Hot-medium effects on Υ yields in p-Pb and Pb-Pb collisions

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Topics

1. Introduction

   2. Bottomonium suppression in **Pb-Pb** @ LHC

   3. Our model for ϒ 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**

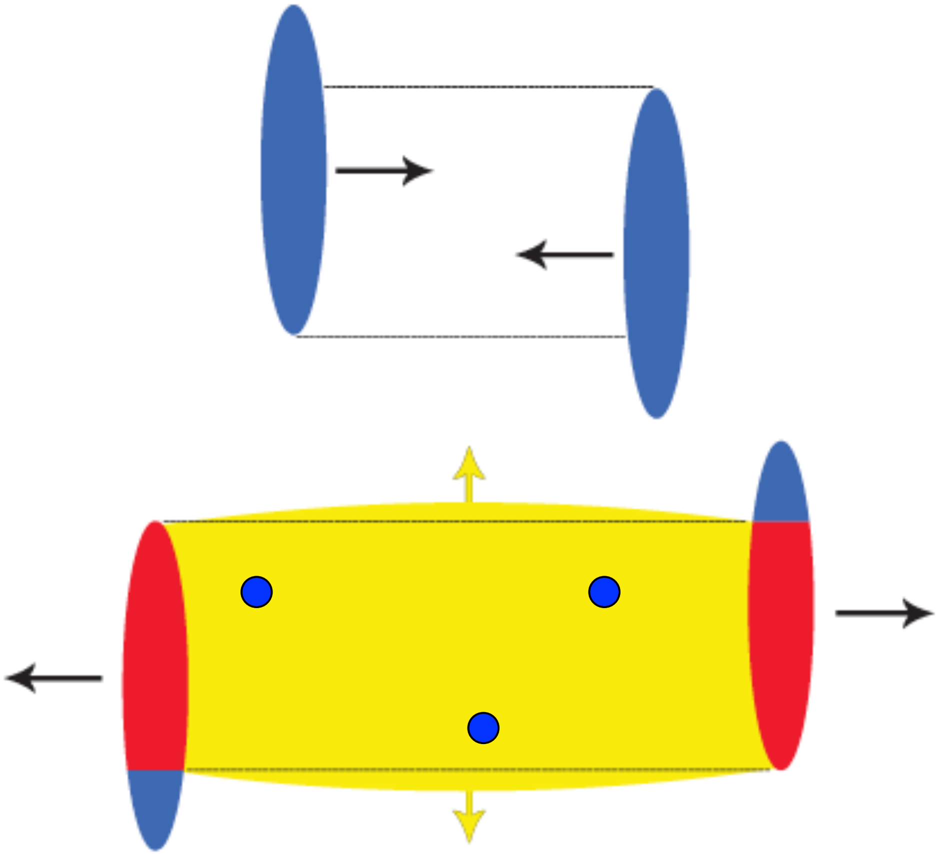
   6. Comparison p-Pb with LHCb and ALICE data

7. Conclusion

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

... 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



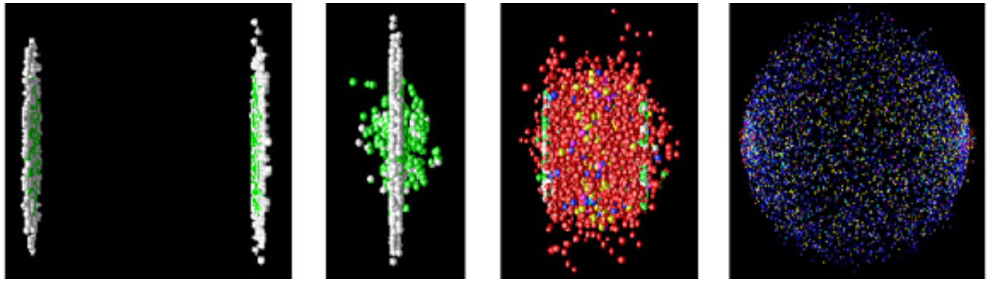
● Heavy quarkonia in the QGP of gluons and light (u, d, s) quarks

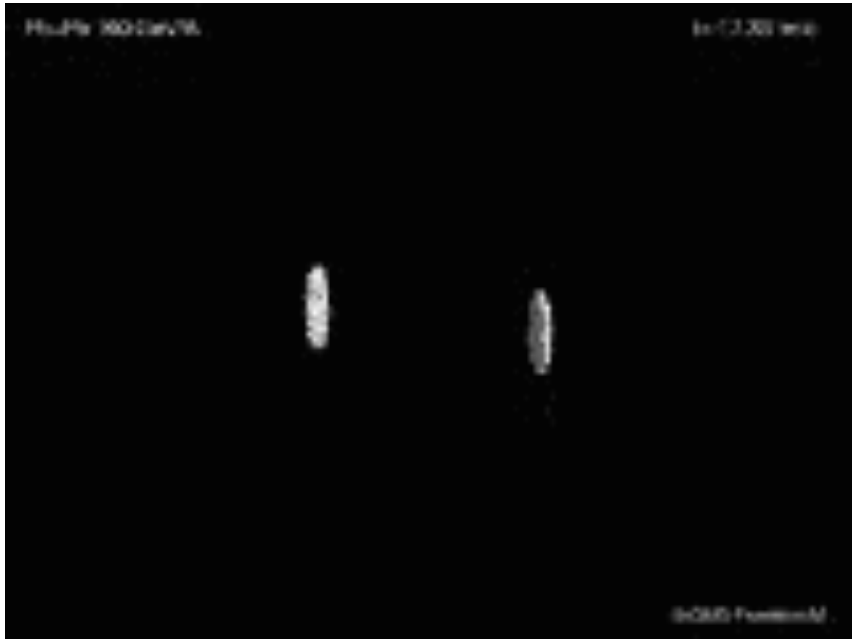
graphic from: B. Kellers&GW, PTEP 2019, 053 (2019)

Time-dependent simulation:

Quark-gluon plasma (QGP) created in relativistic heavy-ion collisions

$t_{int} \approx$ 5-8 fm/c @ LHC





In the first stages of the collision, gluons equilibrate, quarks and **heavy quarkonia** form, later more matter and antimatter is being created from the relativistic energy in the fireball, $E = \sqrt{(p^2 + m^2)}$, it expands and cools, then hadronizes completely. Created baryons, mesons (or their decay products), photons, leptons are then detected:

→ Conclusions regarding the QGP properties are drawn.

Large Hadron Collider (LHC) / CERN

SPS

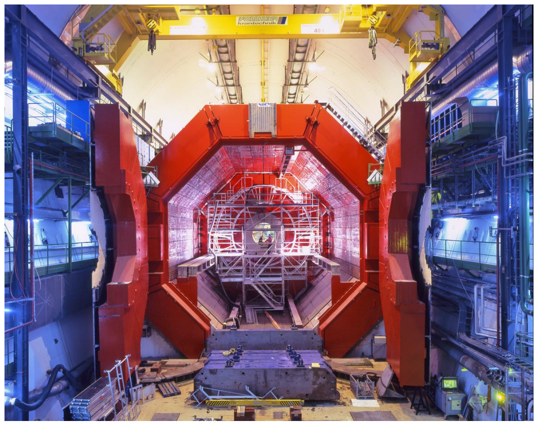
p+p @ 7,8,13,(14) TeV

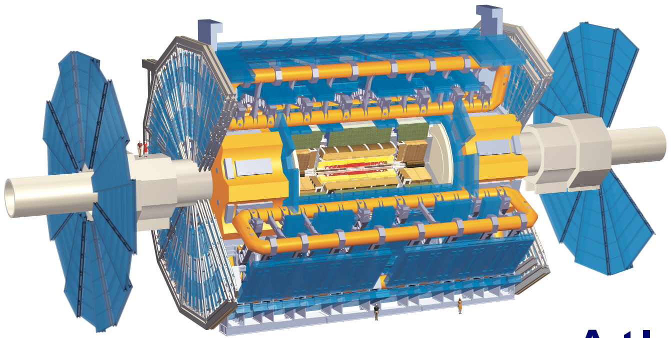
p+Pb @ 5.02 TeV 2012/13
@ 5.02, 8.16 TeV Nov. 2016

