# Spectroscopy
# in the quark-gluon plasma with bottomonia

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# Topics

1. Introduction

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

3. Comparison with $p_T$ - and centrality-dependent data:

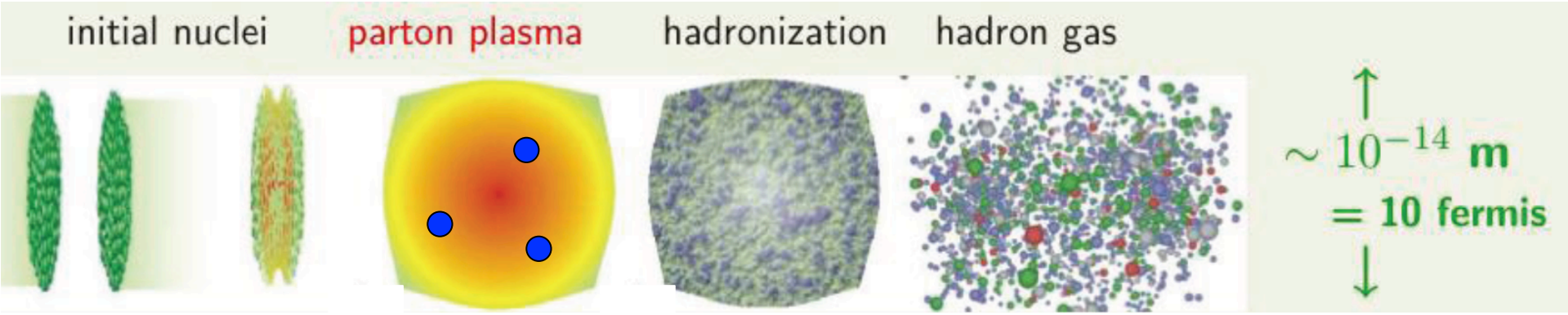
   2.76 TeV PbPb - CMS and ALICE @ LHC

4. Prediction for 5.02 TeV PbPb, comparison to CMS data

5. Conclusion

# 1. Introduction

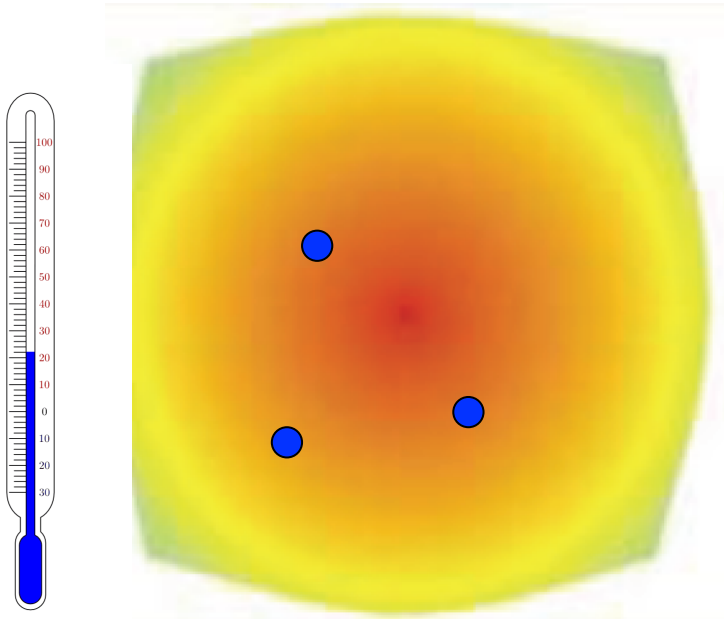
- **Heavy mesons coexist with the QGP due to their short formation times, $t_F \approx 0.2 - 0.6$ fm/c for Υ**




**~ $10^{-23}$ s = 10 yoctoseconds**

Artwork © Nikhef / S. Bass

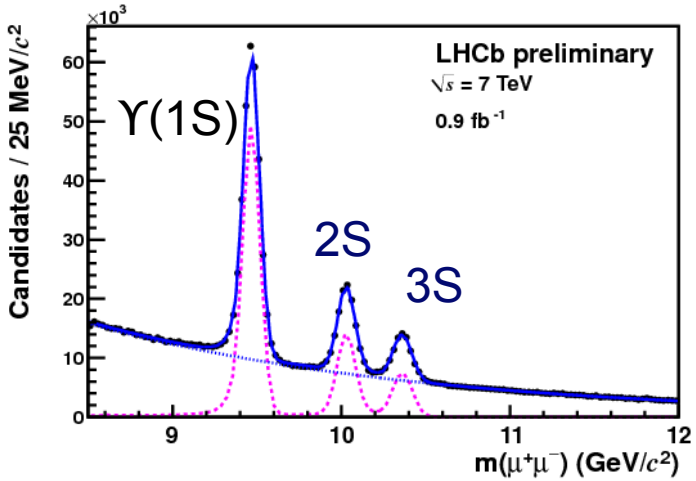
# Spectroscopy of heavy quarkonia in the QGP



- **Heavy mesons:** $J/\psi(c\bar{c}), \Upsilon(b\bar{b})$

- **Investigate their spectroscopy in the QGP**
- **Deduce QGP properties such as the temperature T: "QGP-Thermometer"**
- **Focus on ϒ because there recombination is negligible**
- **Expected central temperature in the (4-6)·10$^2$ MeV range**

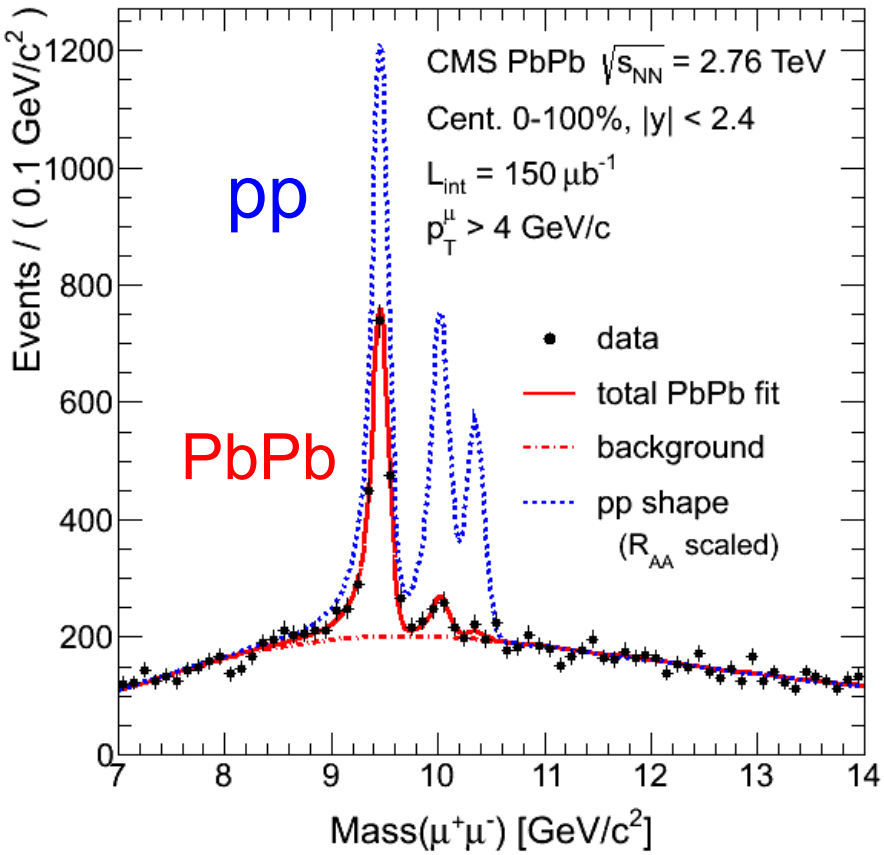
  **(100 MeV ≈ 1.16·10$^8$ Kelvin)**




ϒ spectrum in vacuum => in the QGP medium?

