Bottomia physics at RHIC and LHC energies

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Topics

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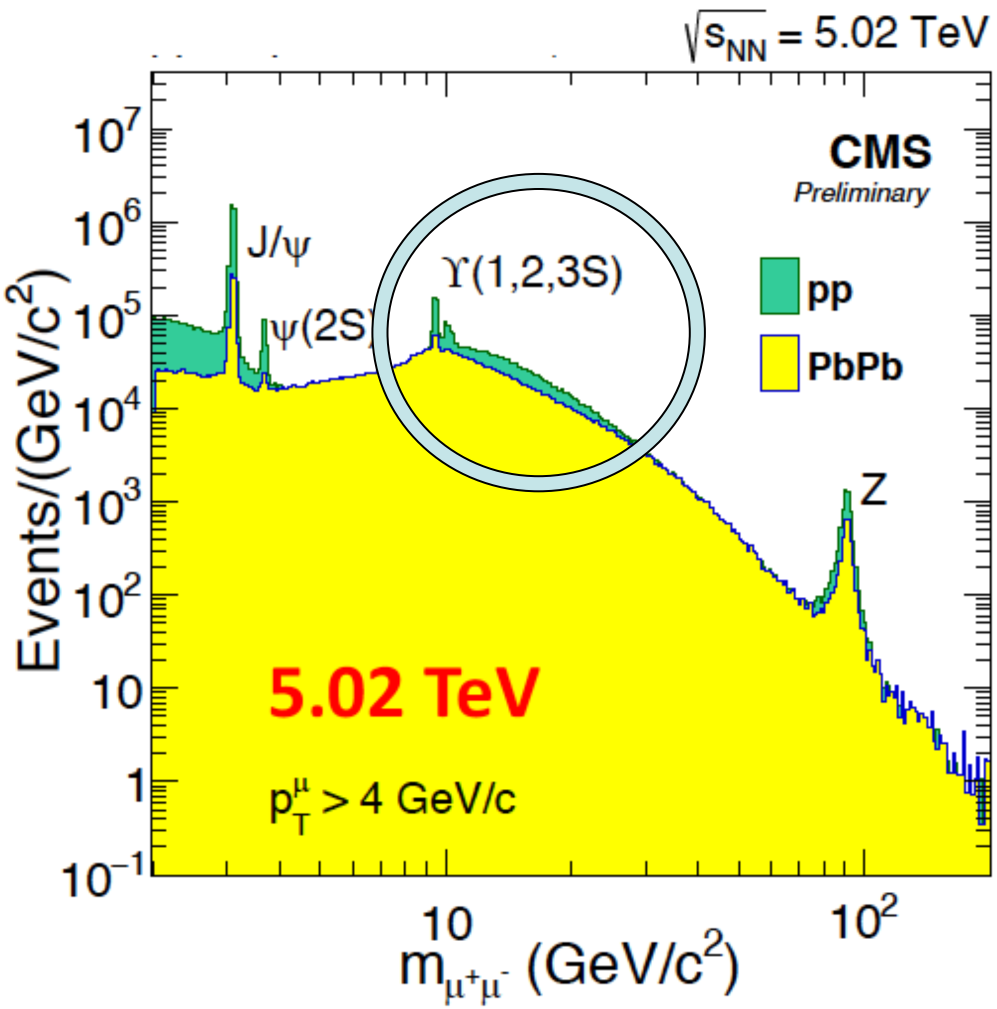
1. Introduction: Υ Suppression in PbPb @ LHC



CMS Collab., Hard Probes Wuhan (2016)

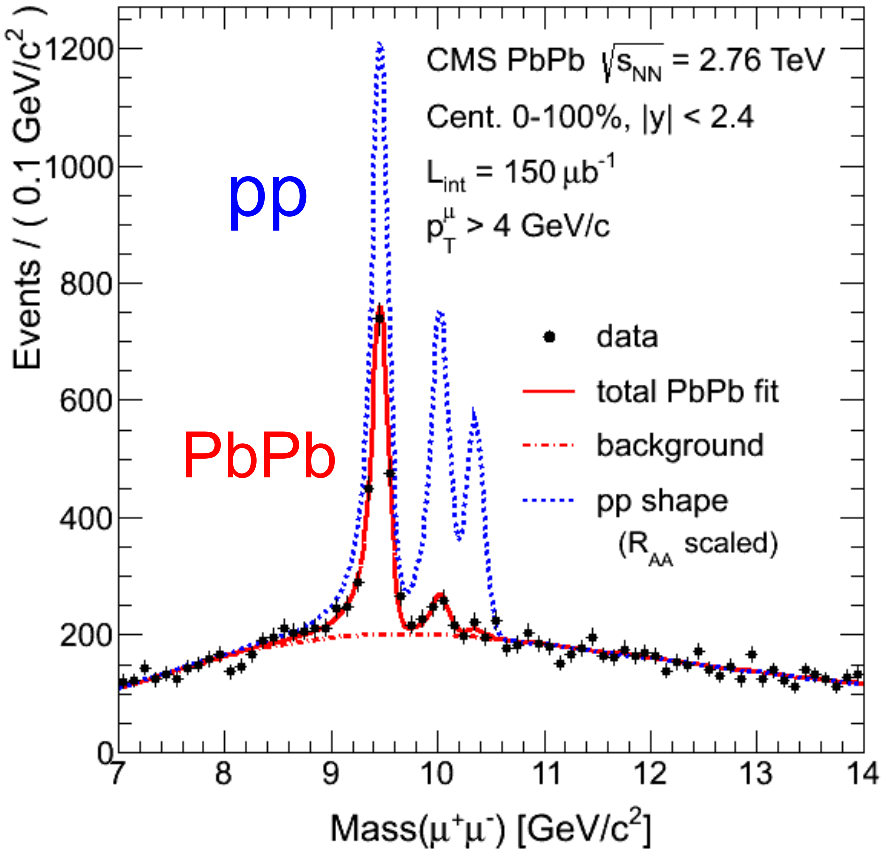
Υ suppression as a sensitive probe for the QGP