Pb+Pb @ 2.76 TeV 2011/12 Run 1
@ 5.02 TeV Nov. 2015 Run 2
Nov. 2018 Run 2

(design energy 5.52 TeV)

LHC Detectors: pp, plus Relativistic heavy-ion physics: Pb-Pb, p-Pb

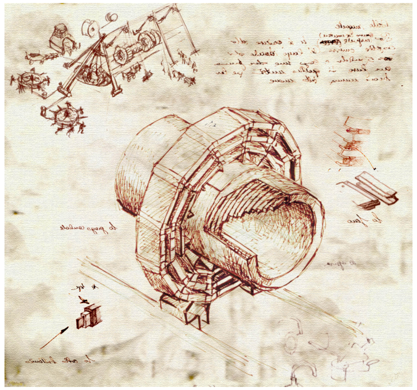


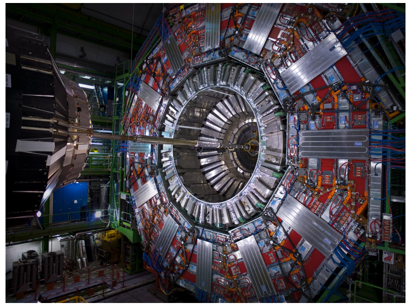


Higgs‘ boson

Atlas

≈ 35 HI people



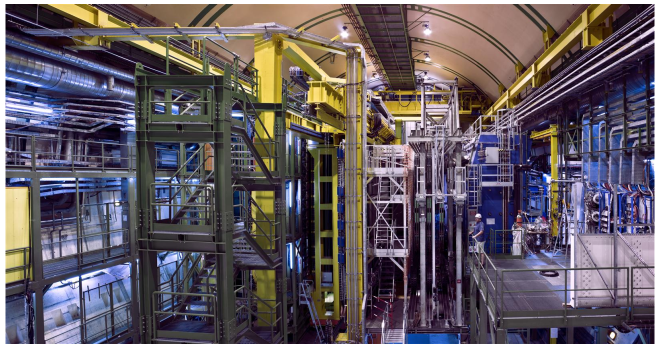


CMS

da Vinci style

≈ 60 HI people

Pb-Pb, p-Pb



Pb-Pb

p-Pb

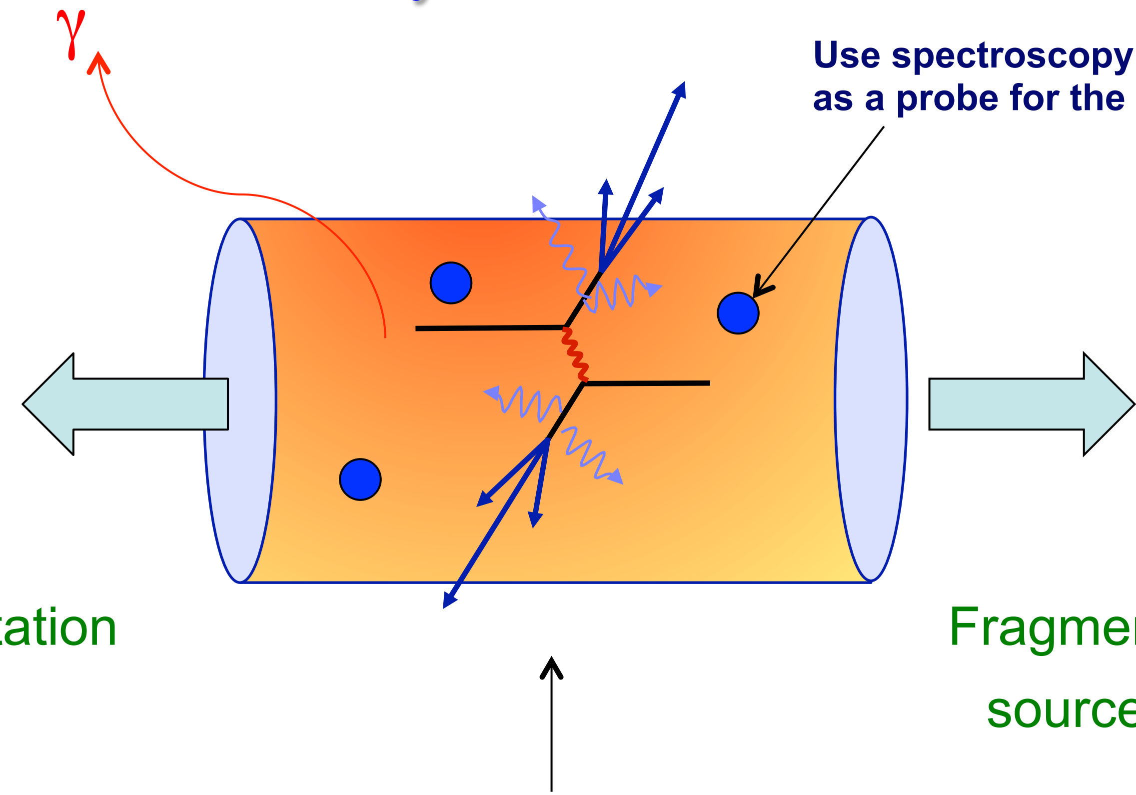
LHCb

p-Pb; peripheral PbPb

Alice: L3 magnet

> 1,000 HI people

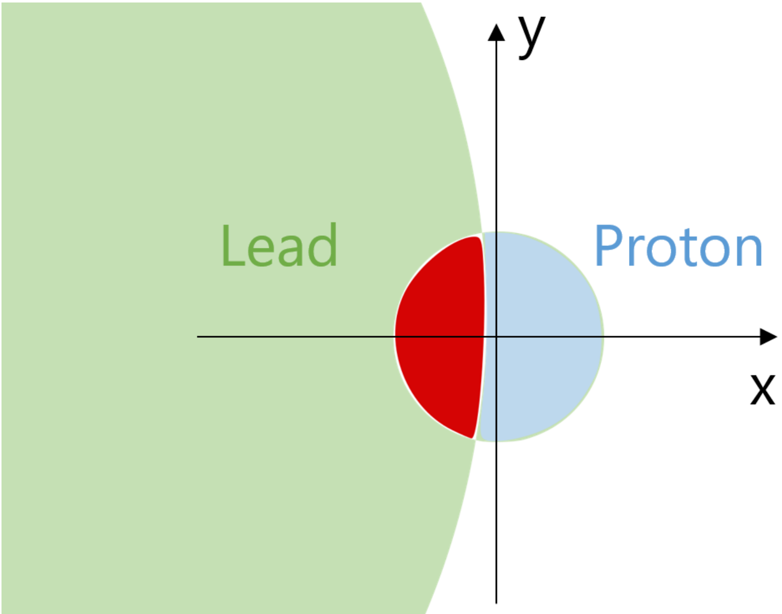
Three sources for particle production in a symmetric relativistic heavy-ion collision such as Pb-Pb



Particle production in the midrapidity source is often considered in a **Thermal Model with a limiting temperature T_H** (which dates back to R. Hagedorn of CERN) − in spite of the short interaction time of $\sim 10^{-23}$ s

Asymmetric p-Pb collisions

Overlap of the thickness functions θ in the transverse plane



Thickness functions

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

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

Overlap function

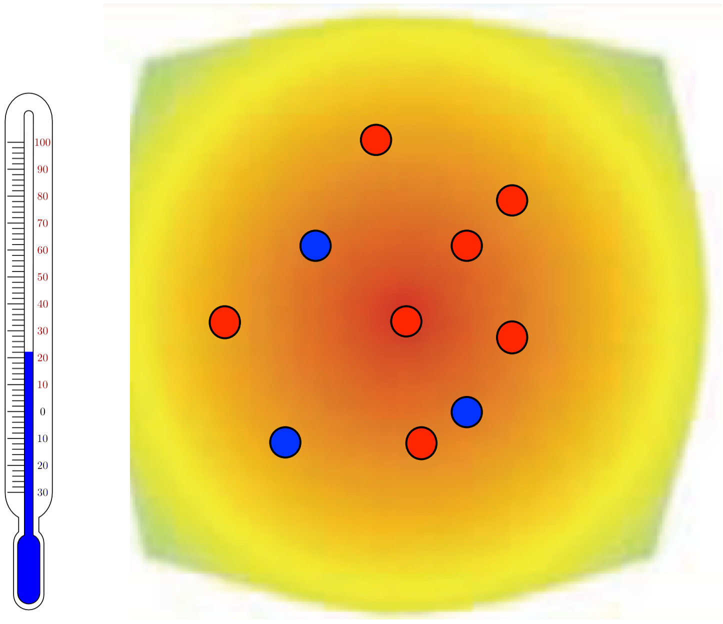
$$\theta_{\rm pPb}(b;x^1,x^2) = \theta_{\rm p}(b;x^1,x^2) \times \theta_{\rm Pb}(b;x^1,x^2)$$