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

© CMS




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

ϒ spectroscopy as a clear QGP indicator

- ϒ (1S) is suppressed in 2.76 TeV PbPb:

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

- ϒ (2S, 3S) states are > 4 times more suppressed in PbPb than Y(1S)

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

- 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

## 2. The model: Screening, Gluodissociation and Collisional broadening of the $\Upsilon$(nS) states

① Debye screening of all states involved: Static suppression

② The imaginary part of the potential (effect of collisions) contributes to the broadening of the $\Upsilon$(nS) states: damping

③ Gluon-induced dissociation: dynamic suppression, in particular of the $\Upsilon$(1S) ground state due to the large thermal gluon density

④ Reduced feed-down from the excited $\Upsilon/\chi_b$ states to $\Upsilon$(1S) substantially modifies the populations: indirect suppression

**F. Vaccaro, F. Nendzig and GW, Europhys.Lett. 102, 42001 (2013); J. Hoelck and GW, EPJA 53, 241 (2017)**
**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 in a nonrelativistic potential model

Screening of the real part

Damping through the imaginary part

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

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

Screened potential: $m_D$ = Debye mass,

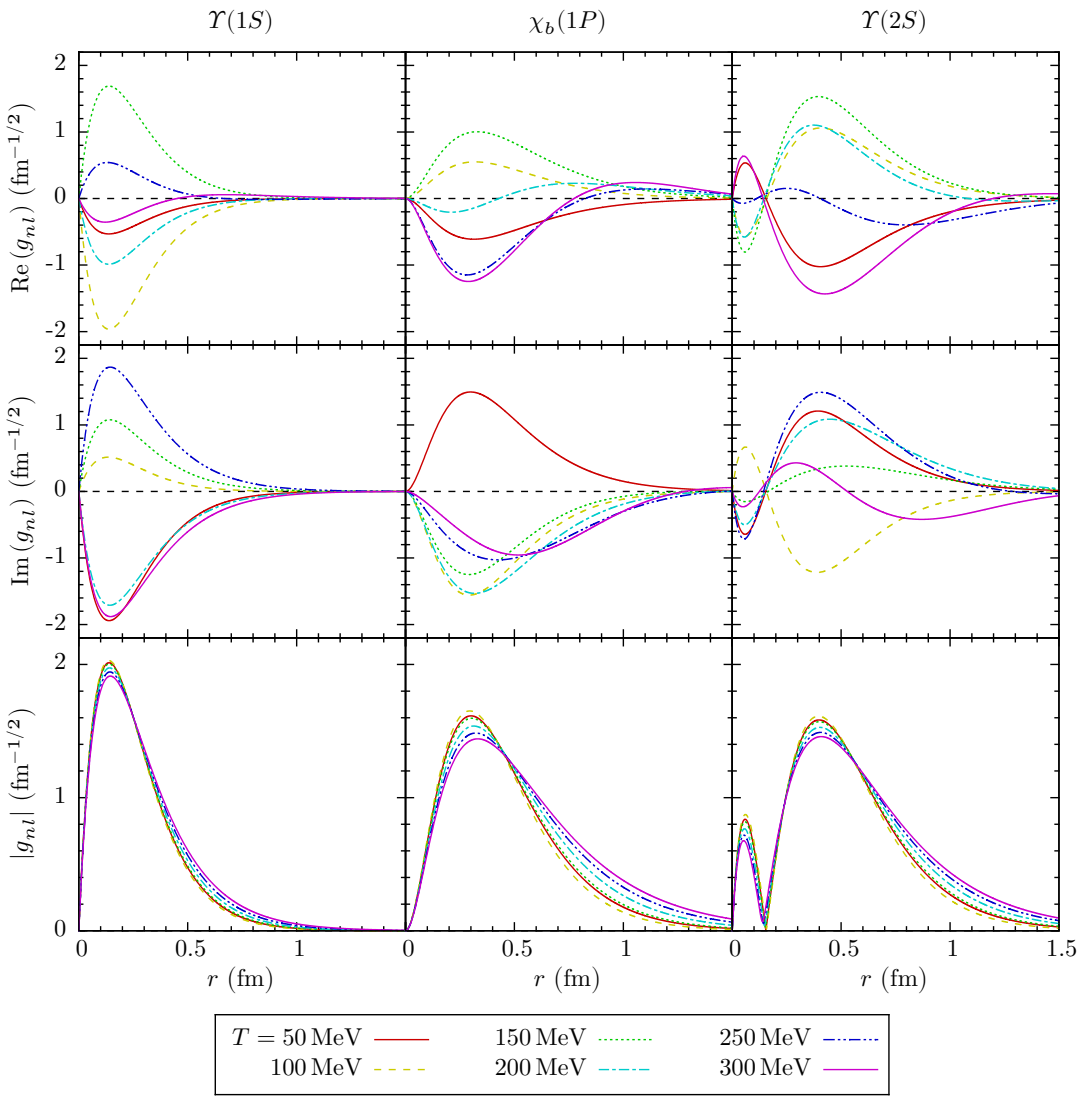
$\alpha_{nl}(T)$ the strong coupling constant;

$C_F = (N_c^2 - 1) / (2N_c)$

$\sigma \approx 0.192$ 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 $2\pi T >> \langle 1/r \rangle$; different form for $2\pi T << \langle 1/r \rangle$.

# Radial wave functions of $\Upsilon$(nS), $\chi_b$(nP) states at temperature T




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

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

Calculate the damping widths $\Gamma_{damp}$(T) for all six states

$\Upsilon$(nS), $\chi_b$ (nP), n = 1, 2, 3

From: J. Hoelck and GW, unpublished

## 2.2 Gluon-induced dissociation of heavy mesons in the QGP

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 $\chi_b$(nP) states.