- 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

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]

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F. Vaccaro, F. Nendzig and GW, Europhys.Lett. 102, 42001 (2013); J. Hoelck and GW, unpublished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

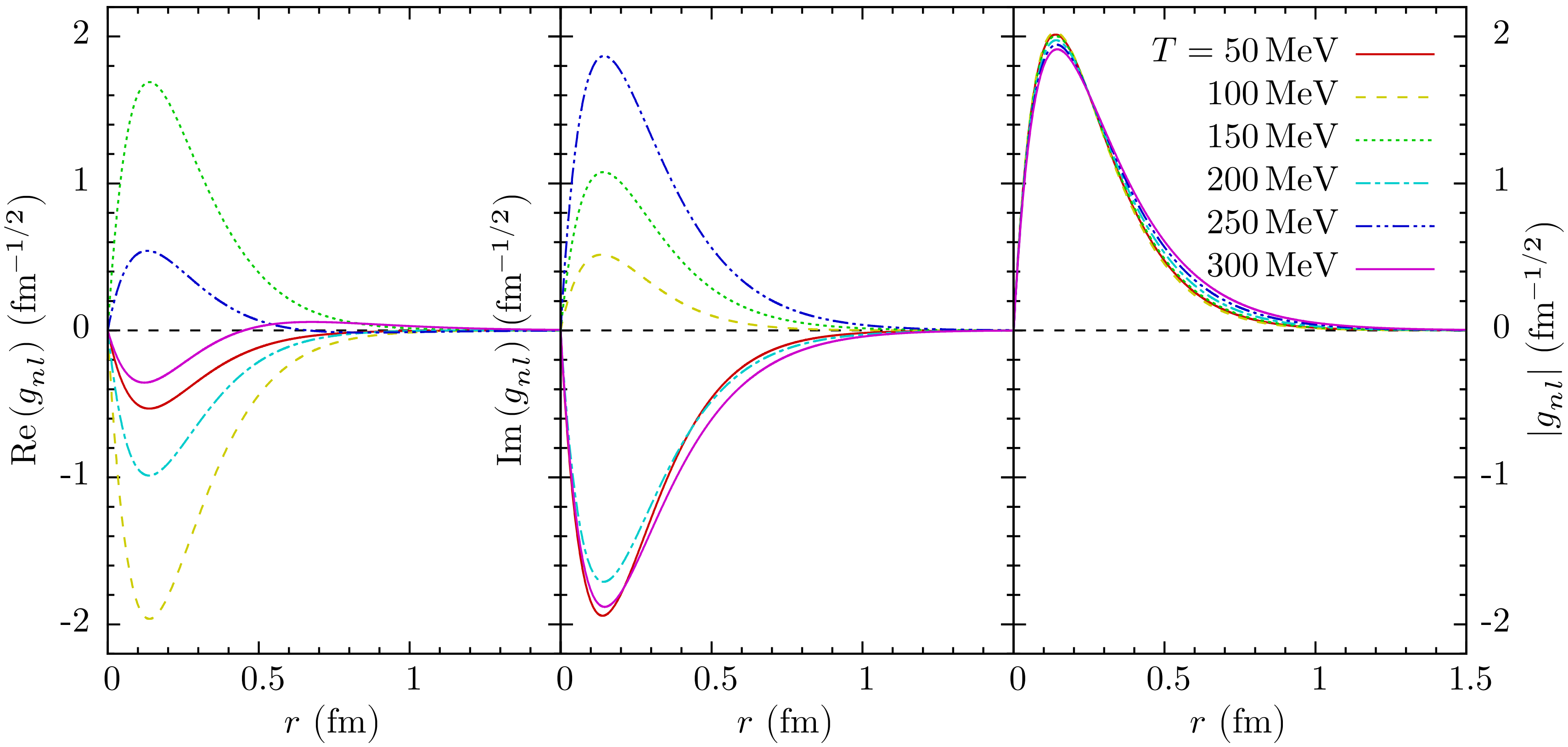
Screened potential: m_D = Debye mass,
$\alpha_{nl}(T)$ the strong coupling constant;
$C_F = (N_c^2 - 1) / (2N_c)$
$\sigma \approx 0.192$ the string tension (Jacobs et al.; Karsch et al.)