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

(In the transverse plane)

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

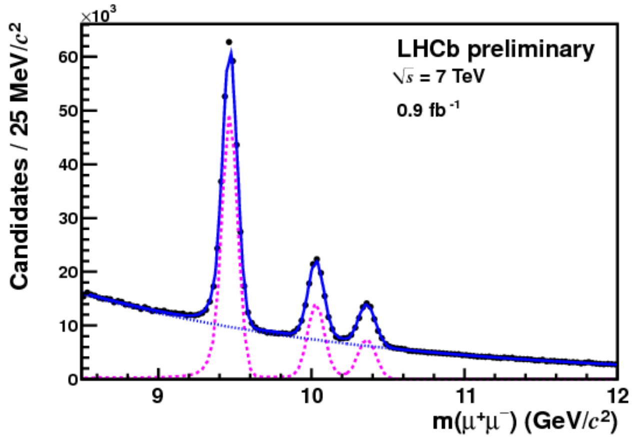
2. Heavy quarkonia in the QGP



● $J/\psi\ (c\bar{c})$

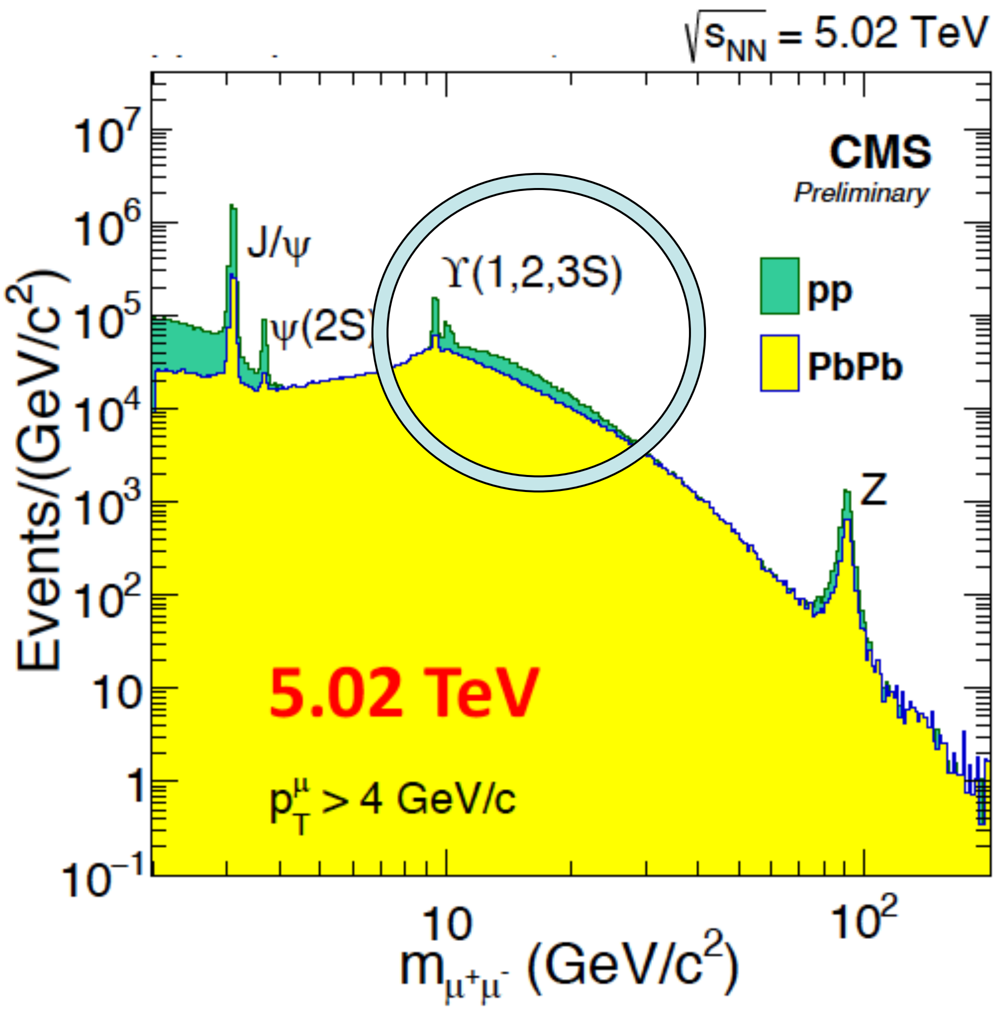
● $\Upsilon\ (b\bar{b})$

- **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?

Υ suppression in PbPb @ LHC



© CMS Collab., Hard Probes Wuhan (2016)

Υ suppression as a sensitive probe for the QGP

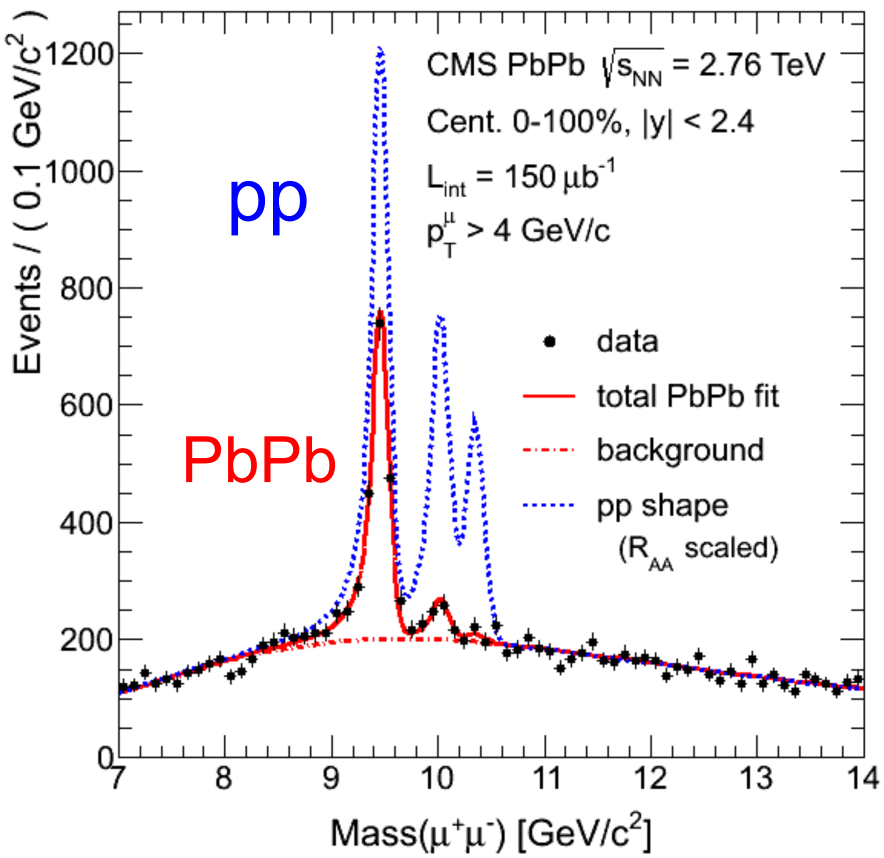
- No significant effect of regeneration
- $m_b \approx 3m_c$ ⇨ cleaner theoretical treatment
- More stable than J/ψ

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

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

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

CMS



ϒ spectroscopy as
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 more 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]