# Gluodissociation cross section

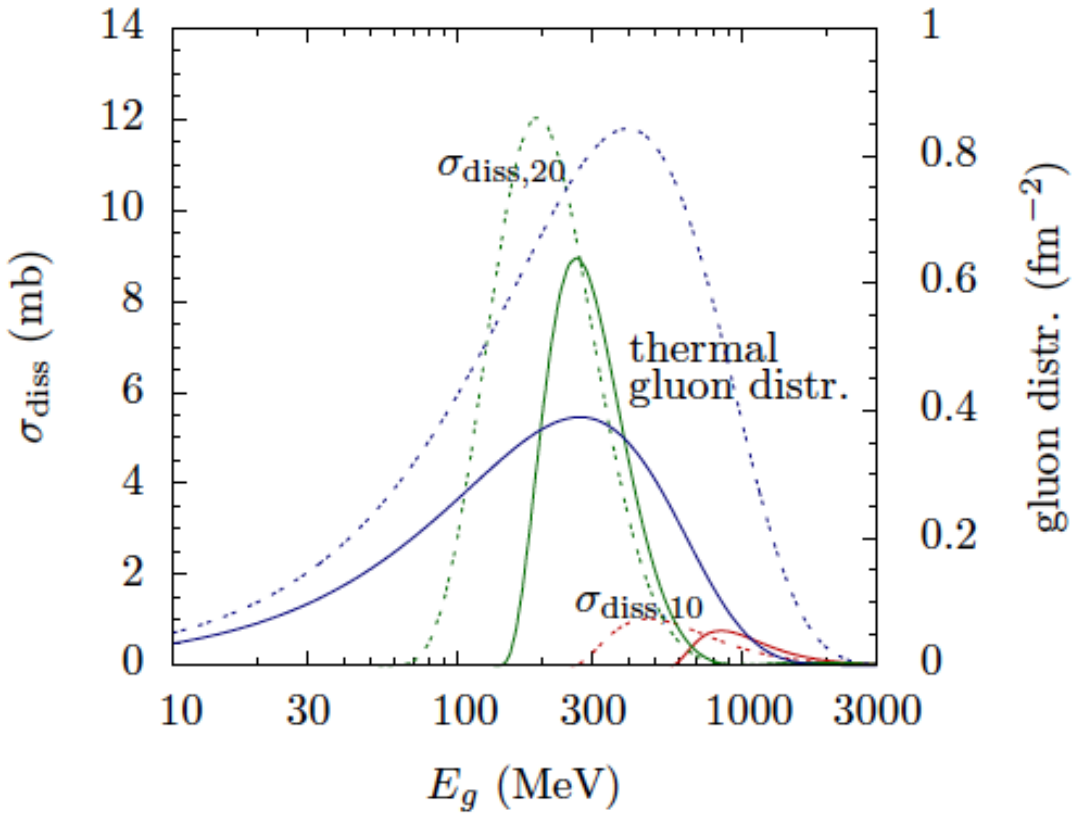



**Figure 3.** Gluodissociation cross section $\sigma_{diss}$ (left scale) of the $\Upsilon(1S)$ and $\Upsilon(2S)$ and the thermal gluon distribution (right scale) plotted for temperature $T = 170$ (solid curves) and 250 MeV (dotted curves) as functions of the gluon energy $E_g$.

**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

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

($g_d$ = 16)

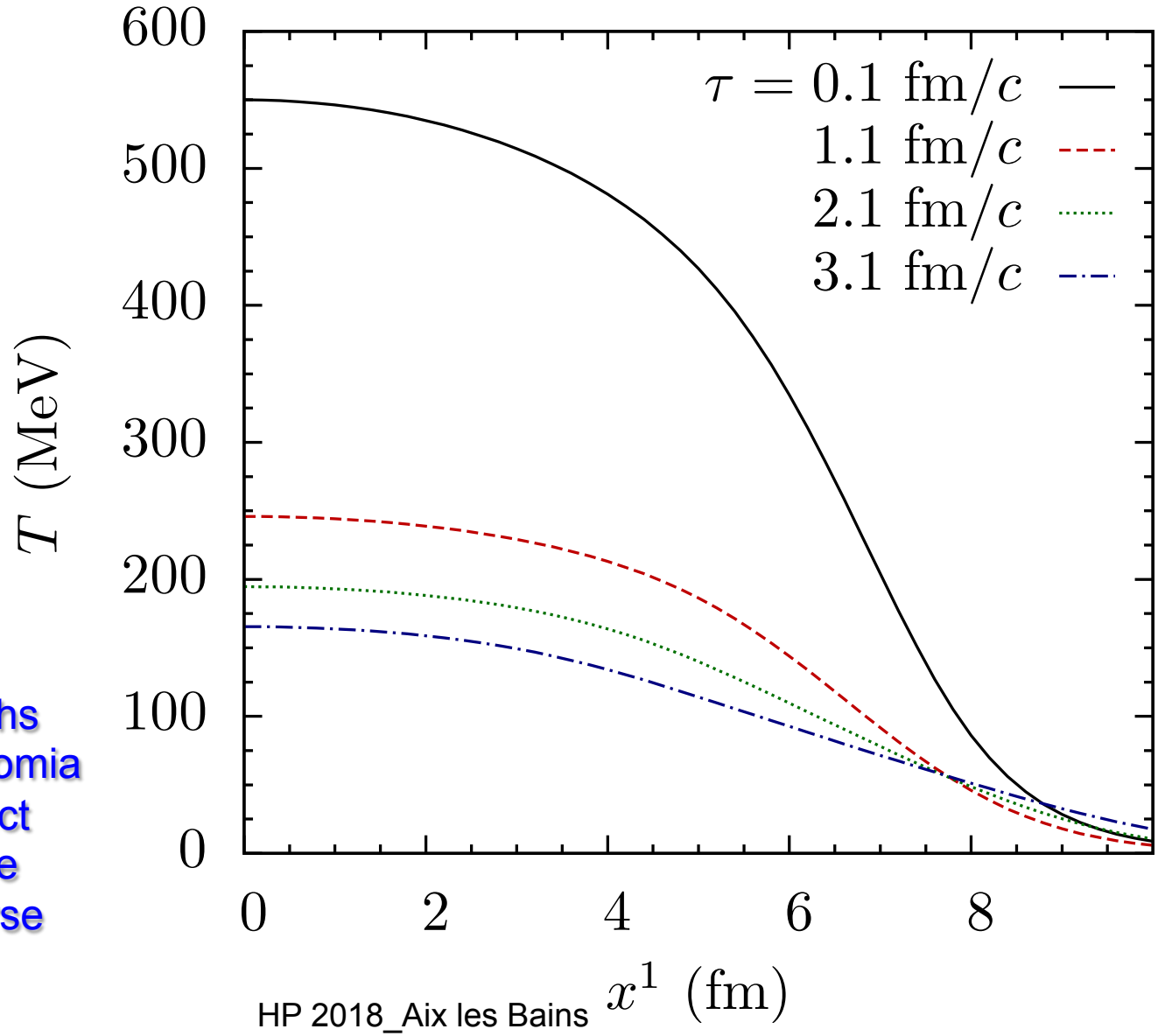
With rising temperature, the peak of the gluon distribution moves to larger gluon energies $E_g$, whereas the dissociation cross sections move to smaller $E_g$, giving rise to a maximum in the gluodissociation width for fixed coupling $\alpha_s$.
(Larger cross sections at higher temperatures due to running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

$$\Gamma^{nl}_{\text{tot}}(T) = \Gamma^{nl}_{\text{damp}}(T) + \Gamma^{nl}_{\text{diss}}(T)$$

# 2.3 Hydrodynamic expansion (ideal)

Temperature profile for central collisions at different times $\tau$

PbPb @ LHC




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):

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

# 2.4 Feed-down cascade

including $\chi_{nP}$ states; relative initial populations in pp computed using an inverted cascade from the final populations measured by CMS and CDF($\chi_b$ ).