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

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

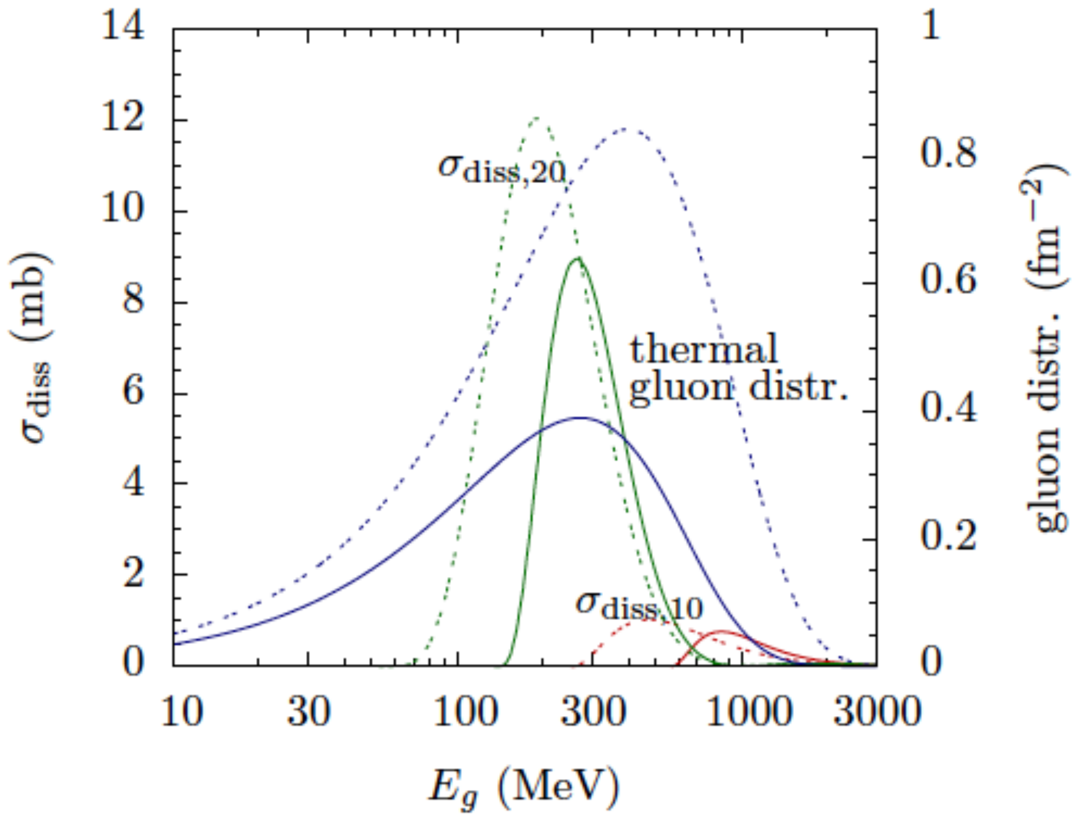


Figure 3. Gludissociation cross section σ_{diss} (left scale) of the $\Upsilon(1S)$ and $\Upsilon(2S)$ and the thermal gluon distribution (right scale) plotted for temperature $T = 170$ (solid curves) and 250 MeV (dotted curves) as functions of the gluon energy E_g.

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

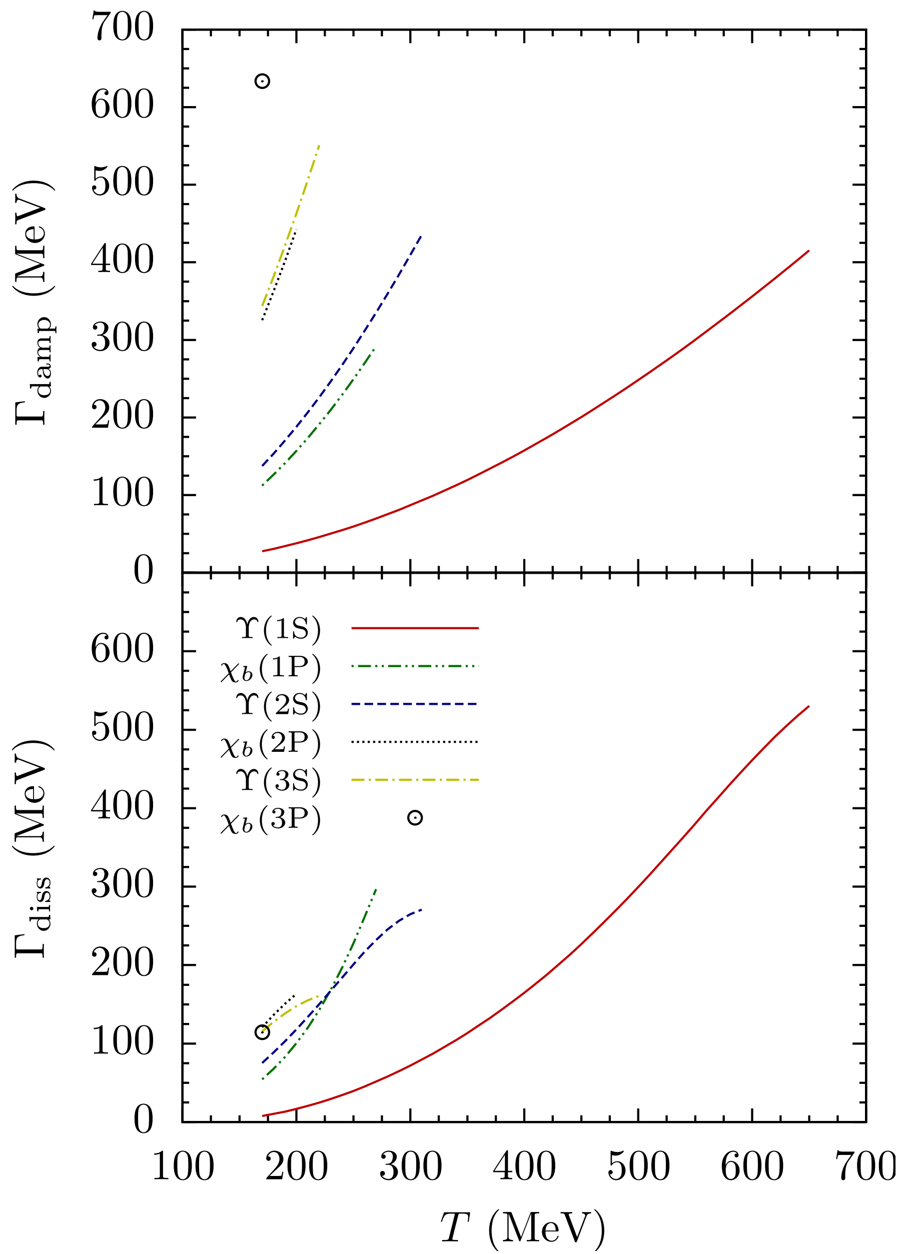
$$\Gamma_{\mathrm{diss},\,nl}(T) \equiv \frac{g_d}{2\pi^2} \int_0^\infty \frac{\mathrm{d}E_g\, E_g^2\, \sigma_{\mathrm{diss},\,nl}\left(E_g\right)}{\mathrm{e}^{E_g/T} - 1}$$