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

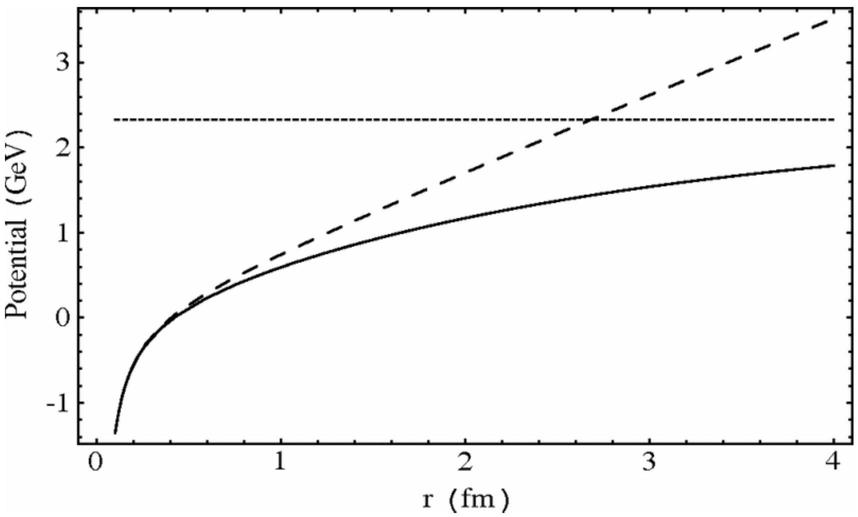
③ Gluon-induced dissociation: dynamic suppression, in particular of the ϒ(1S) ground state due to the large thermal gluon density

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



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

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

σ string tension, κ Coulomb-parameter

λ_D = Debye length, T = temperature

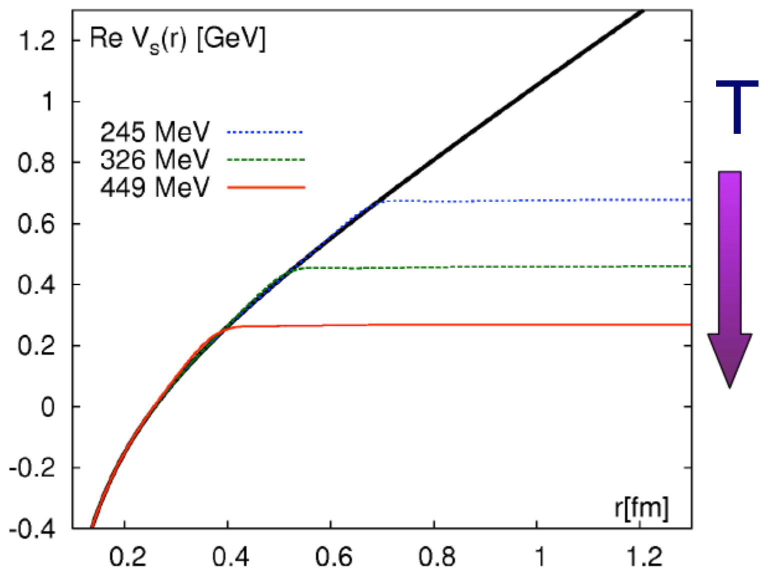
=> Heavy mesons can “melt” in the hot medium

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

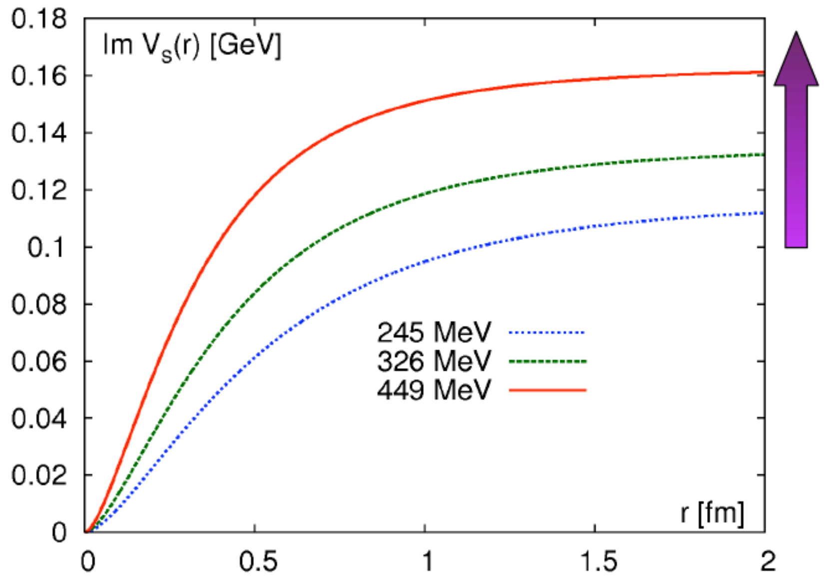
Maximal value



Mócsy, Petreczky, PRL 99 (07) 211602

Take Im$V_s(r)$ from pQCD calculations

Minimal value



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

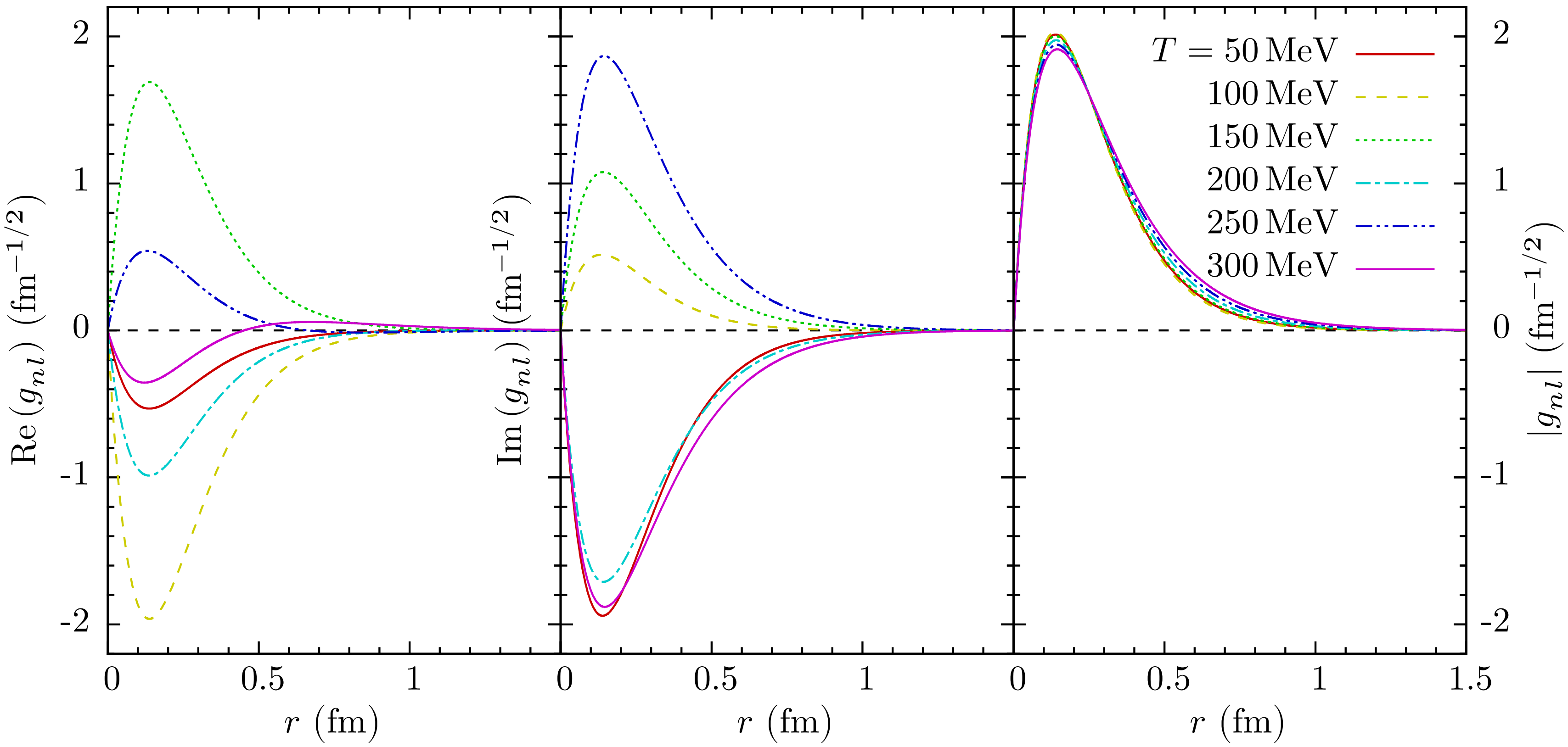
Screening

From: A. Mocsy et al.