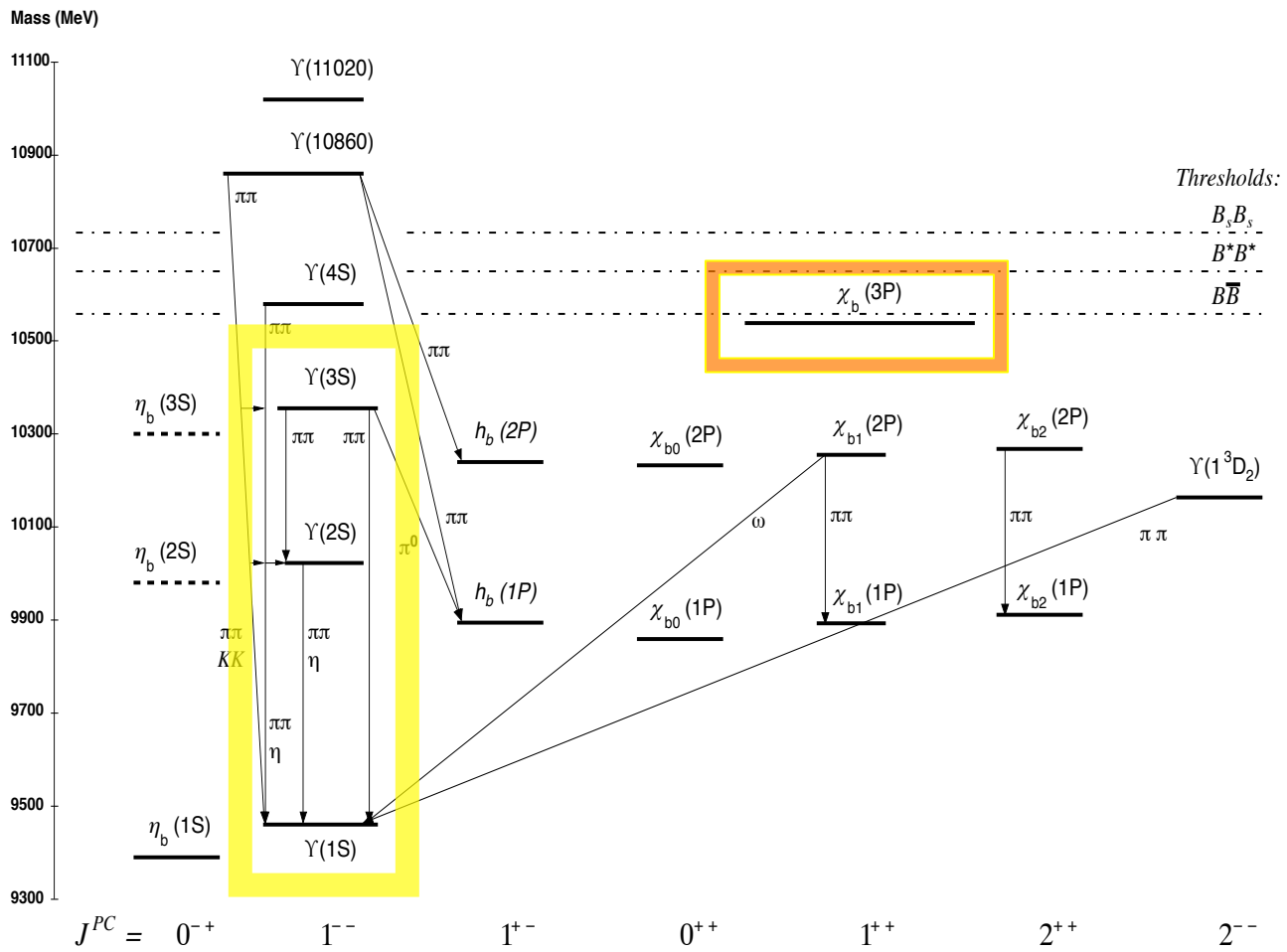
Feed-down is reduced if excited states are screened or depopulated

$N_{initial}$

3S: 0.324

2S: 0.367

1S: 0.373

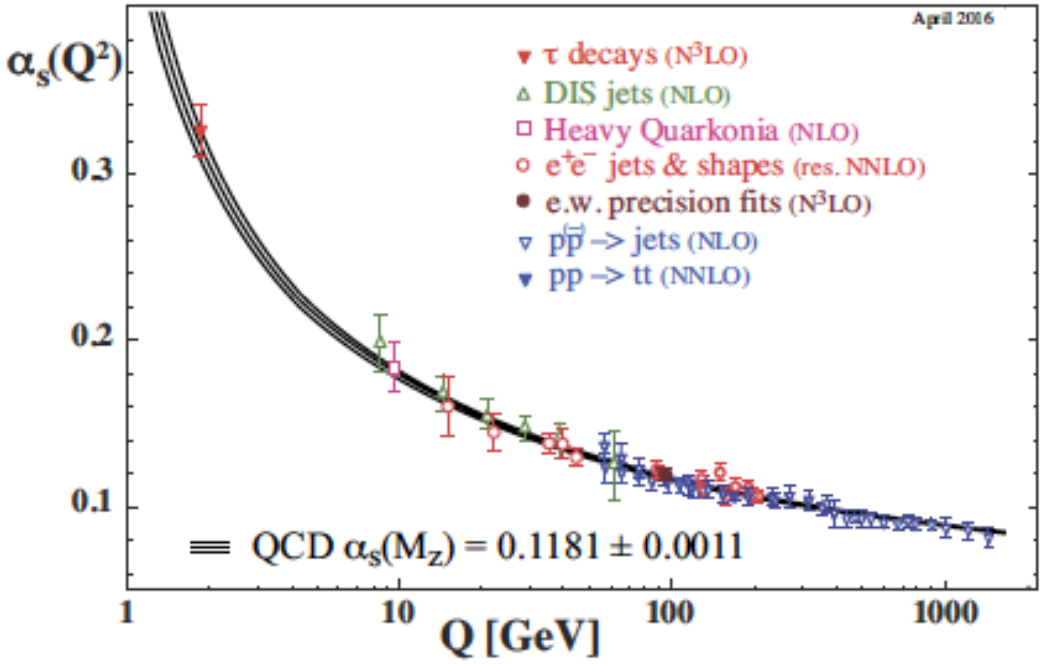



$N_{initial}$

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

Parameters:
1) ϒ formation time $t_F$
2) initial central temp. $T_0$

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

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

$\alpha_{nl}(T)=\alpha_s[\langle 1/r \rangle_{nl}(T)]$ depends on the solution $g_{nl}(r,T)$ of the Schrödinger eq.: Iterative solution

