Medium effects on Υ yields in Pb-Pb and p-Pb collisions

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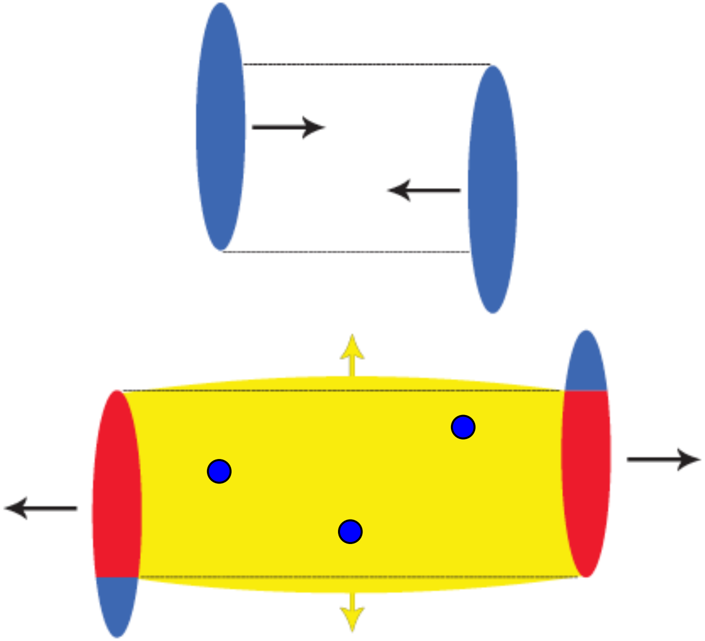
Topics

1. Introduction
2. Heavy-quarkonia spectroscopy in the QGP @ LHC energies
3. Our model for Υ and χ_b dissociation in the QGP
4. Comparison **Pb-Pb** with p_T - and centrality-dependent CMS data
5. Cold nuclear matter (CNM) and QGP effects in 8.16 TeV **p-Pb**
6. Comparison **p-Pb** with LHCb and ALICE data
7. Conclusion

1. Intro: Quark-gluon plasma (QGP) and heavy quarkonia: Symmetric collisions

QGP is being created in relativistic heavy-ion collisions in the mid-rapidity gluon-gluon source, and in the fragmentation sources provided the spatial overlap is sufficiently strong

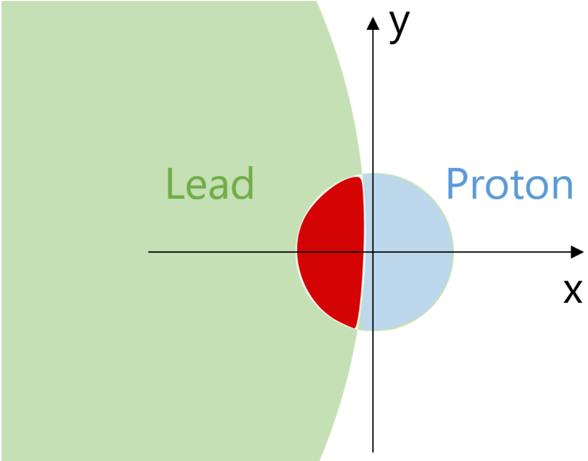
Red: fragmentation sources



Heavy quarkonia in the QGP of gluons and light (u, d, s) quarks

Asymmetric collisions: p-Pb

Overlap of the thickness functions θ in the transverse plane



(in the transverse plane)

Thickness functions

$$\theta_{\mathrm{p}}(b; x^1, x^2) = \int \mathrm{d}x^3 \rho_{\mathrm{p}}(|b\vec{e}_1 - \vec{x}|)\,,$$

$$\theta_{\mathrm{Pb}}(b; x^1, x^2) = \int \mathrm{d}x^3 \rho_{\mathrm{Pb}}(|\vec{x}|)\,,$$

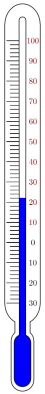
Overlap function

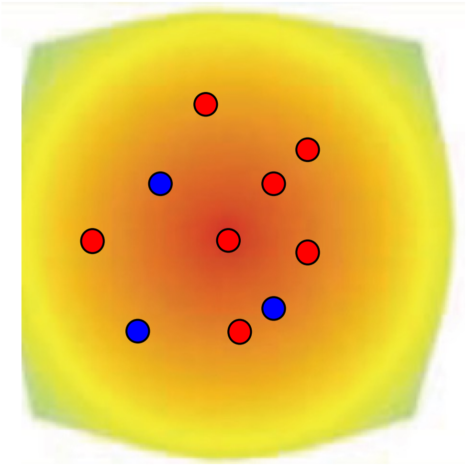
$$\theta_{\mathrm{pPb}}(b; x^1, x^2) = \theta_{\mathrm{p}}(b; x^1, x^2) \times \theta_{\mathrm{Pb}}(b; x^1, x^2)$$

graphic from: V.H. Dinh, MSc thesis, Heidelberg (2019)

Most of the system remains ‘cold‘: $T \ll T_H$
⇒ Consider CNM effects on ϒ yields,
plus suppression in the hot QGP

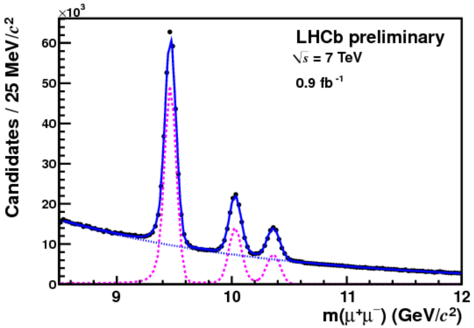
2. Heavy-quarkonia spectroscopy in the QGP





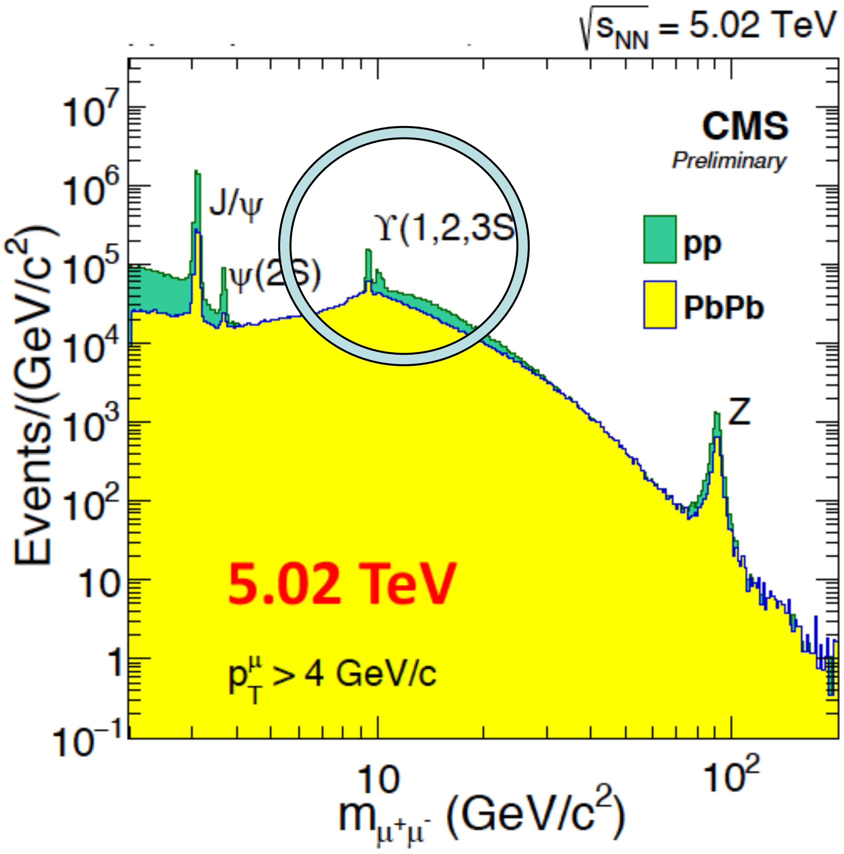
- ● $J/\psi\ (c\bar{c})$
- ● $\Upsilon\ (b\bar{b})$

- **Investigate their spectroscopy in the QGP**
- **Deduce QGP properties such as the temperature T: “QGP-Thermometer“**
- **Focus on ϒ because there, recombination is negligible**



ϒ spectrum in vacuum => in the QGP medium?