Damping

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.

Gludissociation cross section

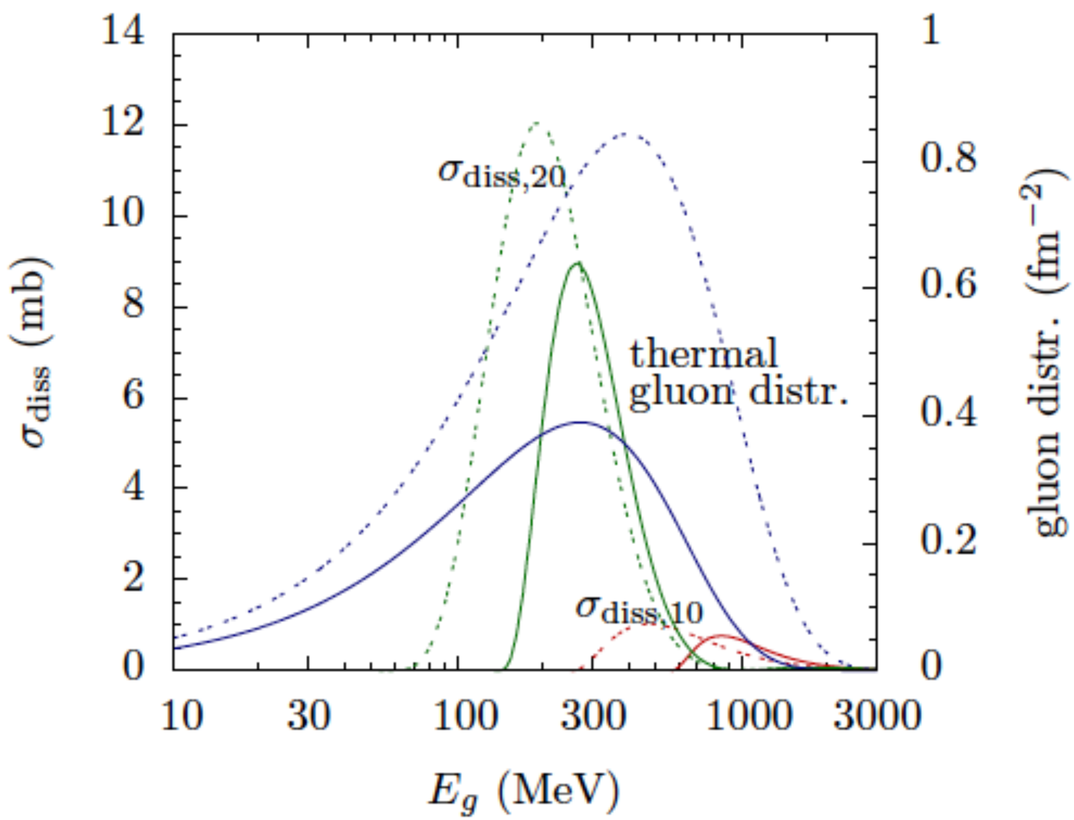


Figure 3. Gludissociation cross section σ_{diss} (left scale) of the $\Upsilon(1S)$ and $\Upsilon(2S)$ and the thermal gluon distribution (right scale) plotted for temperature $T = 170$ (solid curves) and 250 MeV (dotted curves) as functions of the gluon energy E_g.

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

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

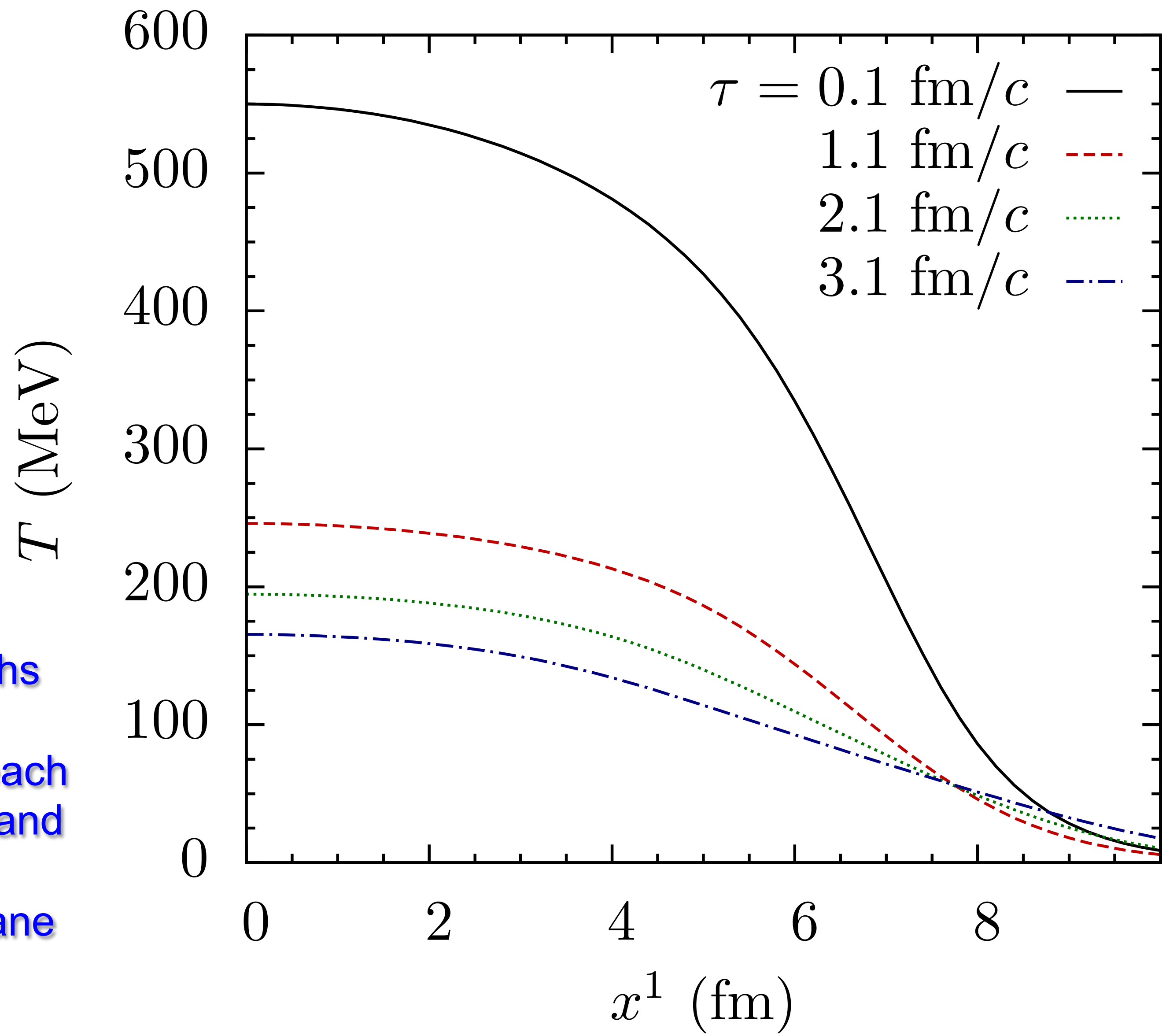
($g_d = 16$)

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 α_s.
(Larger cross sections at higher temperatures due to running coupling counteract.)