# Relativistic Doppler effect

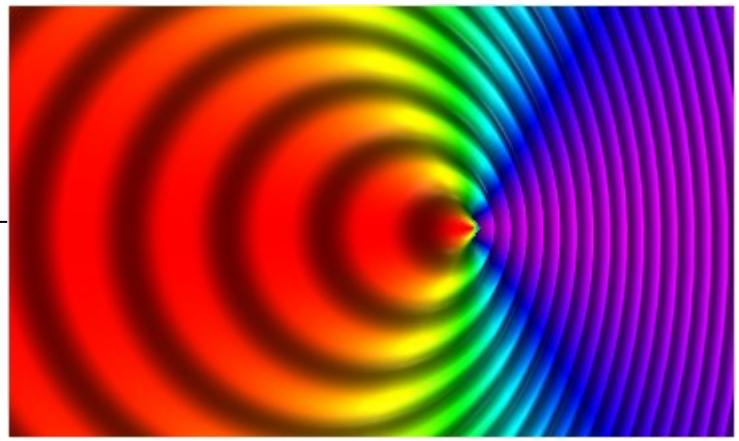
For a finite relative velocity between the expanding QGP and the bottomium states the relativistic Doppler shift results in an angle-dependent effective temperature

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

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.

**θ = 180°**

**redshift**

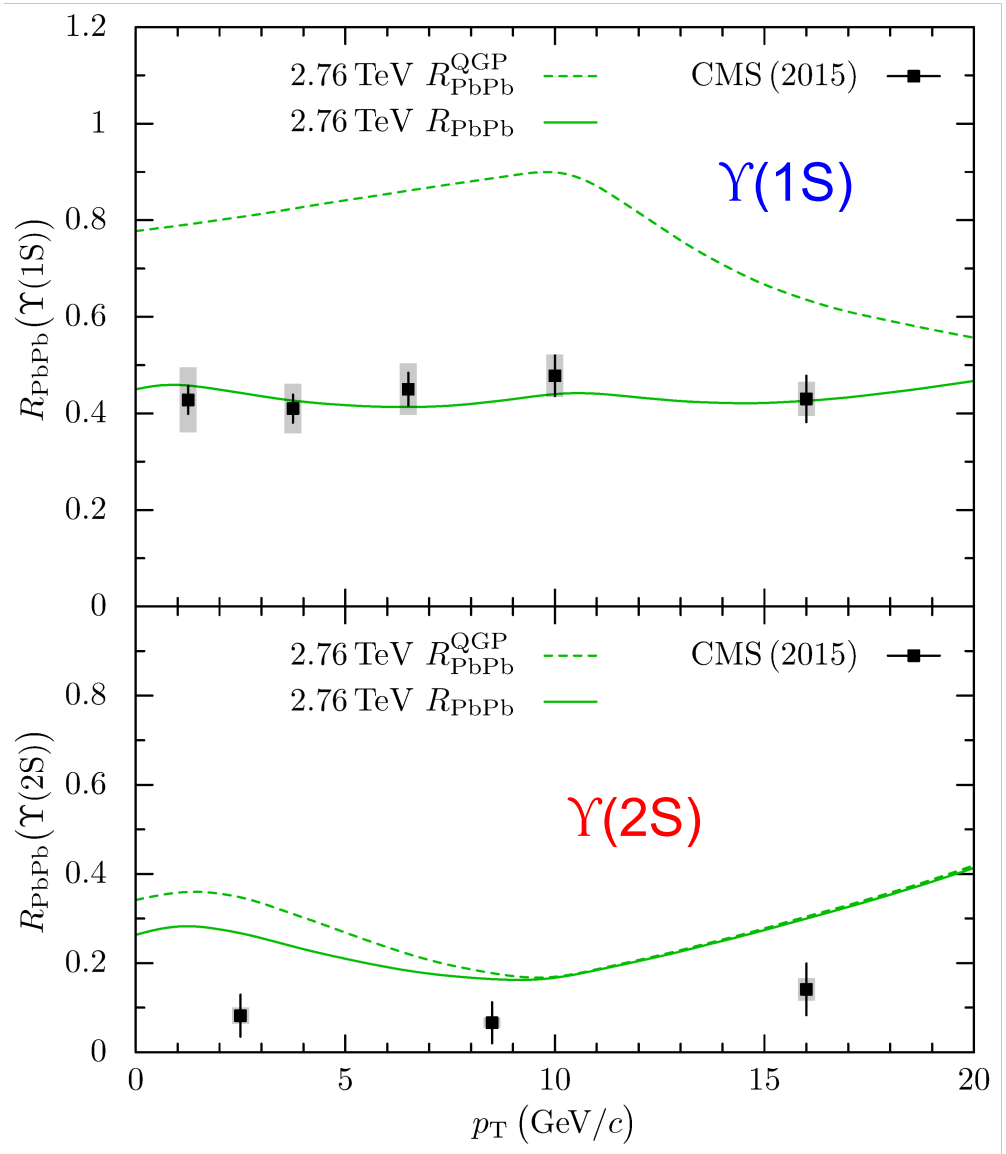


**θ = 0°, blueshift**

**u = 0.7 c**

This has a significant effect on the transverse momentum distributions of the ϒ's.