J/ψ, ϒ suppression in Pb-Pb @ LHC



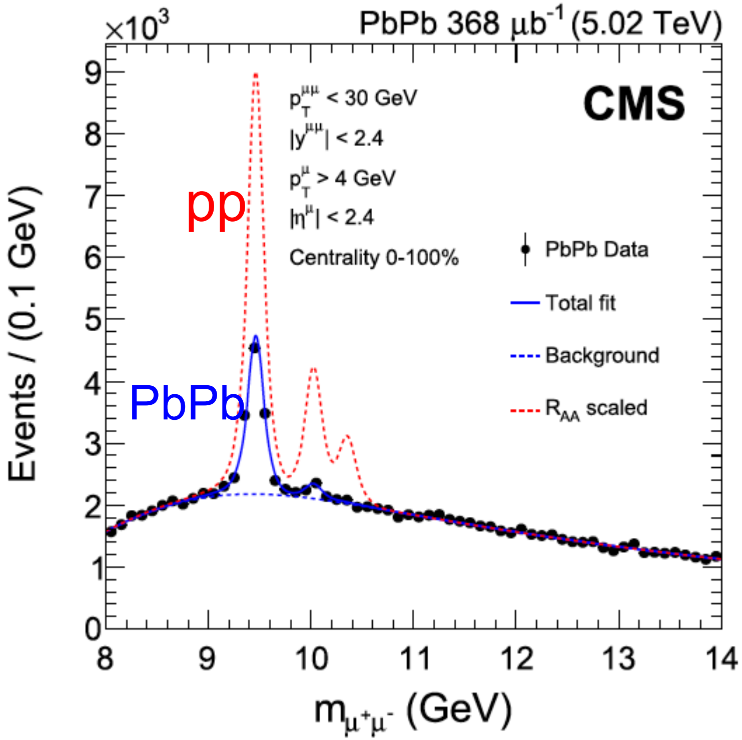
ϒ suppression as a sensitive probe for the QGP

- 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

Use $\Upsilon_{1S,\ 2S,\ 3S}$ for spectroscopy in the QGP

ϒ(nS) states are suppressed in Pb-Pb @ LHC:



ϒ spectroscopy as a clear QGP indicator

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

R_{AA} (ϒ(1S)) = 0.38 ± 0.01 ± 0.04, min. bias

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

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

R_{AA}(ϒ(3S)) = 0.02 ± 0.04 (stat.) ± 0.02 (syst.)

© CMS Collab., PLB 790, 270 (2019)

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

3. The model: Screening, Gluodissociation and Collisional broadening of the ϒ(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 ϒ(nS) states: damping

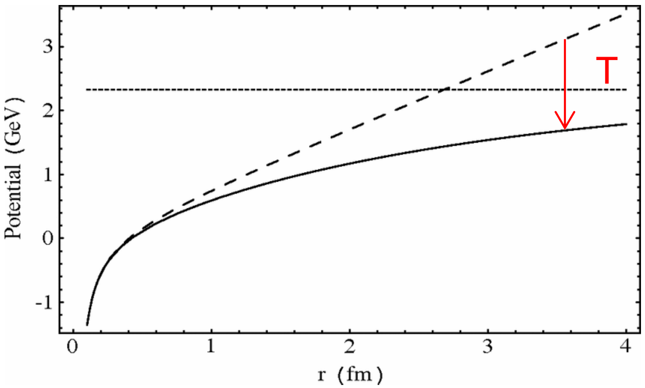
③ Gluon-induced dissociation: dynamic suppression, in particular of the ϒ(1S) ground state due to the large thermal gluon density

④ Reduced feed-down from the excited Υ/χ_b states to ϒ(1S) substantially modifies the populations: indirect suppression

J. Hoelck, F. Nendzig and GW, Phys. Rev. C 95, 024905 (2017); J. Hoelck and GW, EPJA 53, 37 (2017)
F. Vaccaro, F. Nendzig and GW, EPL102, 42001 (2013); 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)

① 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 ‘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, κ Coulomb-parameter

λ_D = Debye length, T = temperature

=> Heavy mesons can “melt” in the hot medium

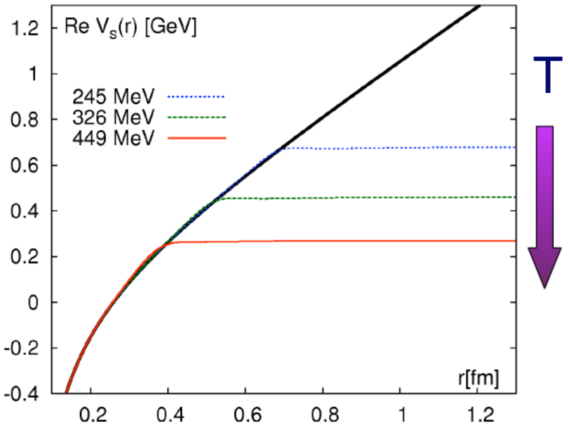
② Optical quark-antiquark potential:

Screened real part, T-dep. imag. part

Constrain Re$V_s(r)$ by lattice QCD data on the singlet free energy

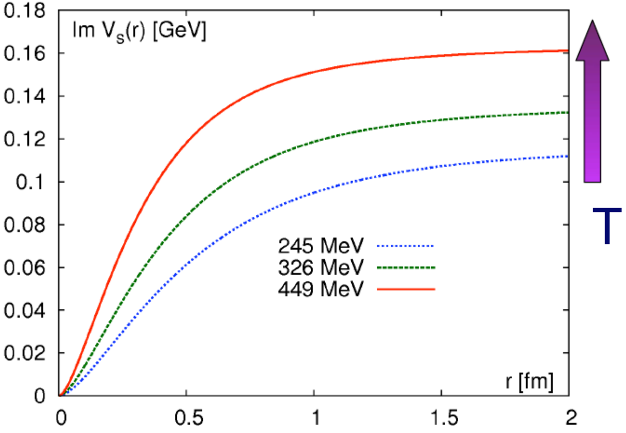
Take Im$V_s(r)$ from pQCD calculations

Maximal value



Mócsy, Petreczky, PRL 99 (07) 211602

Minimal value



Burnier, Laine, Vepsalainen JHEP 0801 (08) 043
Beraudo, arXiv:0812.1130

From: A. Mocsy et al.

Screening

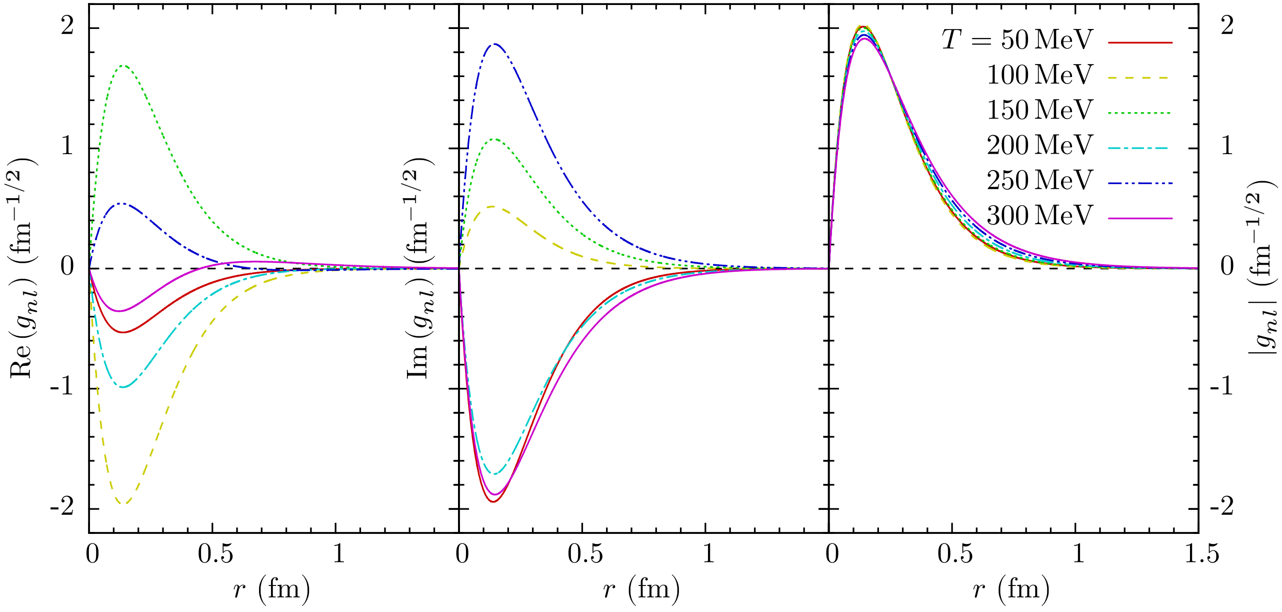
Damping

Solve the Schödinger equation with complex potential $V(r,T,\alpha_s)$ for the radial wave functions $g_{nl}(r,T)$, $[H(r,T,\alpha_s) - E + i\Gamma/2]g(r) = 0$

①, ② Radial wave function of ϒ(1S) at temperatures T

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

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



From: J. Hoelck and GW, unpublished

③ 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 χ_b(nP) states.

Gluodissociation cross section

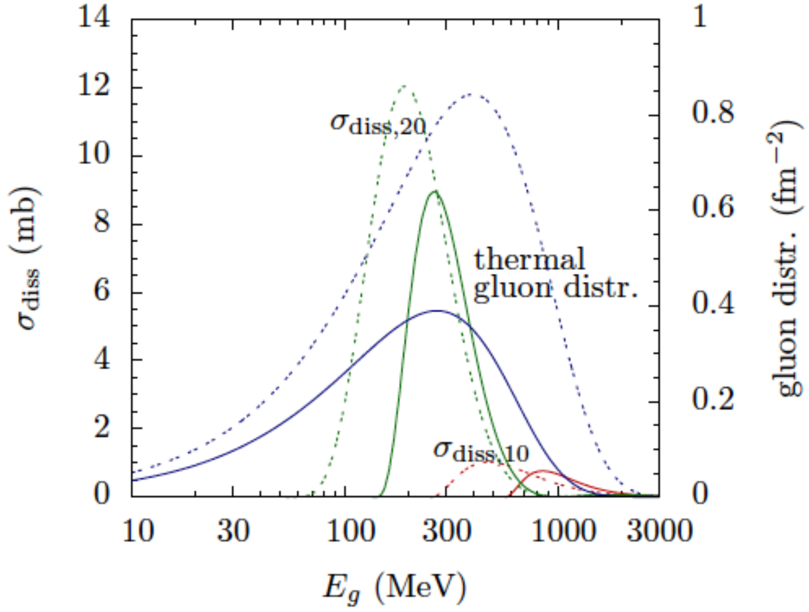


Figure 3. Gluodissociation cross section σ_{diss} (left scale) of the $\Upsilon(1S)$ and $\Upsilon(2S)$ and the thermal gluon distribution (right scale) plotted for temperature $T = 170$ (solid curves) and 250 MeV (dotted curves) as functions of the gluon energy E_g.