($g_d = 16$)

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

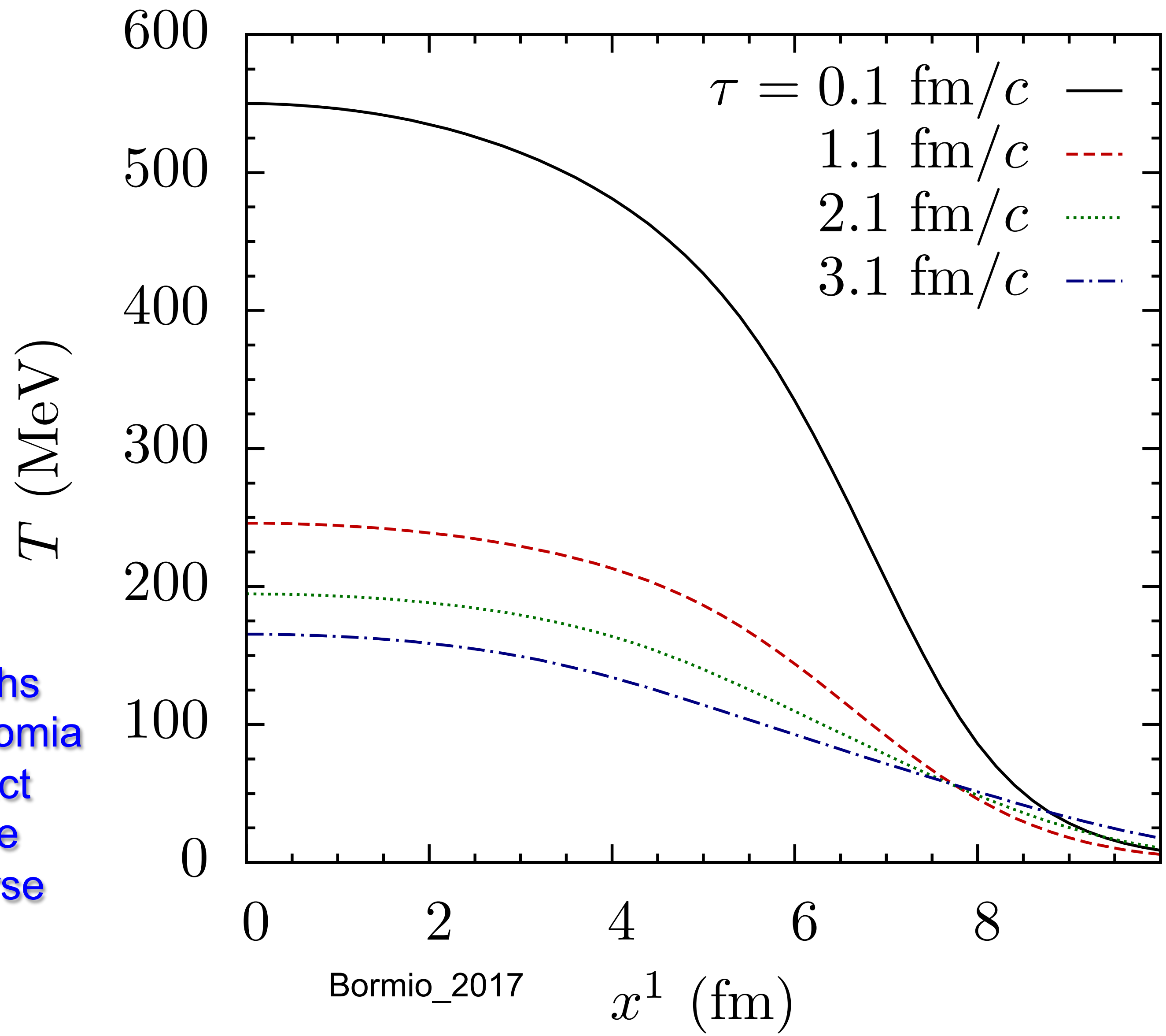
$\Gamma_{tot}(T) = \Gamma_{damp}(T) + \Gamma_{diss}(T)$