# 3. Transverse momentum dependence of ϒ(1S) suppression in PbPb at 2.76 TeV




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

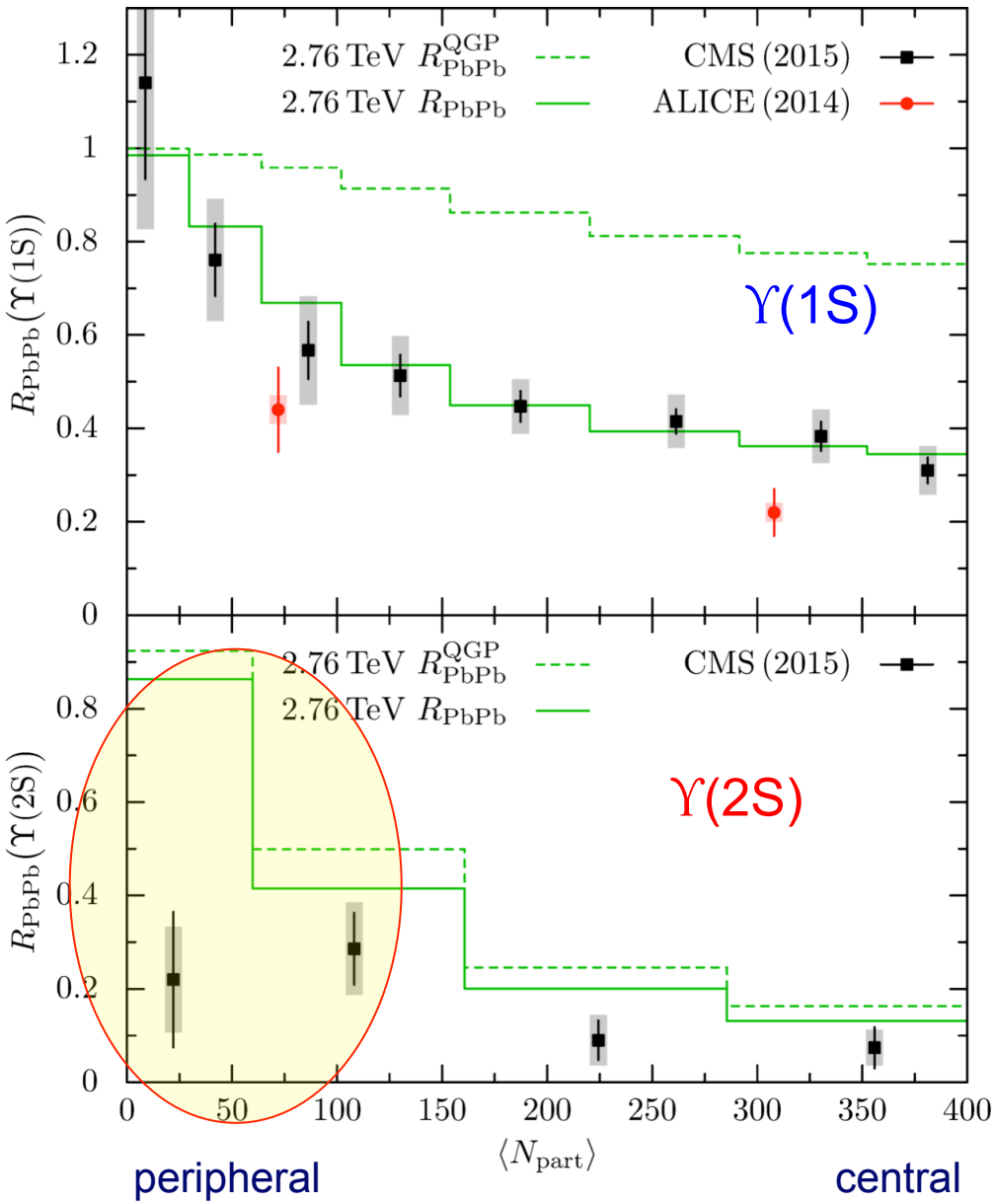
← In-medium suppression only
← Including reduced feed-down

($T_0$= 480 MeV; $t_F$= 0.4 fm/c; CMS data 2015)

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

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

# Centrality-dependent LHC data: CMS and ALICE




## 2.76 TeV PbPb: Υ (1S) and Υ(2S)

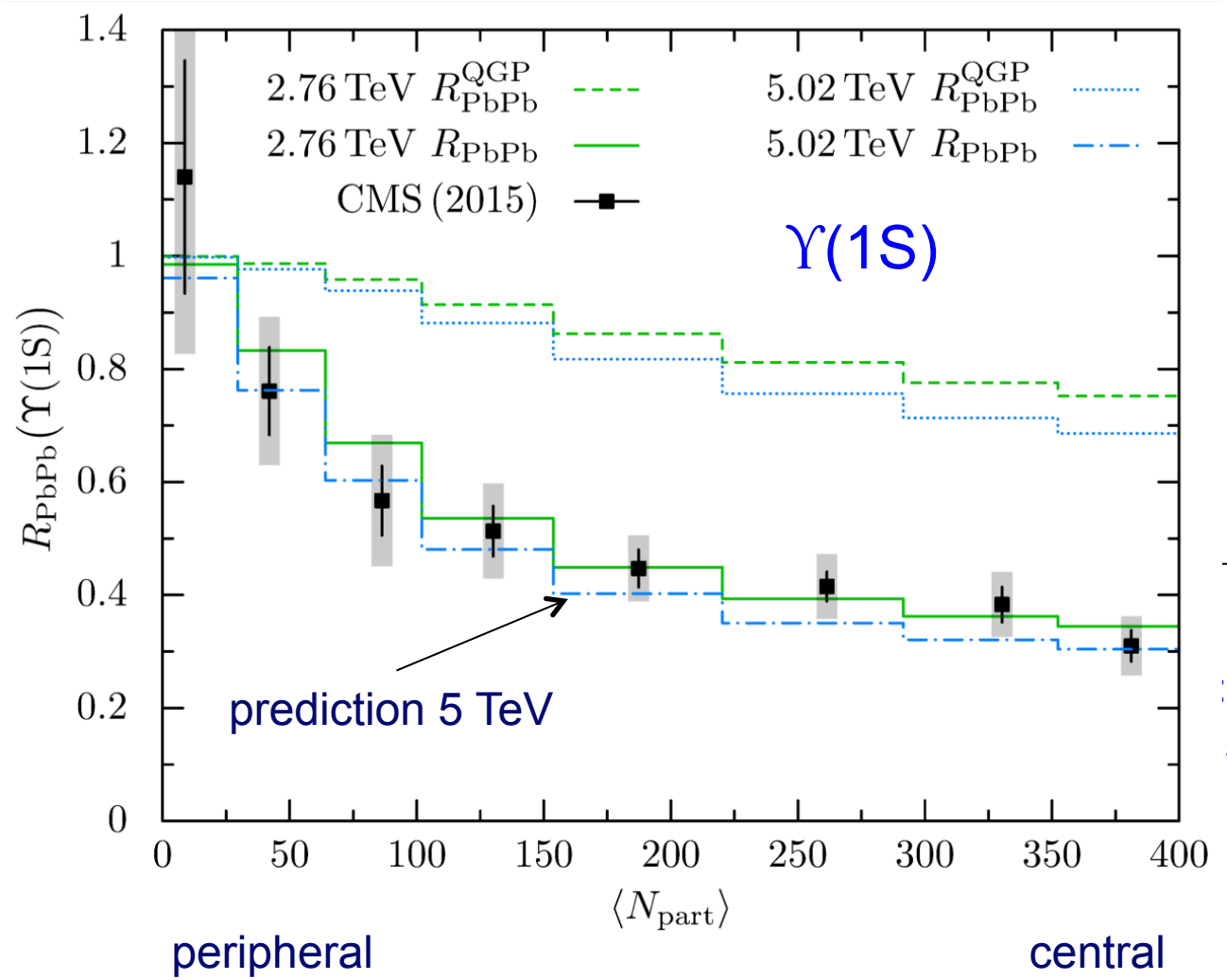
$t_F$= 0.4 fm/c: Υ formation time

$T_0$= 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; electromagnetic dissociation is negligible.