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

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 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

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

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

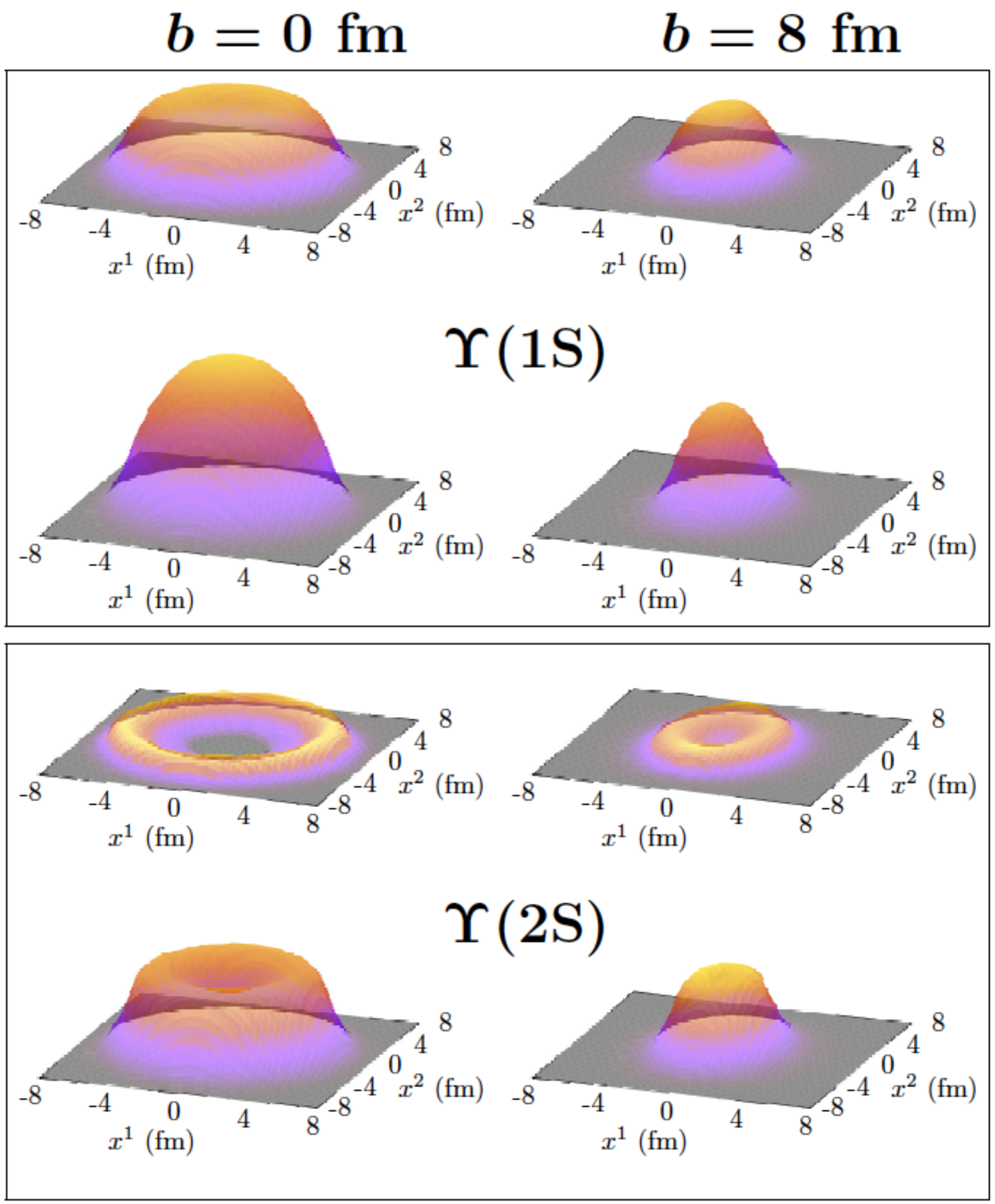
The number of produced $b\bar{b}$-pairs is proportional to the number of binary collision, and the nuclear overlap

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

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

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

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).

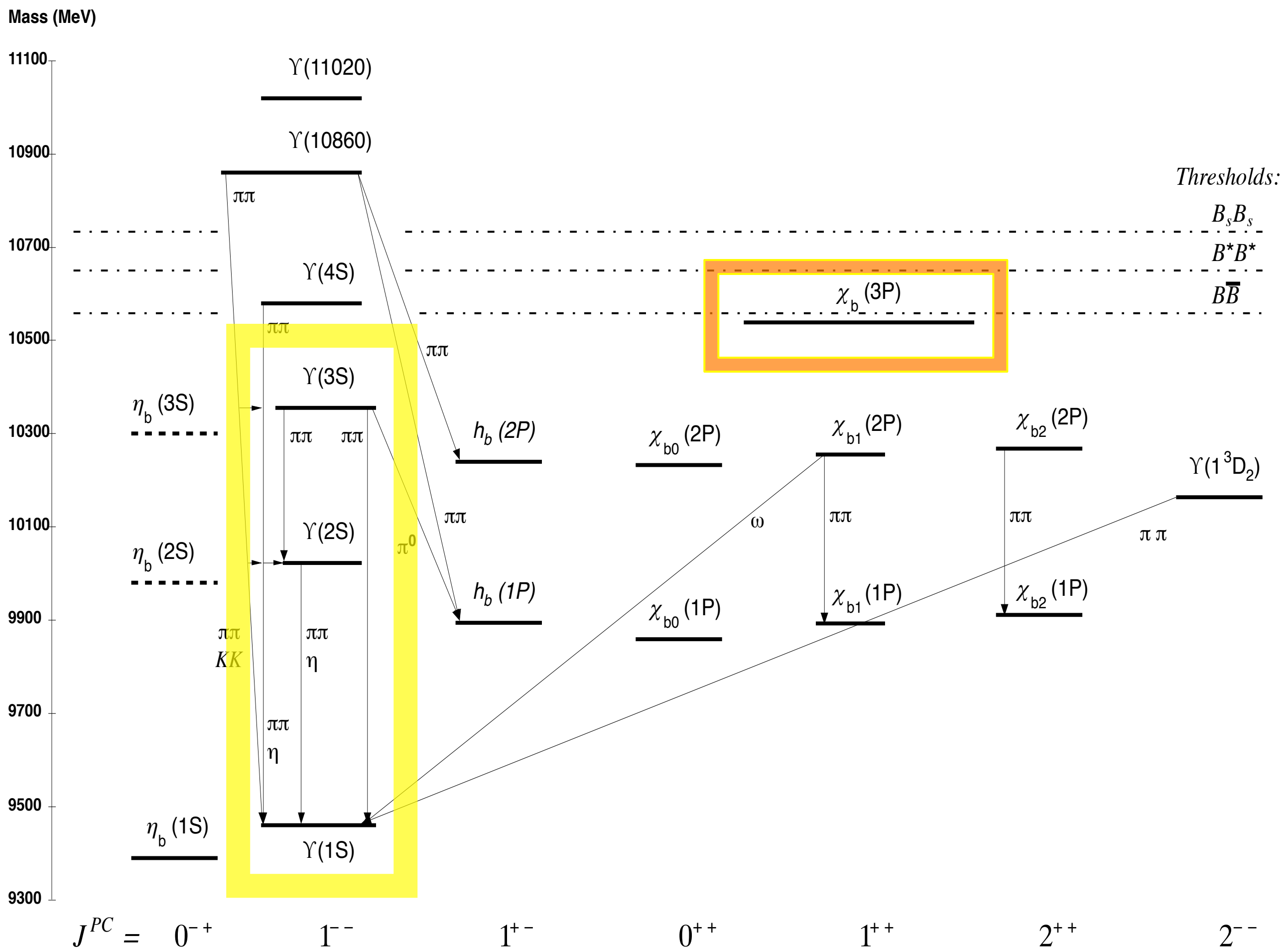
Feed-down is reduced if excited states are screened or depopulated