Thermal gludissociation cross section

Average the gludissociation 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

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

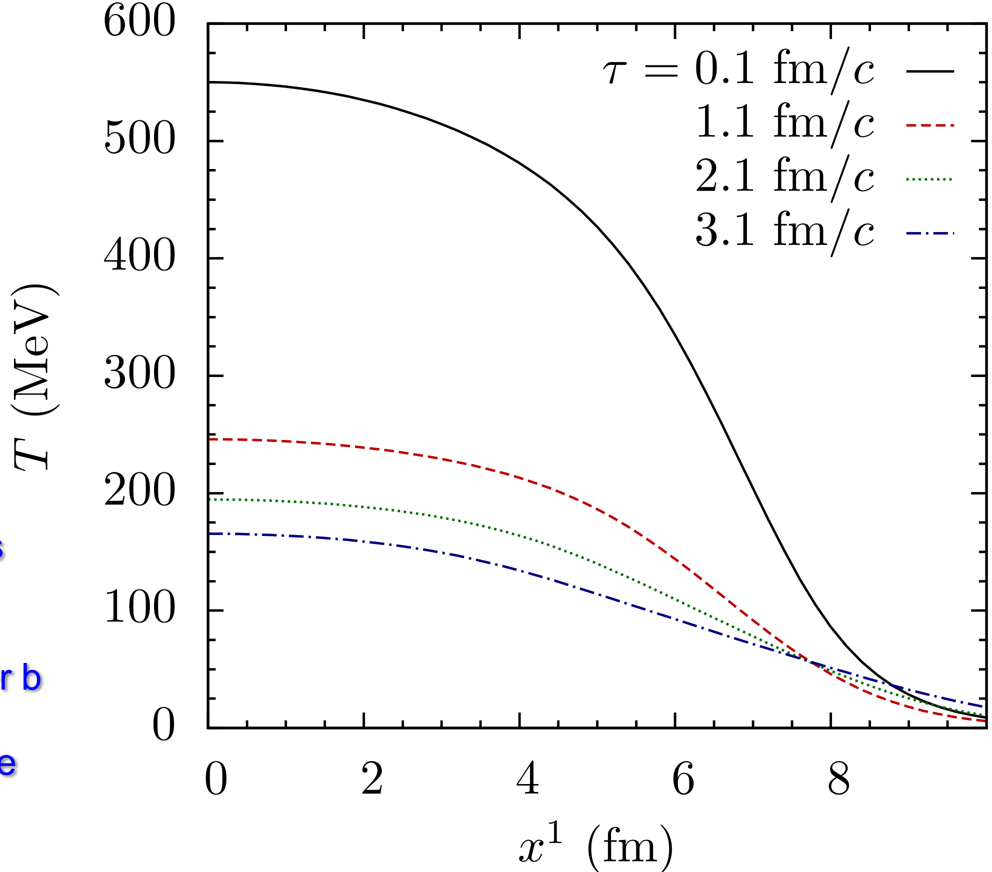
(g_d = 16)

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 gludissociation width for fixed coupling α_s.
(Larger cross sections at higher temperatures due to running coupling counteract.)

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

Hydrodynamic expansion (ideal)

Temperature profile for central collisions at different times τ



Use total decay widths $\Gamma_{tot}(b,x^1,x^2)$ of the bottomonia 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

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

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

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

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

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

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

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).

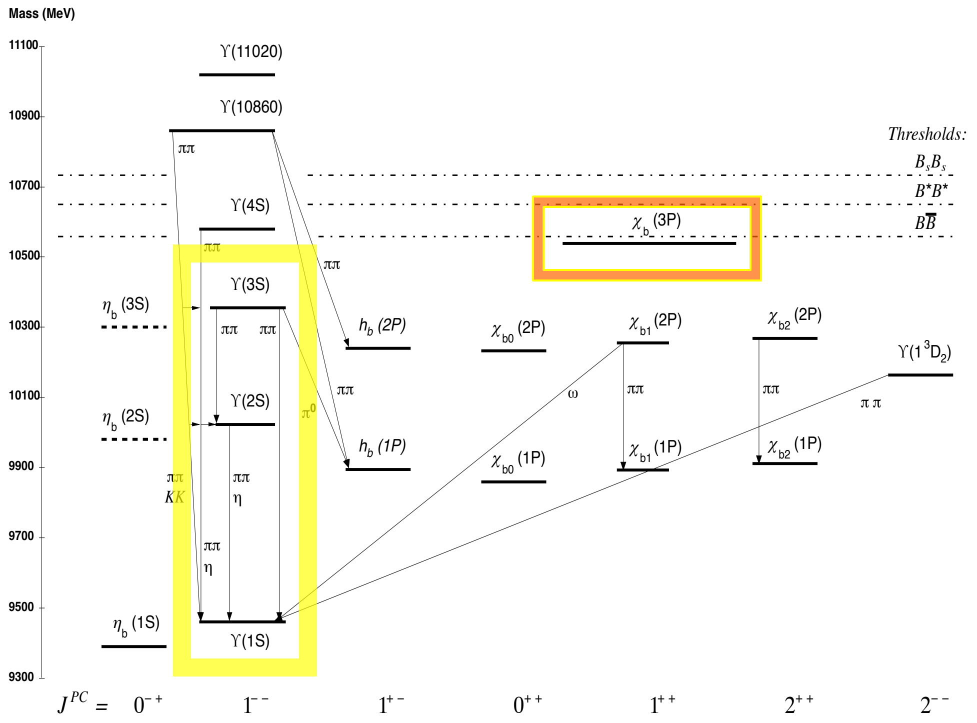
Feed-down is reduced if excited states are screened or depopulated

$N_{initial}$

3S: 0.324

2S: 0.367

1S: 0.373



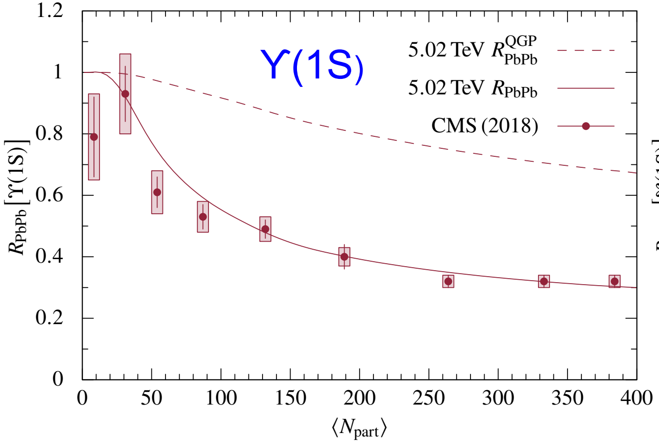
$N_{initial}$

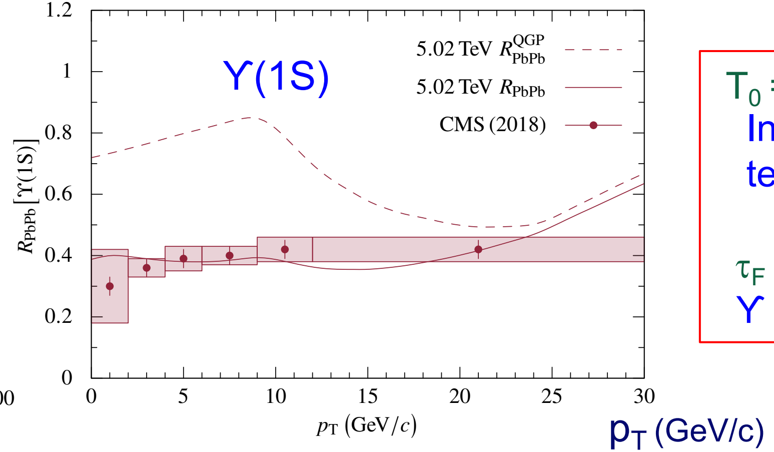
2P: 0.881

1P: 1.084

17

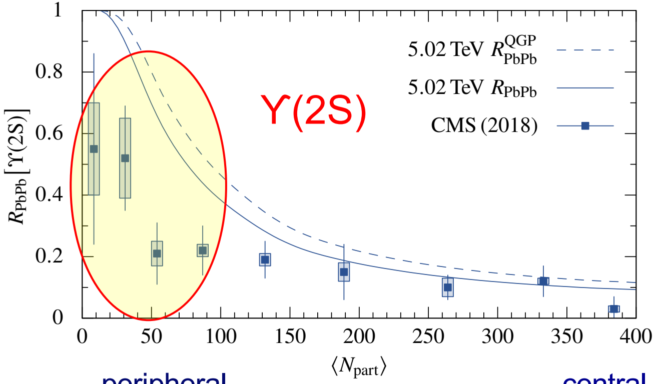
4. Prediction for Υ suppression in 5.02 TeV Pb-Pb vs. CMS data