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

# 4. Prediction for ϒ(1S) suppression in 5.02 TeV PbPb




$T_{max}$ @ $t_F$: 513 MeV

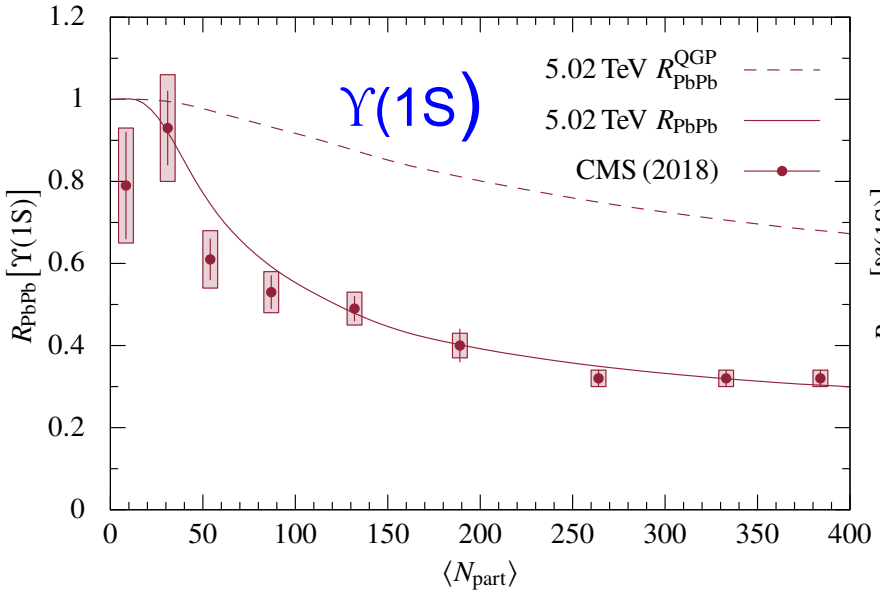
$t_F$= 0.4 fm/c

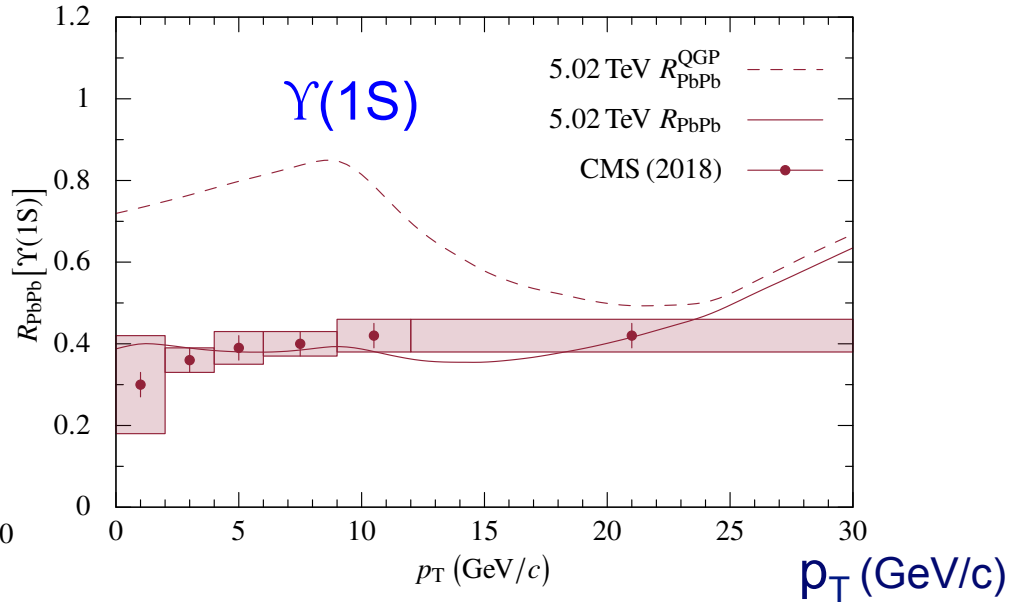
$$s_0 \propto dN_{ch}/d\eta \propto T_0^3$$

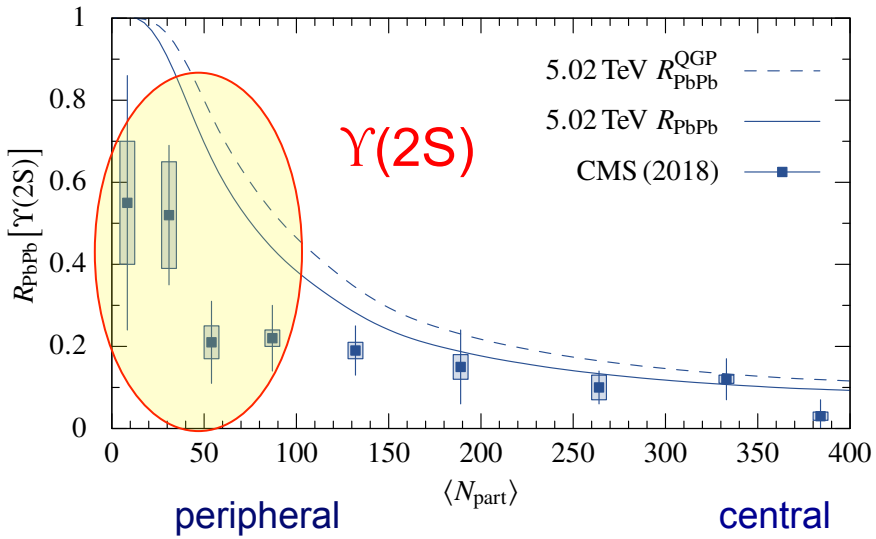
with reduced feed-down
<10% higher suppression at 5.02 TeV vs 2.76 TeV, within experimental error bars

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

# Prediction for ϒ suppression in 5.02 TeV PbPb vs. data




**Predictions** (dashed/ solid curves) as calculated in

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

**Prel. CMS data** from CERN-EP-2018-110

**Electromagnetic field effects are negligible even with large medium conductivities due to the short lifetimes: J. Hoelck and GW, EPJA 53, 241 (2017)**

# 5. Conclusion

- The spectroscopy of $\Upsilon$ mesons in PbPb collisions at LHC energies provides information about QGP properties, in particular the initial central temperature.

- The theoretical model is found to be in agreement with the CMS results for $\Upsilon$ (1S). Screening is not decisive for the 1S state except for central collisions.

- The $\Upsilon$ (1S) suppression is mostly reduced feed-down, the $\Upsilon$(2S) primarily in-medium. The prediction for 5.02 TeV PbPb agrees with CMS data.