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

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

2.4 Feed-down cascade

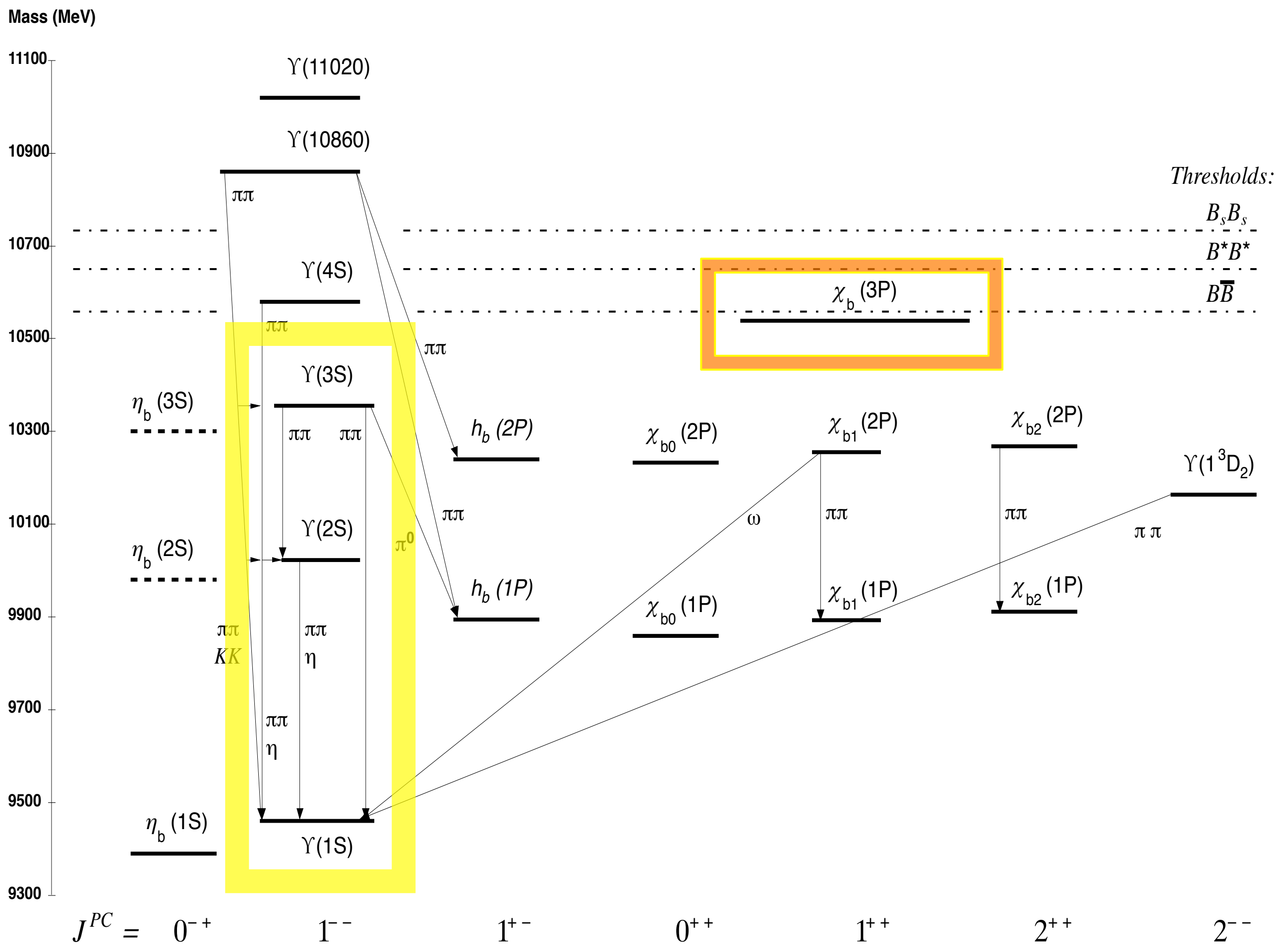
including χ_{nP} states; relative initial populations in pp computed using an inverted cascade from the final populations measured by CMS and CDF(χ_b).
Feed-down is reduced if excited states are screened or depopulated