T_0 = 513 MeV, Initial central temperature

τ_F = 0.4 fm/c, Υ formation time



peripheral central

Predictions (dashed/ solid curves) as calculated using the model of

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

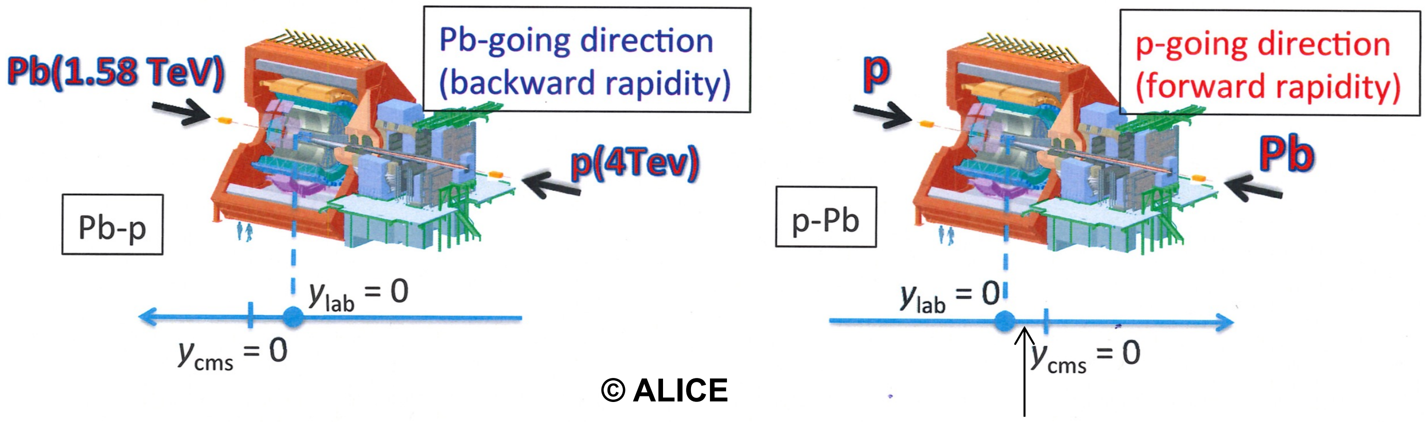
CMS data: Phys. Lett. B 790, 270 (2019)

Comparison model vs. data in
G. Wolschin, Int. J. Mod. Phys. A35, 2030016 (2020)

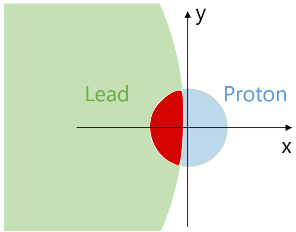
ϒ in Pb-Pb @ LHC energies

- The spectroscopy of ϒ mesons in Pb-Pb 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 ϒ (1S). 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 ϒ(1S) in 5.02 TeV Pb-Pb agrees with CMS data.
- The enhanced suppression of ϒ(2S, 3S) in peripheral collisions leaves room for additional suppression mechanisms.

5. Cold-matter (CNM) and hot-medium (QGP) effects in asymmetric collisions: p-Pb



Rapidity shift: $\Delta y = 0.465$



p-Pb @ $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV

CNM and QGP effects in asymmetric collisions

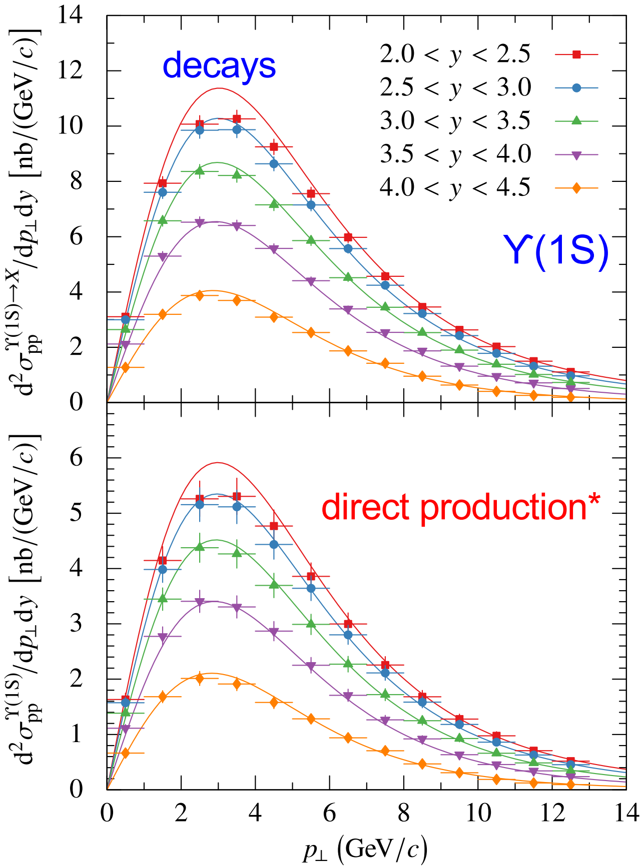
Bottomonia yields are modified by the presence of nuclear matter:
Cold nuclear matter (CNM) effects.

- This includes pure initial-state effects, such as the modification of the initial gluon densities in the nuclear medium [1], and
- Mixed initial- and final-state effects, such as coherent parton energy loss induced by the nuclear medium [2].

We consider these well-established CNM effects together with the additional ϒ suppression in the hot quark-gluon plasma [3,4], as in Pb-Pb.

[1] R. Vogt, Phys. Rev. C 92, 034909 (2015)
[2] F. Arleo et al., JHEP 05, 155 (2013)
[3] V.H. Dinh, J. Hoelck and GW, Phys. Rev. C 100, 024906 (2019)
[4] G. Wolschin, Int. J. Mod. Phys. A 35, 2030016 (2020)

Cross section for Υ(1S) decays&production in pp collisions at 8 TeV



LHCb data **JHEP 2015, 103 (2015)**

Fits:

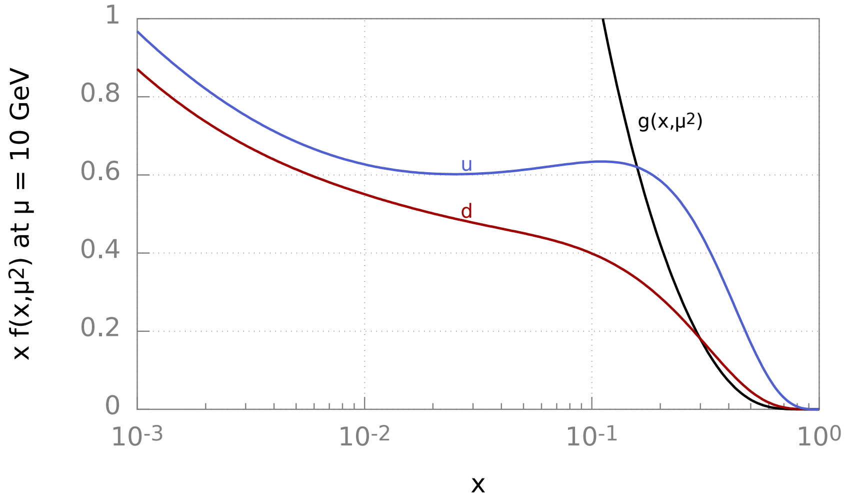
$$\frac{d^2\sigma_{pp}}{dp_\perp dy} = \mathcal{N} p_\perp \left(\frac{p_0^2}{p_0^2 + p_\perp^2}\right)^m \left(1 - \frac{2M_\perp}{\sqrt{s}} \cosh y\right)^n$$

(4 parameters acc. to Arleo et al., JHEP 2013, 155 (2013))

* from inverse feed-down cascade

CNM effects: Parton distribution functions (pdfs)

The parton distribution functions (pdfs) define the probability to find a parton with longitudinal momentum fraction *x* and factorization scale μ



CT14NLO pdf set for u,d,g

S. Dulat et al., PRD 93, 033006 (2016)

$$x f_g^p(x,\mu^2) \propto x^{-\lambda}$$

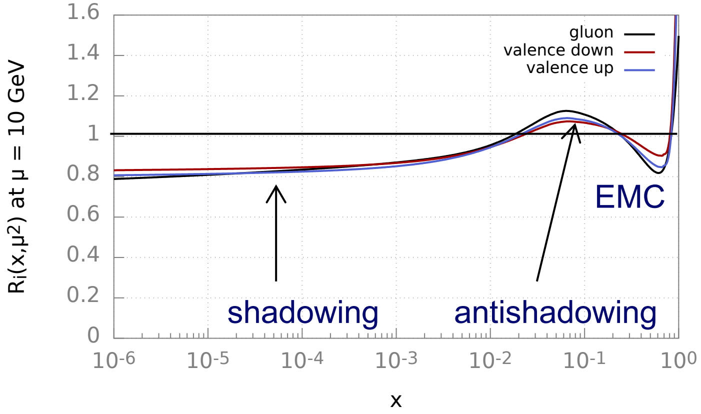
with λ = 0.2 - 0.3

- Gluon pdfs grow rapidly towards small *x*
- they are modified by the presence of a nuclear medium