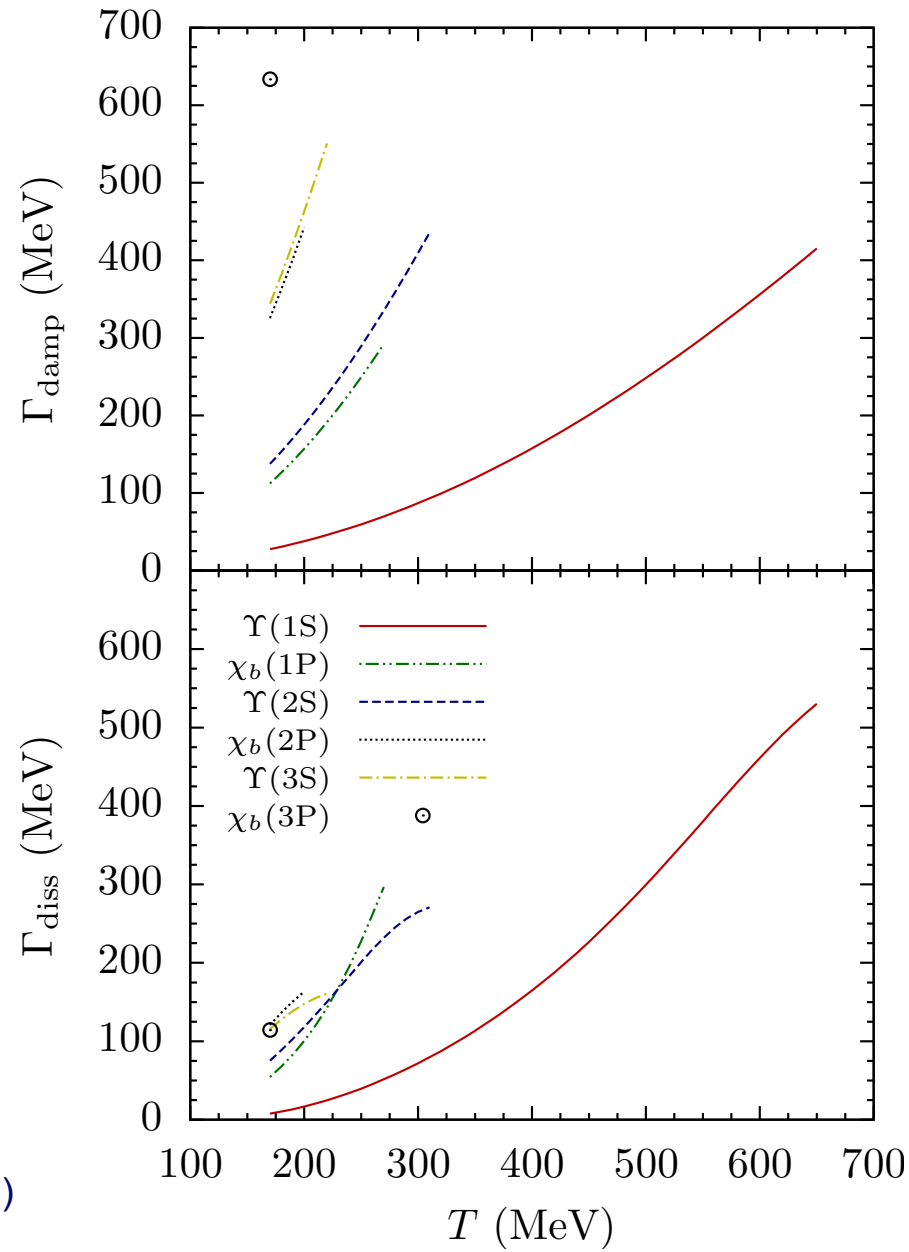
- The enhanced suppression of $\Upsilon$ (2S, 3S) in peripheral collisions leaves room for additional suppression mechanisms.

# Thank you for your attention !

# Extra slides

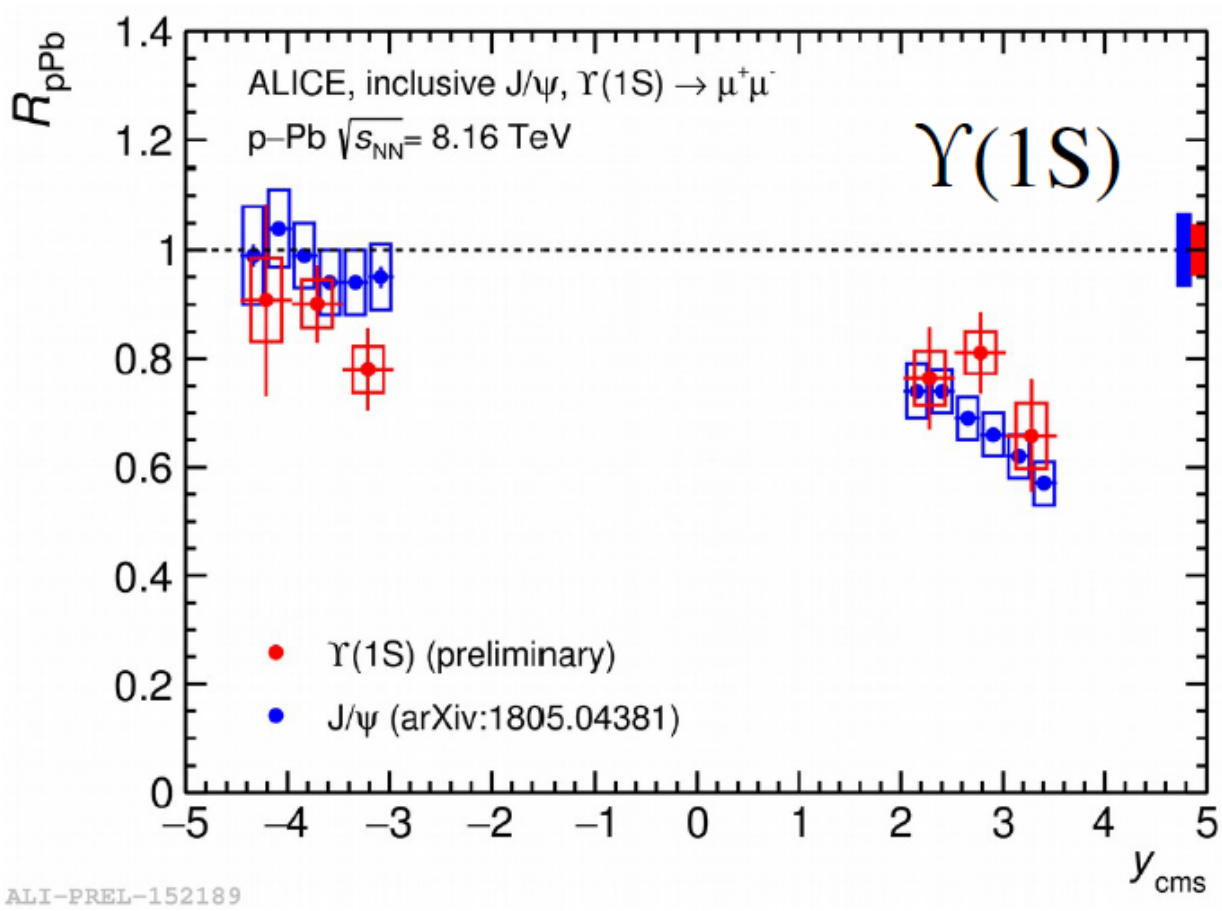
# Damping and gluodissociation widths for six bottomonia states in 2.76 TeV PbPb

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




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

# ϒ suppression in 5.02 TeV pPb




- No significant hot-matter effect in forward-backward difference
- Forward suppression due to shadowing and CNM energy loss

CNM calculation is in progress: Viet Hung Dinh & GW

**Prel. ALICE data** from ALI-PREL-152189