N$_{initial}$

3S: 0.324

2S: 0.367

1S: 0.373



N$_{initial}$

2P: 0.881

1P: 1.084

2.5 Relativistic Doppler effect: p_T-dependent results

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

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

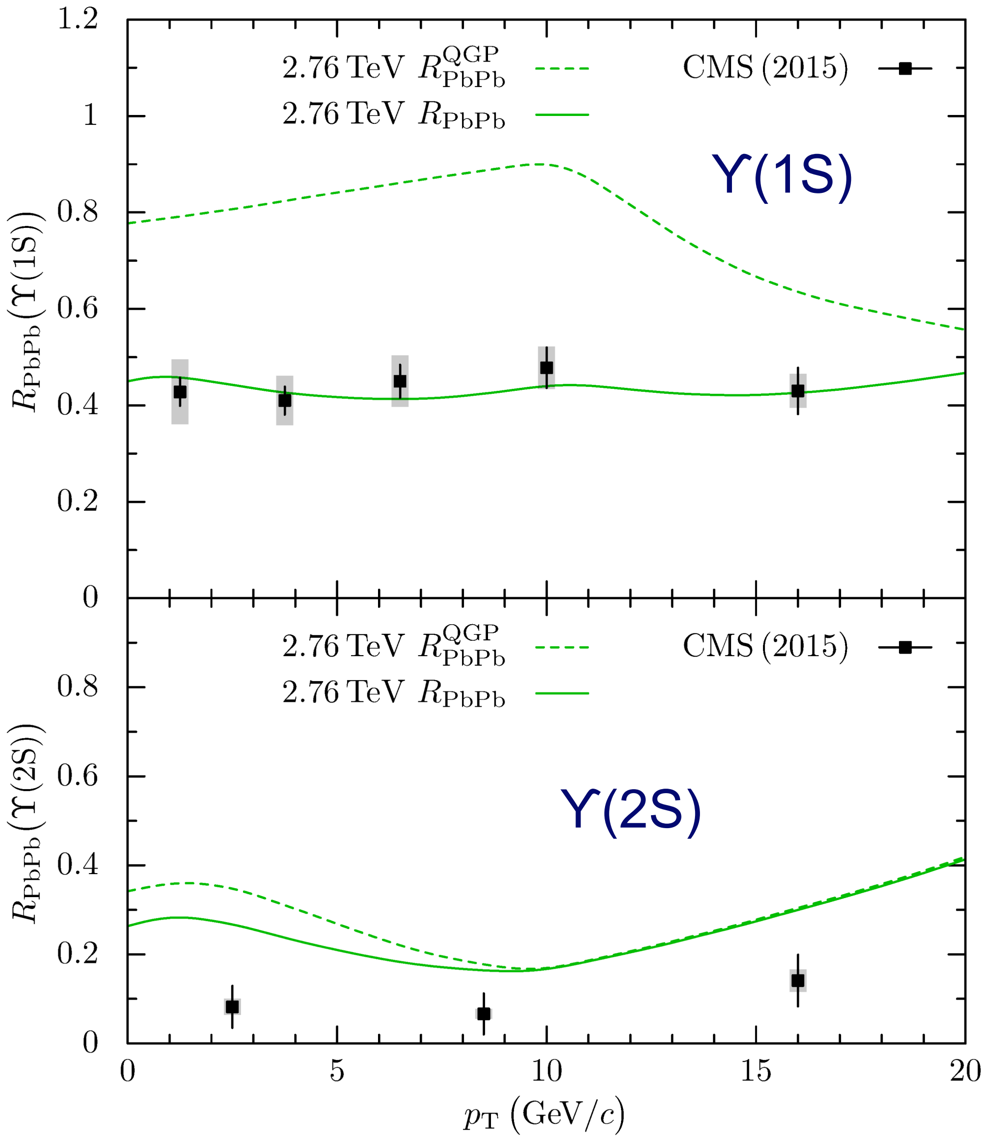
with the angle θ between the medium velocity **u** (in the bottomium restframe) and the direction of the incident light parton. This effective temperature is anisotropic: blue-shifted for θ ≈ 0°, red-shifted in the opposite direction.

We average the time-dependent total decay widths Γ_{nl} of the six ϒ(**n**S) and χ_b(**n**P) states over Ω = (θ, ϕ) with the azimuthal angle ϕ

$$\langle \Gamma_{nl} \rangle (T, |\boldsymbol{u}|) = \frac{1}{4\pi} \int \mathrm{d}\Omega \; \Gamma_{nl} \left[T_{\text{eff}}(T, \boldsymbol{u}) \right]$$

This yields the flat $\mathbf{p_T}$-dependence seen in the data, and we have adopted it for the six states considered.