CNM effects: Modified pdfs in the medium - gluon shadowing

Gluonic nuclear modification factors R_g^{Pb} of the gluon pdf in Pb compared to p (main contribution to ϒ production arises from gluon fusion)

Nuclear shadowing with EPPS16 pdf set



The bottomonium momentum fraction is given by the kinematics of 2->1 processes

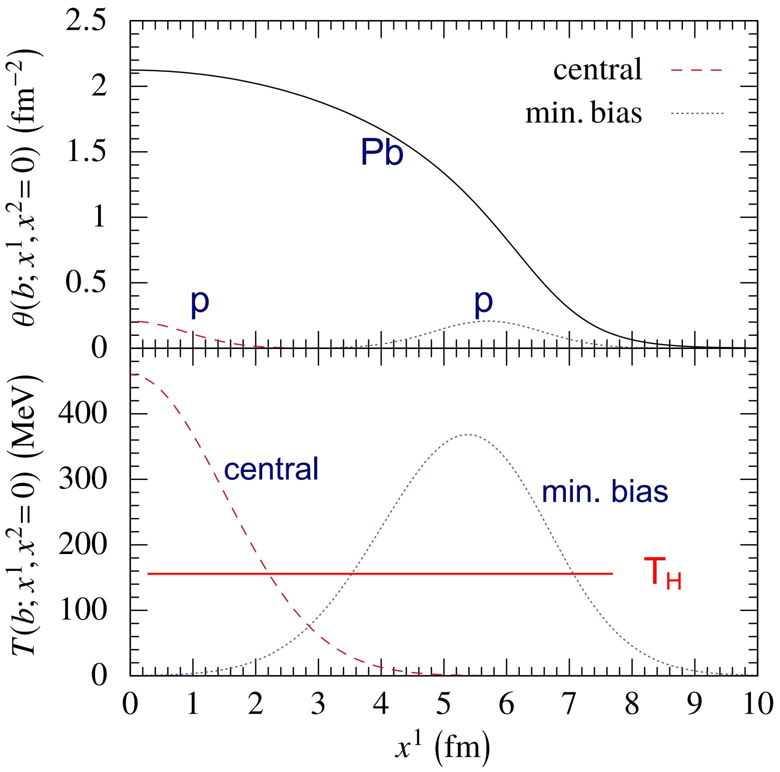
$$x_2(p_\perp, y) = \frac{M_{\Upsilon,\perp}}{\sqrt{s_{NN}}} \exp(-y)$$

e.g. $x_2 = 2.5 \cdot 10^{-5}$ at $y = 4$, $p_T = 6$ GeV/c:
in the shadowing region

($R_i = 1$ for incoherent superposition of nucleons; x = Bjorken‘s parton momentum fraction).

Add the coherent parton energy loss according to **F. Arleo et al., JHEP 05, 155 (2013) ff.**

QGP effects: Thickness functions and initial temperature profiles in 8.16 TeV pPb collisions



top: thickness functions

$\theta_{\rm Pb}(x^1, x^2 = 0)$ for Pb (solid curve),

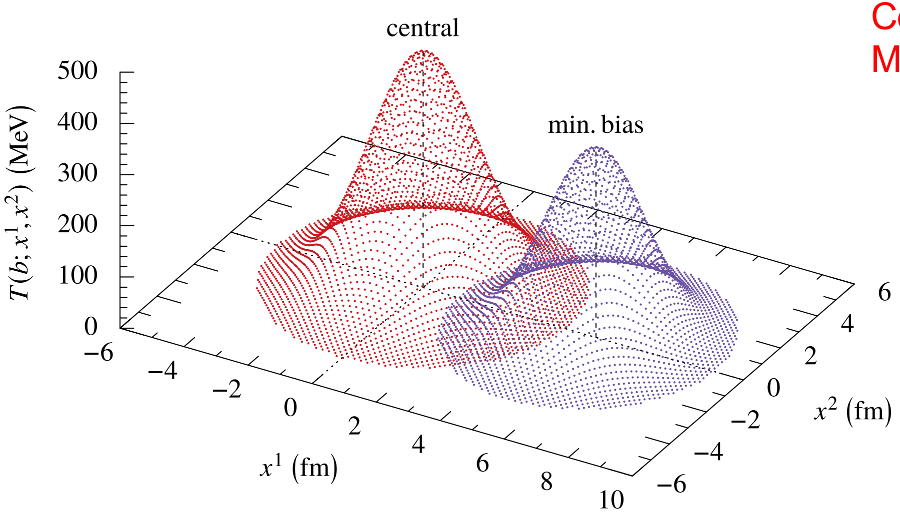
$\theta_{\rm p}(x^1, x^2 = 0)$ for p

bottom: temperature profiles for central (dashed) and minimum-bias (dotted) collisions; T_0 = 460 MeV

Deconfined for
$T > T_H \approx 160$ MeV

$$T(b; \tau_{\rm init}, x^1, x^2) = T_0 \sqrt[3]{\frac{\langle n_{\rm coll}\rangle(b; x^1, x^2)}{\langle n_{\rm coll}\rangle(0; 0, 0)}}$$

Initial temperature profiles in 8.16 TeV p-Pb collisions



Transverse plane (x^1,x^2)

Central collisions: $\langle N_{coll} \rangle \approx 15.6$
Min. bias: $\langle N_{coll} \rangle \approx 7$

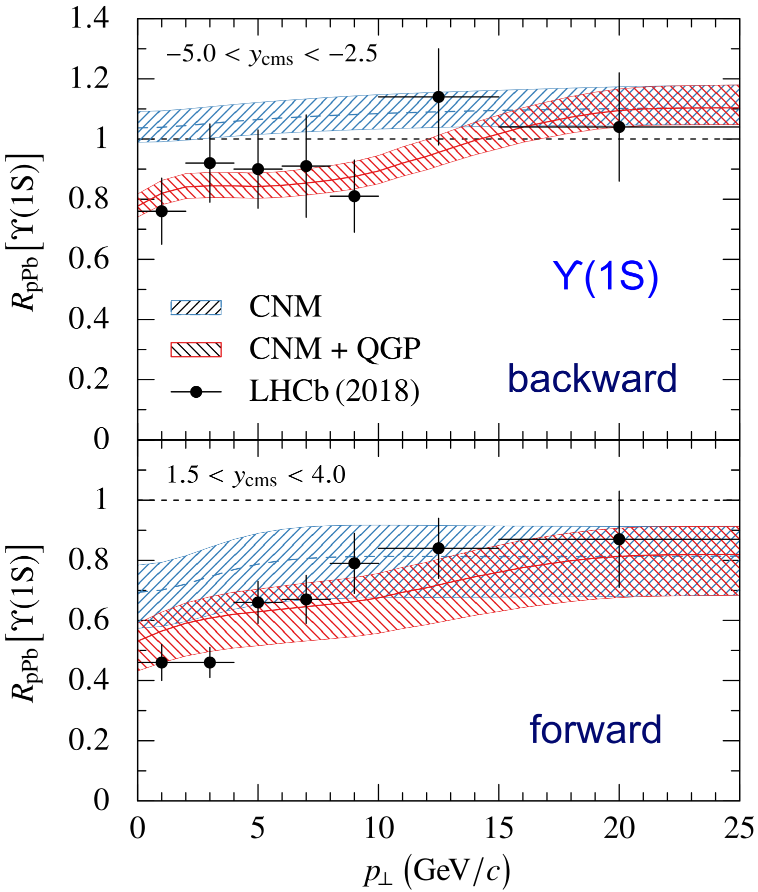
$T_0 = 460$ MeV

Deconfined for
$T > T_H \approx 160$ MeV

$$T(b;\tau_{\rm init},x^1,x^2) = T_0 \sqrt[3]{\frac{\langle n_{\rm coll}\rangle(b;x^1,x^2)}{\langle n_{\rm coll}\rangle(0;0,0)}}$$

6. Comparison with LHC data:

Transverse momentum dependence of Υ(1S) yields in p-Pb at 8.16 TeV vs. LHCb data



Blue: CNM effects only,
backward: antishadowing
forward: shadowing

Energy-loss effects at $p_T \leq 8$ GeV/*c*

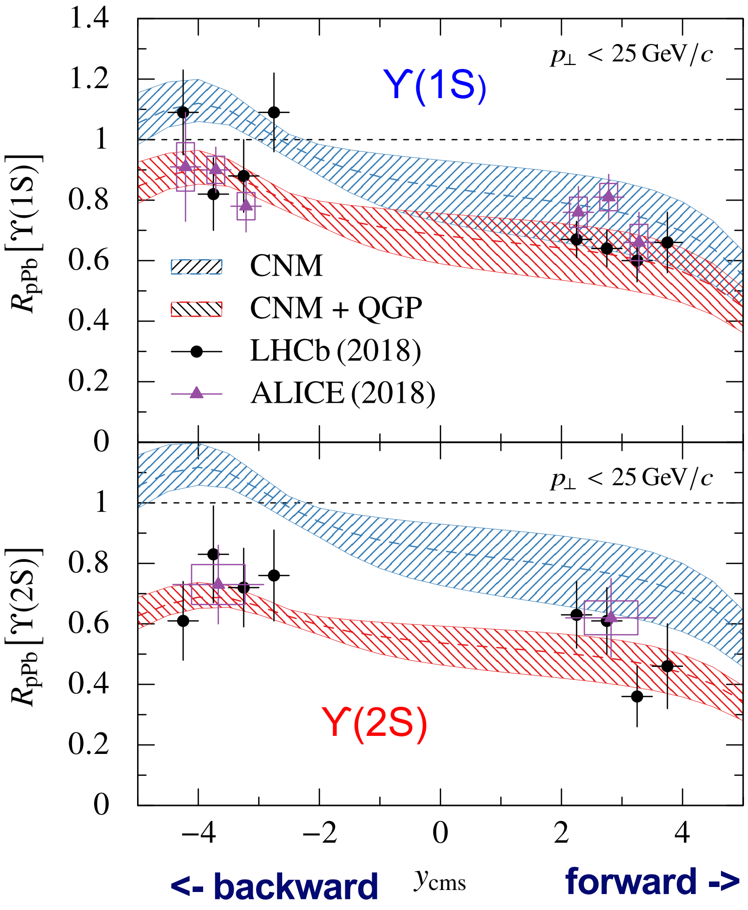
Red: With hot-medium suppression
(T_0= 460 MeV; t_F= 0.4 fm/c):
Essential to understand the data.

