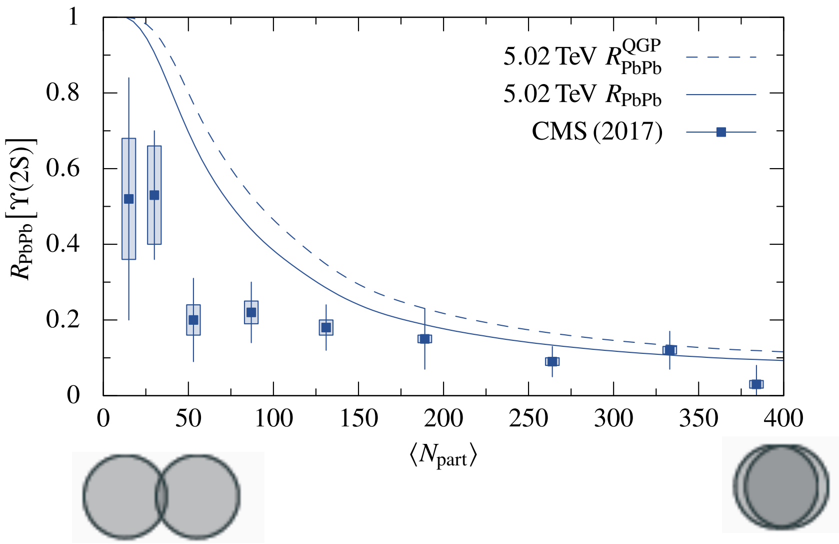
CMS data: Phys. Lett. 770, 357 (2017)

J. Hoelck and GW, submitted to EPJA

4. Prediction for Υ suppression at 5.02 TeV vs. prel. CMS data







Prel. CMS data from QM2017, Chicago

T_{max} @ t_F: 513 MeV

< 10% higher suppression at 5.02 TeV vs 2.76 TeV: within experimental error bars

J. Hoelck and GW (2017)

5. Conclusion Υ suppression

- The suppression of the Υ(1S) ground state in PbPb collisions at LHC energies through gluodissociation, damping, screening, and reduced feed-down has been calculated as function of p_T, and 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 Υ(1S) suppression is mostly reduced feed-down, the Υ(2S) primarily in-medium. The prediction for 5.02 TeV PbPb gives good results cp. to prel. CMS data.

- The enhanced suppression of Υ(2S, 3S) leaves room for additional suppression mechanisms, in particular for peripheral collisions where discrepancies to the CMS data persist. Electromagnetic effects are not strong enough. Hadronic dissociation of the excited states or other cold nuclear matter (CNM) effects may be relevant.

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Thank you for your invitation and attention !