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

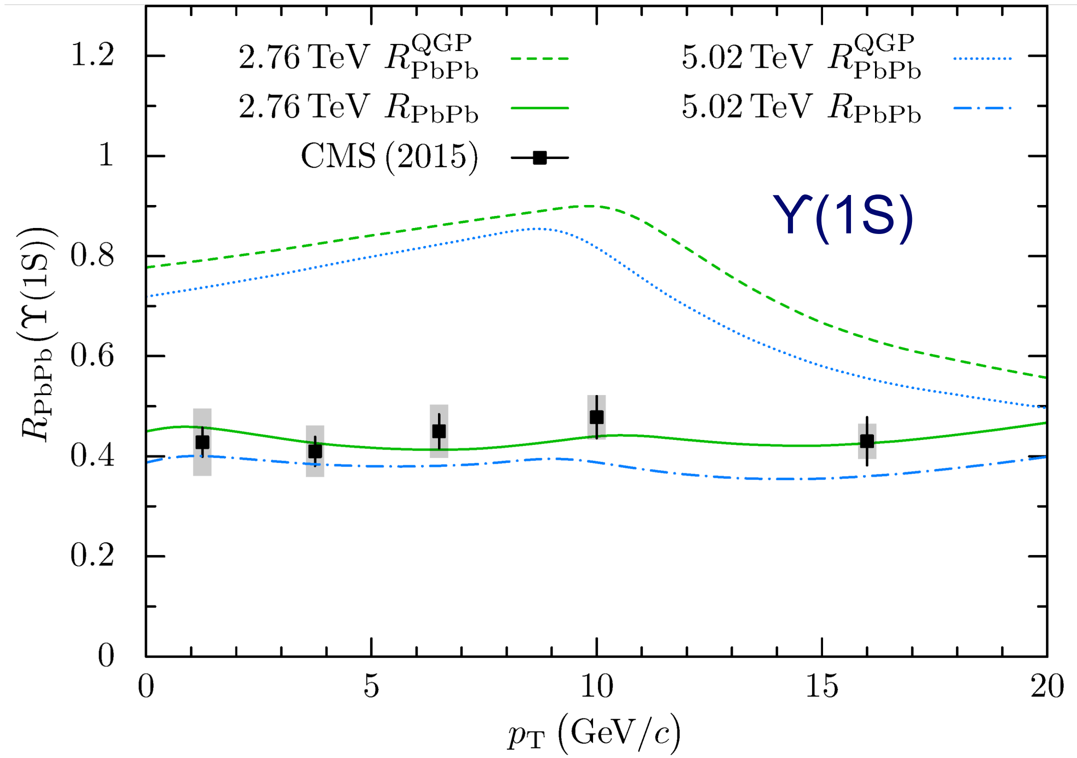
← Including reduced feed-down

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

J. Hoelck, F. Nendzig and GW, arXiv:1602.00019; submitted to PRC

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

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



<-- In-medium suppression only

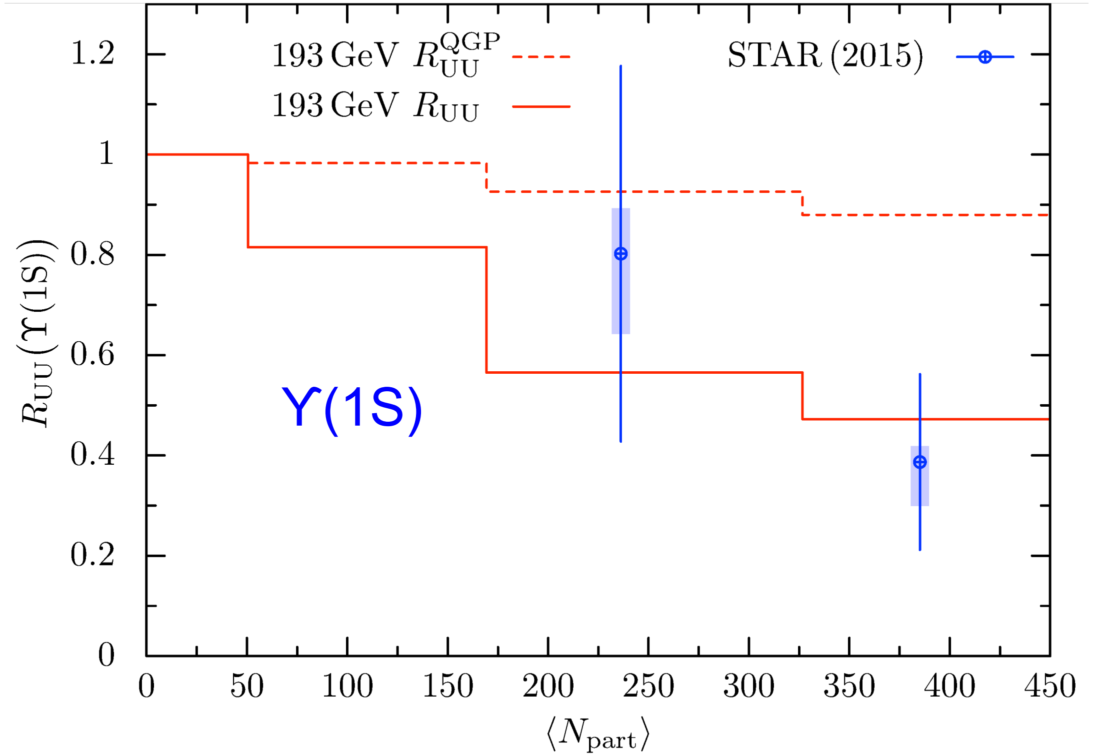
<-- Including reduced feed-down

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

J. Hoelck, F. Nendzig and GW, arXiv:1602.00019

3. Comparison with centrality-dependent data

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

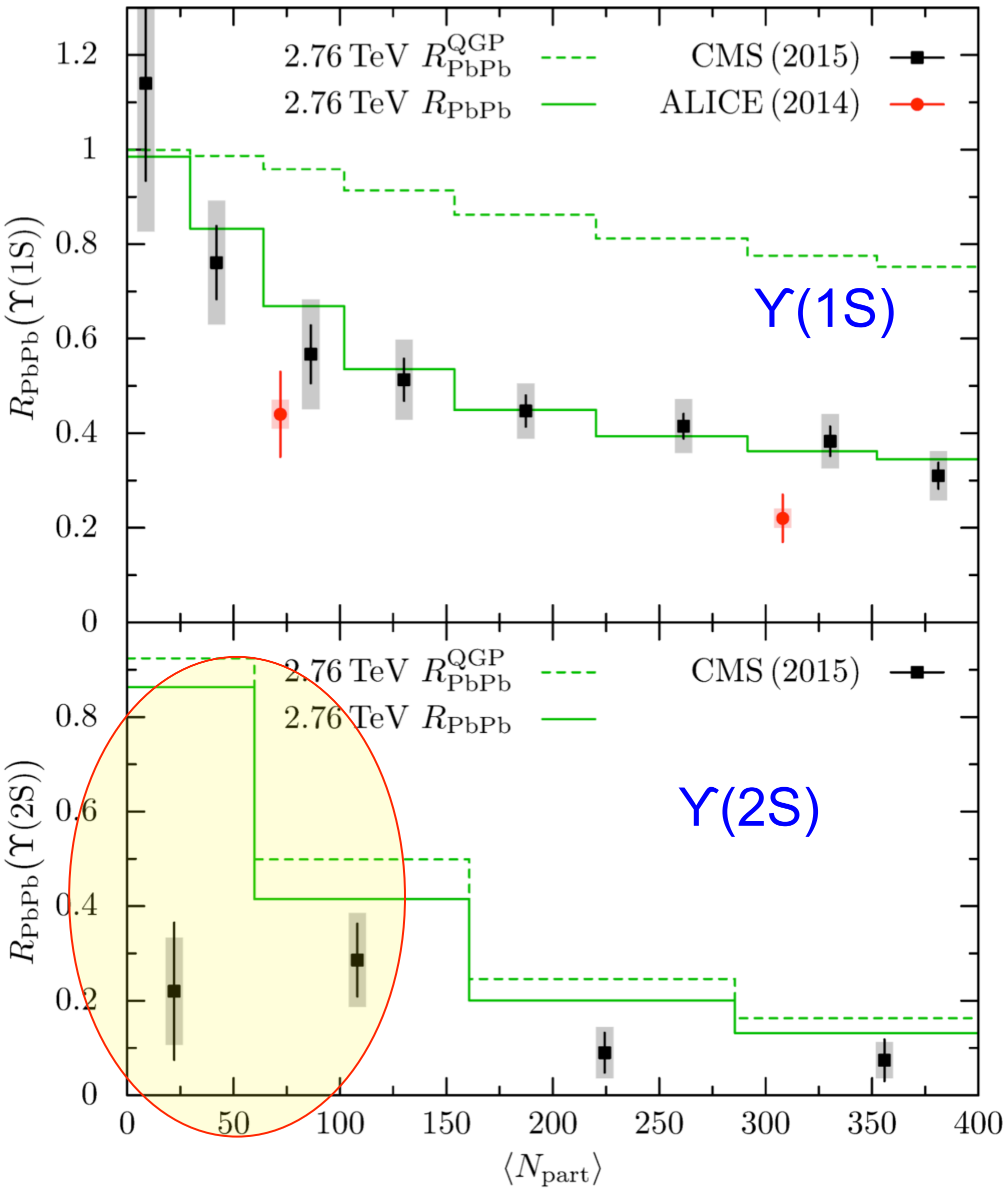


193 GeV UU RHIC