Consistent with the creation of QGP droplets
in pAu, dAu by PHENIX, **Nature Phys. 15, 214-220 (2019).**

LHCb data: **JHEP 11, 194 (2018)**

Alternative interpretation: «Comovers», E.G. Ferreiro, J.P. Lansberg, JHEP 10, 094 (2018)

Rapidity dependence of Υ(1S, 2S) yields in pPb at 8.16 TeV vs. LHCb and ALICE data



Blue: CNM effects only

Red: With hot-medium suppression

Data LHCb: JHEP 11, 194 (2018)
ALICE: Phys. Lett. B 806, 135486 (2020)

(T_0= 460 MeV; τ_F= 0.4 fm/c)

Heidelberg model:

V.H. Dinh, J. Hoelck and GW, Phys. Rev. C 100, 024906 (2019);
G. Wolschin, Int. J. Mod. Phys. A35, 2030016 (2020);
Universe 6, 61 (2020)

7. Conclusion: ϒ in p-Pb @ LHC energies

- The CNM effects shadowing and coherent energy loss are decisive for a proper interpretation of the bottomonia modifications in p-Pb, *but:*
- The hot-medium (QGP) effects play a substantial role in the measured ϒ suppression in p-Pb, which cannot be understood with CNM effects alone.
- Our theoretical model with CNM and QGP effects is found to be in agreement with the LHCb and ALICE results for $\Upsilon(1S,2S)$ in p_T and rapidity dependence; discrepancies remain for the centrality dependence.
- The initial central temperature of the QGP zone is found to be $T_0 \approx 460$ MeV in 8.16 TeV p-Pb, but depends on the ϒ formation time.

Thank you for your attention !

Extra slides

Large Hadron Collider (LHC) / CERN

SPS

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

p-Pb @ 5.02 TeV 2012/13
@ 5.02, 8.16 TeV Nov. 2016

Pb-Pb @ 2.76 TeV 2011/12 Run 1
@ 5.02 TeV Nov. 2015 Run 2
Nov. 2018 Run 2
@ 5.36 TeV Nov 2023 Run 3

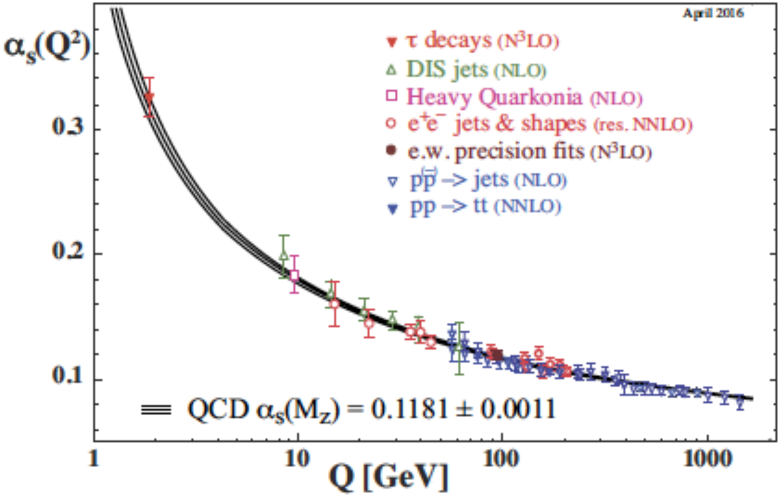
① ,② Screening and damping in a nonrelativistic potential model

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

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

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 $2\pi T << <1/r>$.

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

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

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

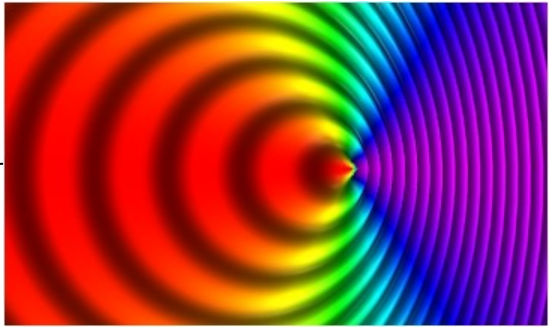
For a finite relative velocity between the expanding QGP and the bottomonium states the relativistic Doppler shift results in an angle-dependent effective temperature

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

with the angle θ between the medium velocity **u** (in the bottomonium 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

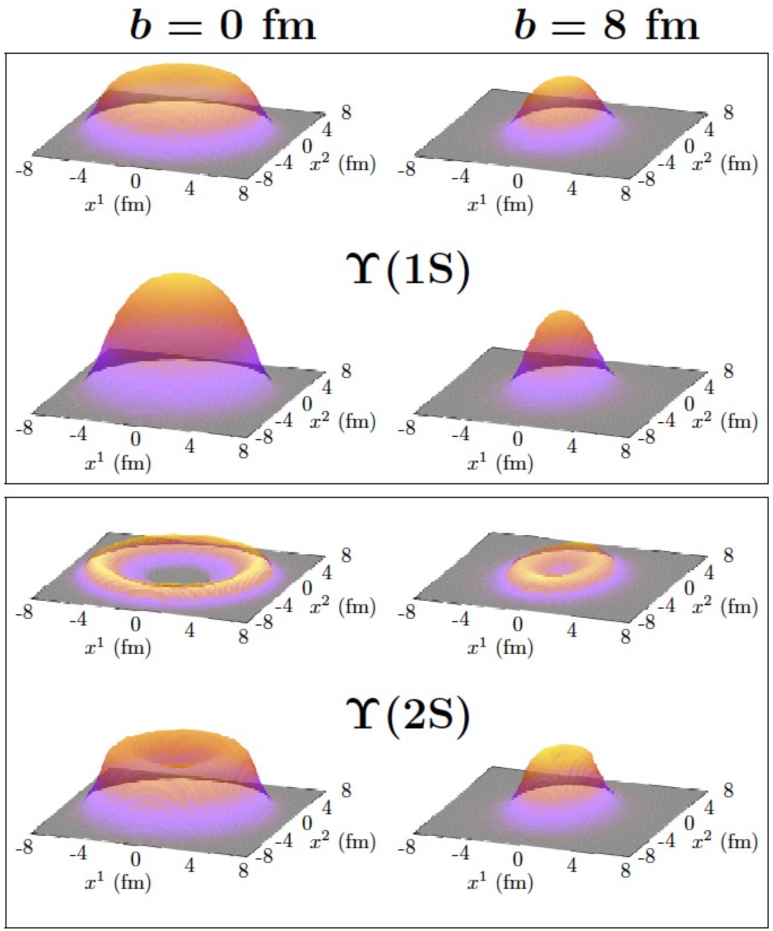


θ = 0° , blueshift

u = 0.7 c

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

Integrand
in the
transverse
plane



$p_T = 0$

$p_T = 12$ GeV/c

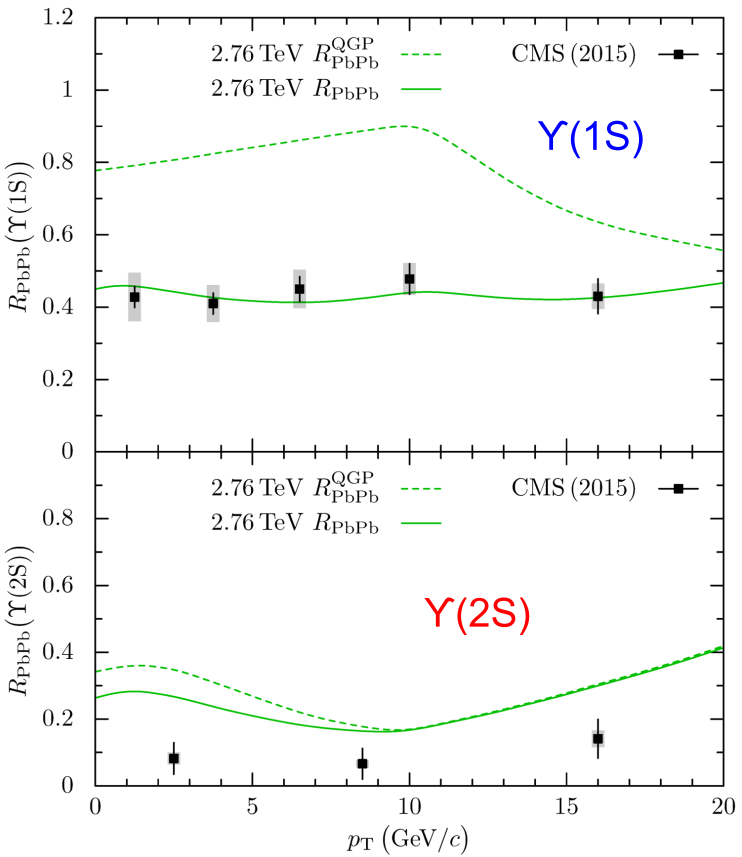
$p_T = 0$

$p_T = 12$ GeV/c

Nendzig&GW,
J. Phys. G41,
095003 (2014)

Selected results Pb-Pb vs. CMS data:

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

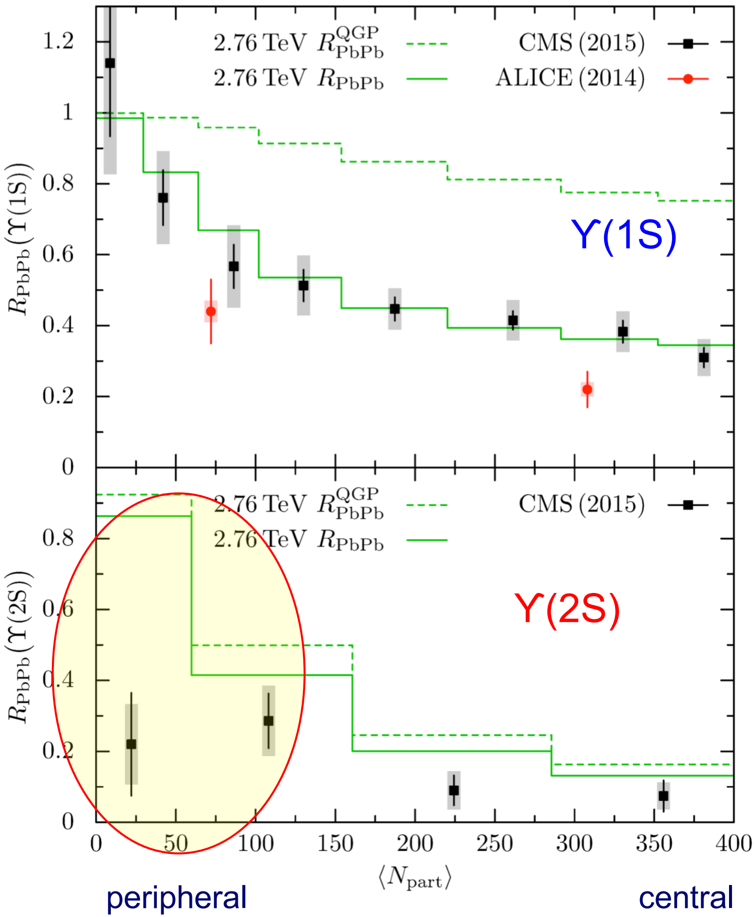
← Including reduced feed-down

(T_0= 480 MeV; τ_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 ϒ(1S), not for excited states

2.76 TeV Pb-Pb centrality-dependent results vs. CMS and ALICE



2.76 TeV PbPb   LHC

τ_F= 0.4 fm/c: ϒ formation time

T_0= 480 MeV: central temp.
at b = 0 and t = t_i = 0.1 fm/c

$$s_0 \propto dN_{ch}/d\eta \propto T_0^3$$ (use for predictions)

Room for additional suppression mechanisms for the excited states: Hadronic dissociation, mostly by pions, is one possibility. Thermal pions are insufficient; direct pions may contribute (magnetic dissociation is too small, the field decays in t < 0.1 fm/c).

J. Hoelck, F. Nendzig and GW, Phys. Rev. C 95, 024905 (2017);
J. Hoelck and GW, Eur. Phys. J. A 53, 241 (2017)

ϒ suppression in 200 GeV Au-Au vs. STAR data (PRL 2023)

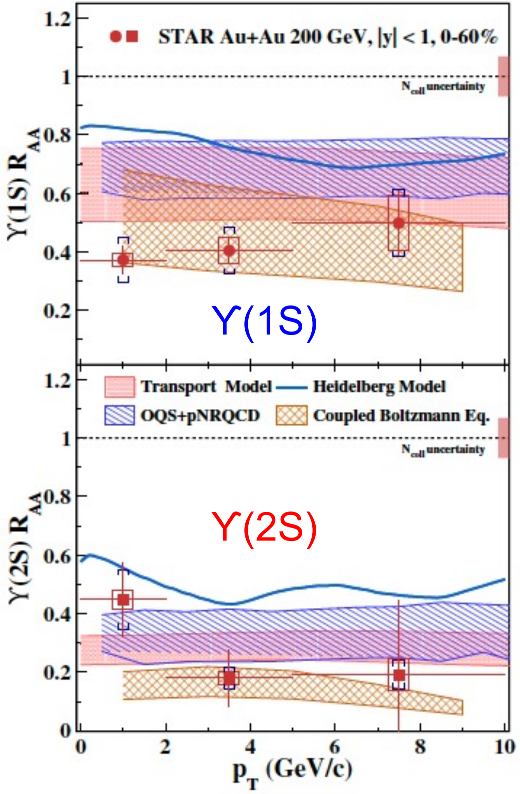


FIG. 4. ϒ(1*S*) (top) and ϒ(2*S*) (bottom) R_{AA} as a function of p_T in the 0%–60% centrality class, compared to different model calculations. The boxes and brackets around the data points represent systematic uncertainties from Au + Au analysis and $p + p$ reference, respectively. The band at unity shows the uncertainty in N_{coll}.

Predictions (solid blue curves) as calculated using the model of

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

('Heidelberg Model'), with T_0= 356 MeV

The p_T-dependent STAR data are overestimated because

- T_0 as obtained from an entropy argument is likely too small: T_0=420 MeV gives much better agreement with the data within the error bars
- CNM effects are neglected, but may be more important at 200 GeV than at 5.02 TeV

© STAR Collab., Phys. Rev. Lett. 130, 112301 (2023)

CNM effects: Shadowing plus coherent parton energy loss

Including the coherent parton energy loss in the model of Arleo&Peigné,
the modification of the ϒ production cross section from pp to pPb becomes

$$\frac{1}{\langle N_{\rm coll}\rangle}\frac{{\rm d}^2\sigma_{\rm pPb}^{\rm CNM}}{{\rm d}p_\perp{\rm d}y} = \int_0^{2\pi}\frac{{\rm d}\varphi}{2\pi}\int_0^{\varepsilon_{\rm max}}{\rm d}\varepsilon\, P(\varepsilon, E, L_{\rm eff})\,\frac{p_\parallel}{p_\parallel^{\rm shift}}\frac{p_\perp}{p_\perp^{\rm shift}}\,R_g^{\rm Pb}(x_2^{\rm shift})\,\frac{{\rm d}^2\sigma_{\rm pp}}{{\rm d}p_\perp{\rm d}y}(p_\perp^{\rm shift}, y^{\rm shift})$$

with the shifted quantities
(energy in the Pb rest frame
-> rapidity in cm frame)

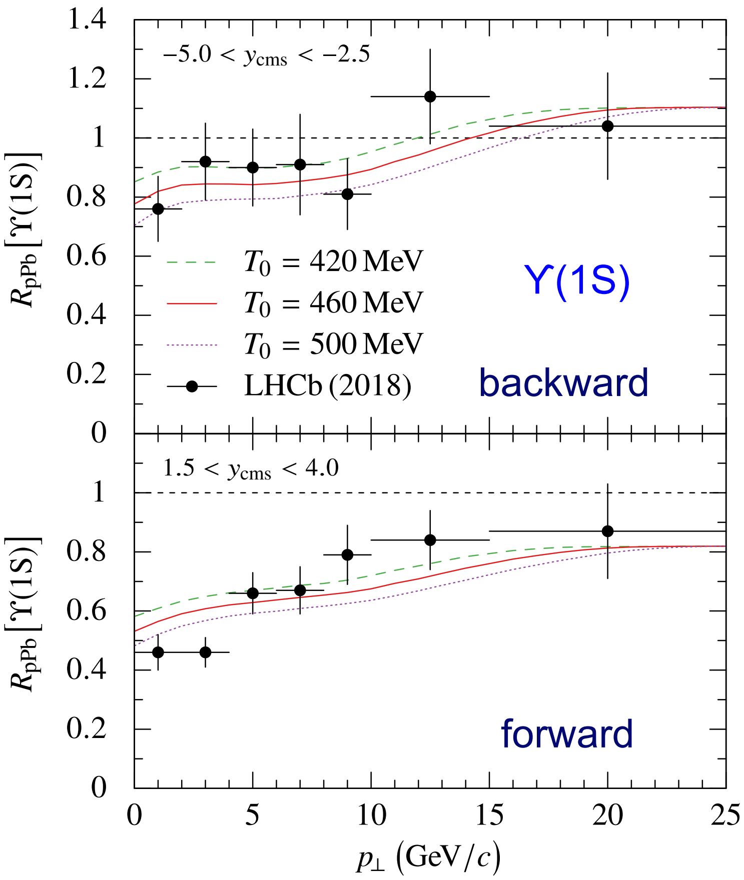
$$y^{\rm shift} = {\rm arcosh}\left[\frac{E(p_\perp, y)+\varepsilon}{M_\perp(p_\perp^{\rm shift})}\right] - y_{\rm beam}\,,$$

$$p_\perp^{\rm shift} = \sqrt{p_\perp^2 + \Delta p_\perp^2 + 2p_\perp\Delta p_\perp\cos\varphi}\,,$$

$$p_\parallel^{\rm shift} = \sqrt{\left[E(p_\perp, y)+\varepsilon\right]^2 - M_\perp^2(p_\perp^{\rm shift})}\,.$$

Partons traversing the (‘cold‘) medium loose energy ε via induced gluon radiation
The angle between the ϒ‘s p_T and the transverse momentum kick Δp_T is φ.