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, arXiv:1602.00019 (2016)

3.2 2.76 TeV PbPb: CMS and ALICE



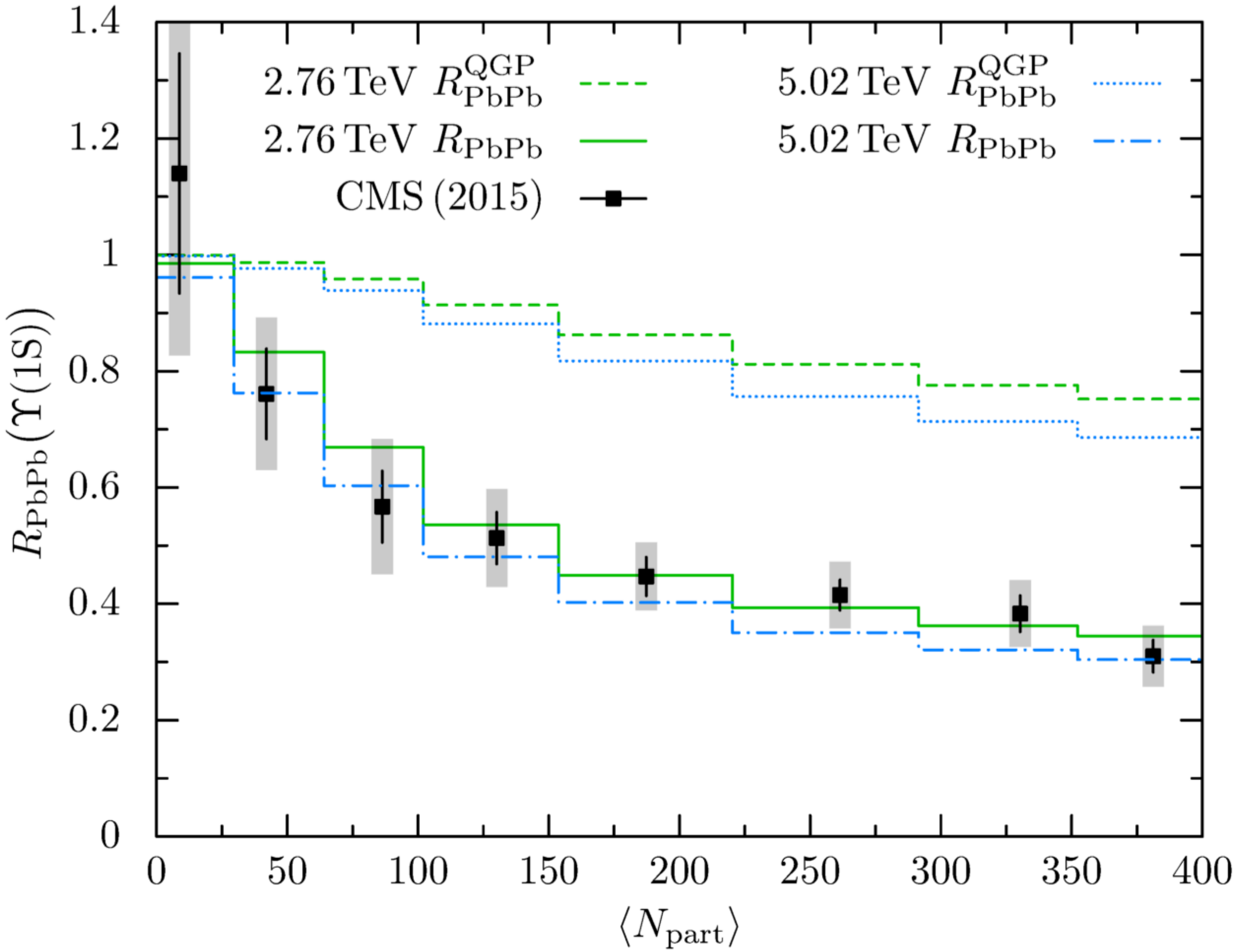
2.76 TeV PbPb LHC

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 magnetic dissociation.

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

4. Prediction for Υ(1S) suppression at 5.02 TeV



t_F: Υ formation time
T_{max} @ t_F: 513 MeV

t_F= 0.4 fm/c; use

$$s_0 \propto dN_{ch}/d\eta \propto T_0^3$$

with reduced feed-down
<10% higher suppression at 5.02 TeV vs 2.76 TeV, within experimental error bars

J. Hoelck, F. Nendzig and GW, arXiv:1602.00019

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 enhanced suppression of Υ(2S, 3S) 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 Bormio 2017 !