Effect of the initial central temperature T_0:
Transverse momentum dependence of ϒ(1S) yields in pPb at 8.16 TeV

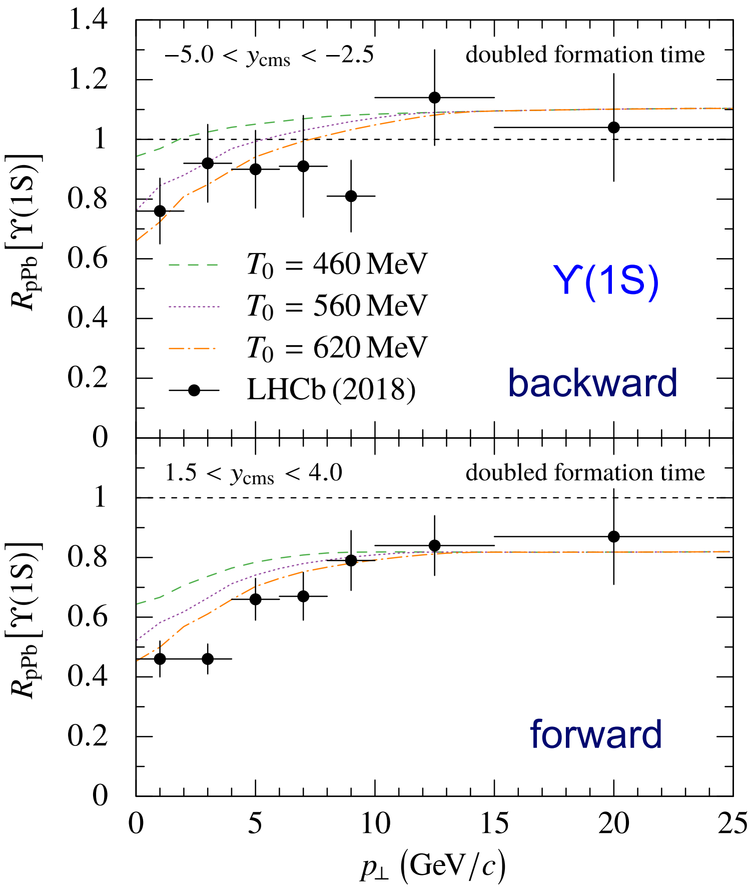


T_0 = 420, 460, 500 MeV

LHCb data **JHEP 2018, 194 (2018)**

(t_F= 0.4 fm/c)

Effect of the formation time t_F:
Transverse momentum dependence of ϒ(1S) yields in pPb at 8.16 TeV

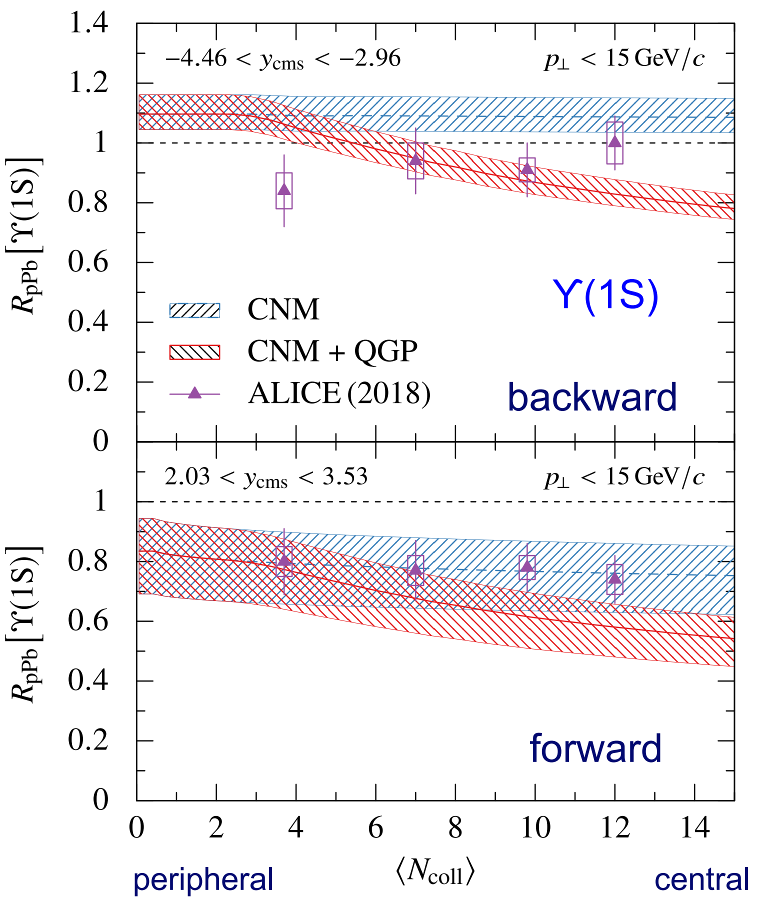


Doubling the formation time to t_F= 0.8 fm/c requires larger initial central temperatures:

T_0 = 460, 560, 620 MeV

LHCb data **JHEP 2018, 194 (2018)**

Centrality dependence of Υ(1S) yields in pPb at 8.16 TeV vs. ALICE data



Blue: CNM effects only

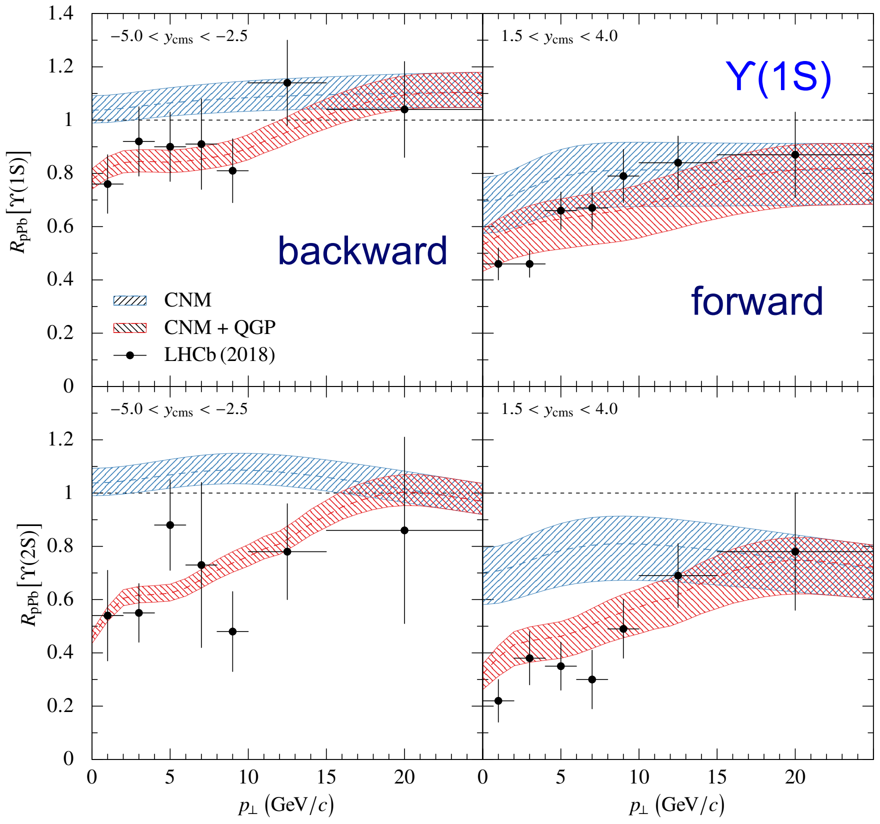
Red: With hot-medium suppression

prel. data: **ALICE-PUBLIC-2018-008**

(T_0= 460 MeV; t_F= 0.4 fm/c)

Comparison with LHC data:

Transverse momentum dependence of ϒ(1S, 2S) yields in pPb at 8.16 TeV vs. LHCb data



LHCb data: **JHEP 2018, 194 (2018)**

Blue: CNM effects only,
backward: antishadowing
forward: shadowing

Energy-loss effects pronounced at
$p_T \leq 8$ GeV/*c*

Red: With hot-medium suppression
(T_0= 460 MeV; τ_F= 0.4 fm/c):
Essential to understand the data.

Consistent with the creation of QGP droplets
in pAu, dAu by PHENIX, **Nature Phys. 15, 214-220 (2019).**

V.H. Dinh, J. Hoelck and GW,
Phys. Rev. C 100, 024906 (2019)