N_{initial}

3S: 0.324

2S: 0.367

1S: 0.373



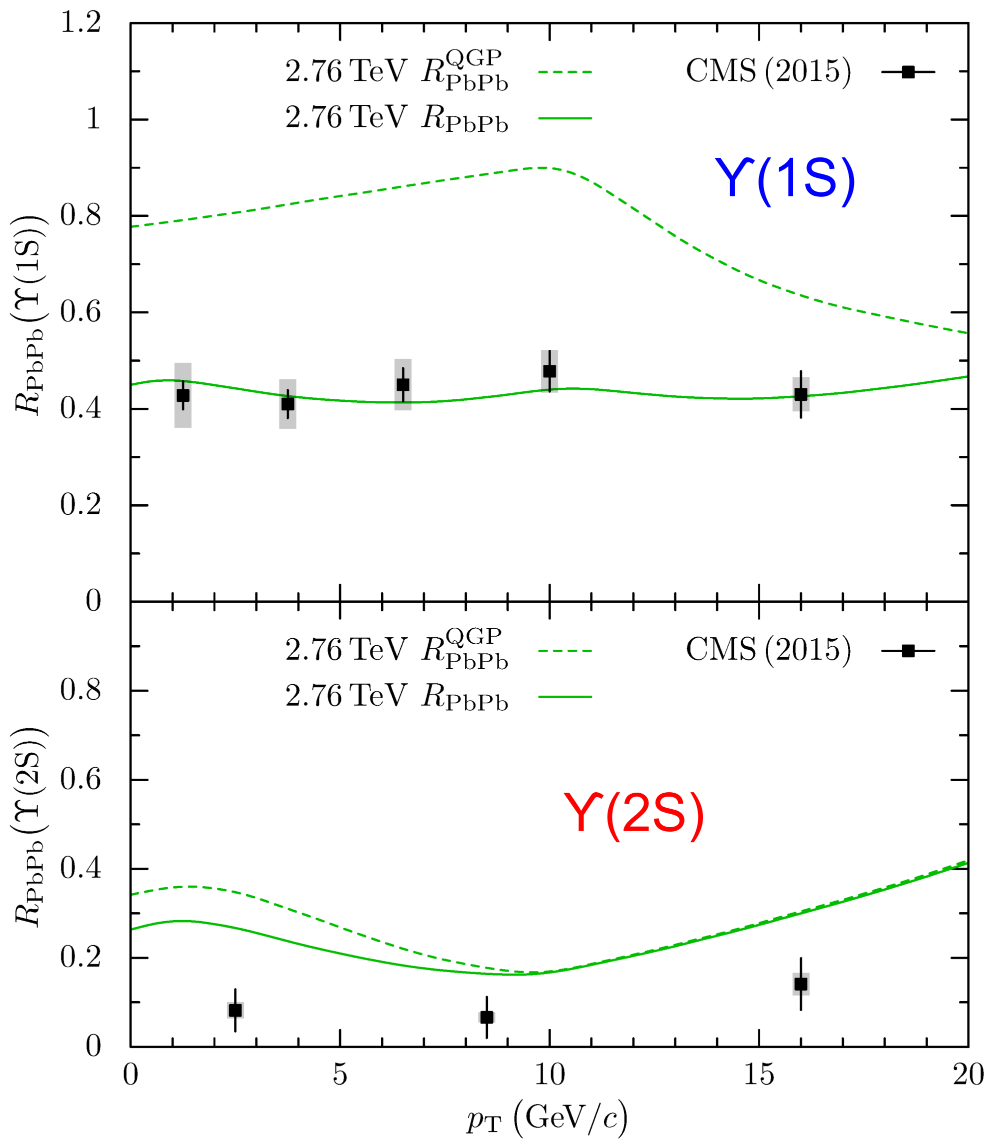
N_{initial}

2P: 0.881

1P: 1.084

4.1 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

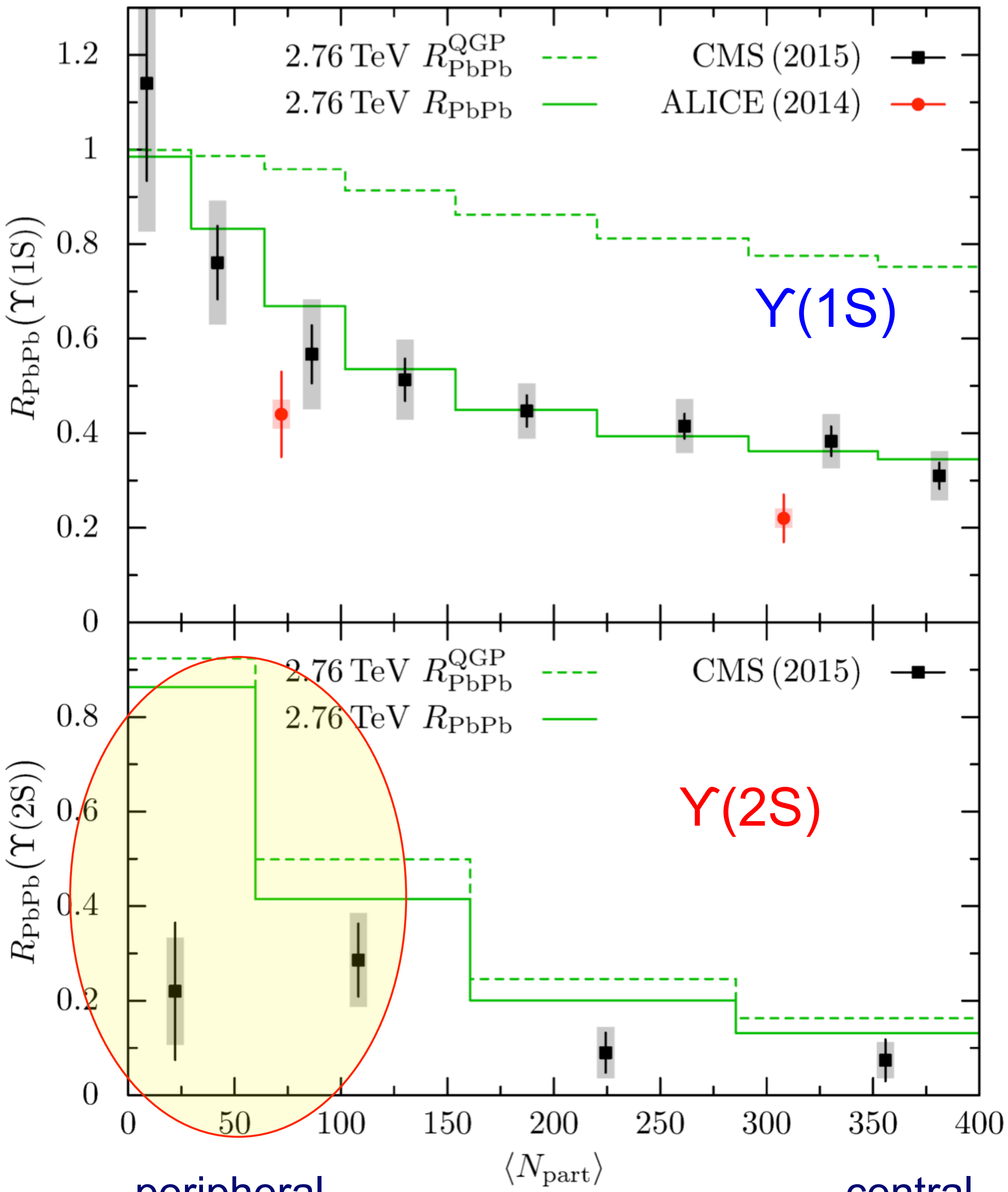
← Including reduced feed-down

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

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



peripheral central

2.76 TeV PbPb LHC

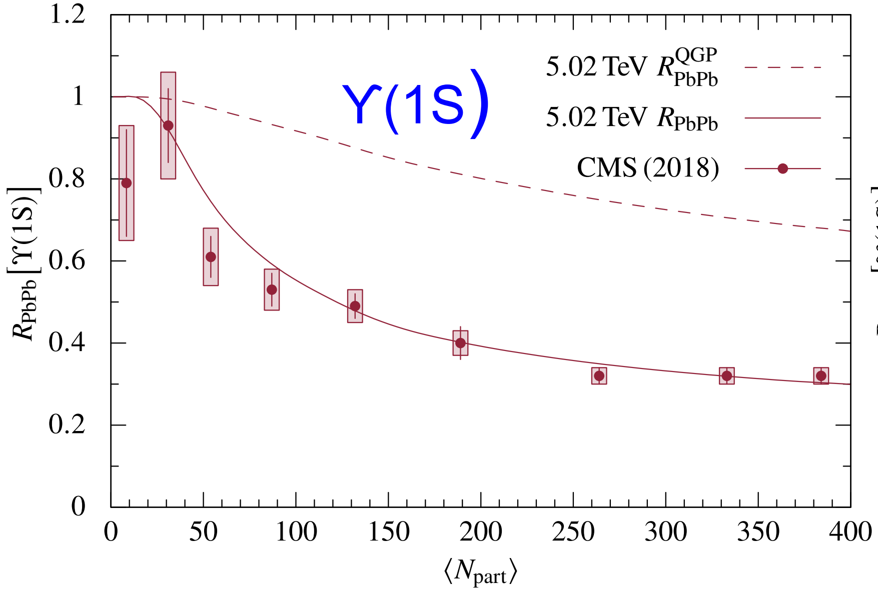
t_F= 0.4 fm/c: Υ formation time

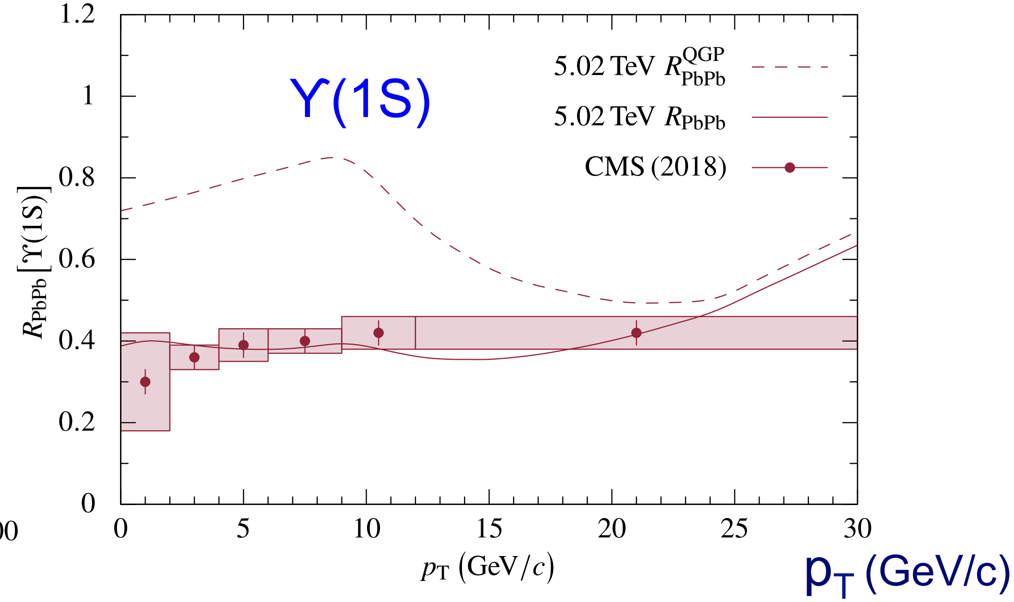
T_0= 480 MeV: central temp. at b = 0 and t = t_F

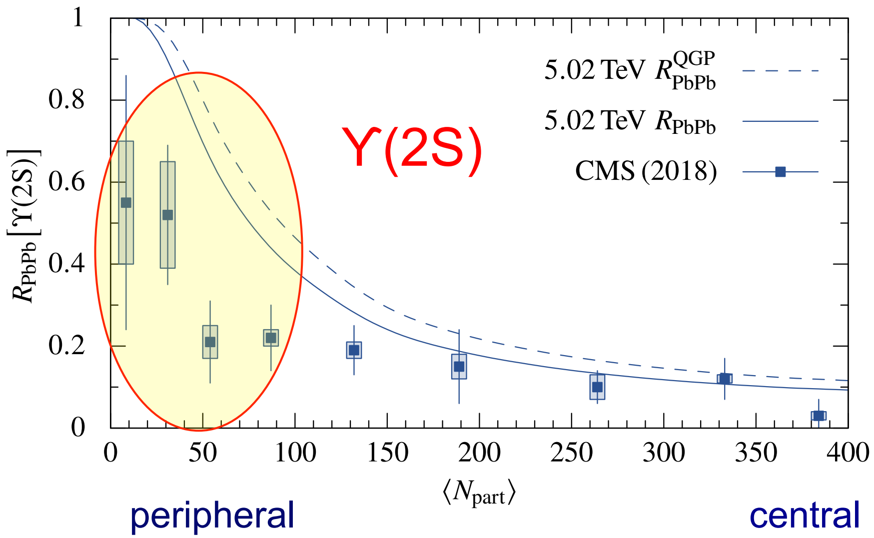
Room for additional suppression mechanisms for the excited states: Hadronic dissociation, mostly by pions, is one possibility. Thermal pions are in-sufficient; direct pions may contribute, and magnetic dissociation.

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

4.2 Prediction for Υ suppression in 5.02 TeV PbPb vs. CMS data







Predictions (dashed/ solid curves) as calculated in

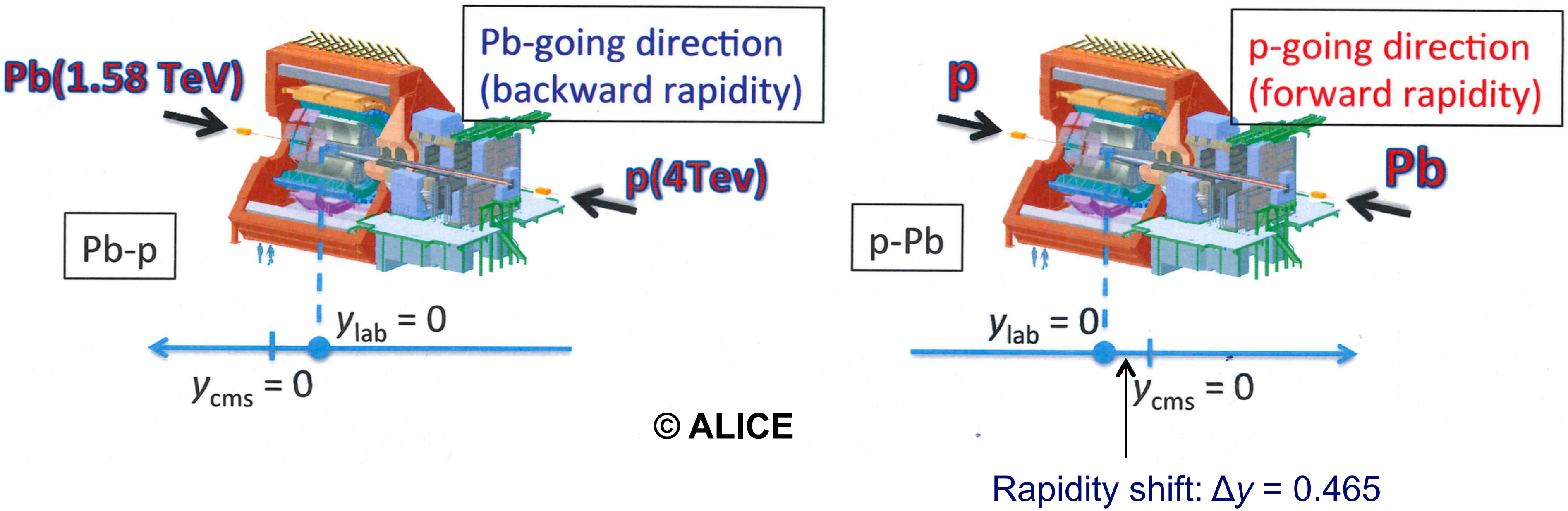
J. Hoelck, F. Nendzig and GW,
Phys. Rev. C 95, 024905 (2017)

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

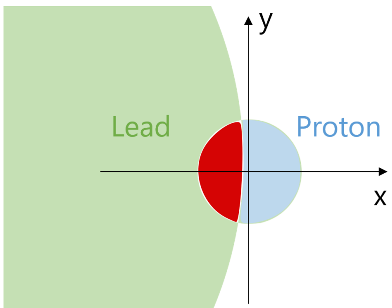
4.3. Υ in Pb-Pb @ LHC energies

- The spectroscopy of Υ 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 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 PbPb agrees with CMS data.
- The enhanced suppression of Υ(2S, 3S) leaves room for additional suppression mechanisms.

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



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



CNM and QGP effects in asymmetric collisions

- Bottomonia yields are influenced 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, and
- Mixed initial- and final-state effects, such as coherent parton energy loss induced by the nuclear medium.

We consider both effects, together with the additional ϒ suppression in the hot quark-gluon plasma – as in Pb-Pb.

V.H. Dinh, J. Hoelck and GW,
Phys. Rev. C, in press (2019)

Modification of bottomonium yields in p-Pb vs. pp

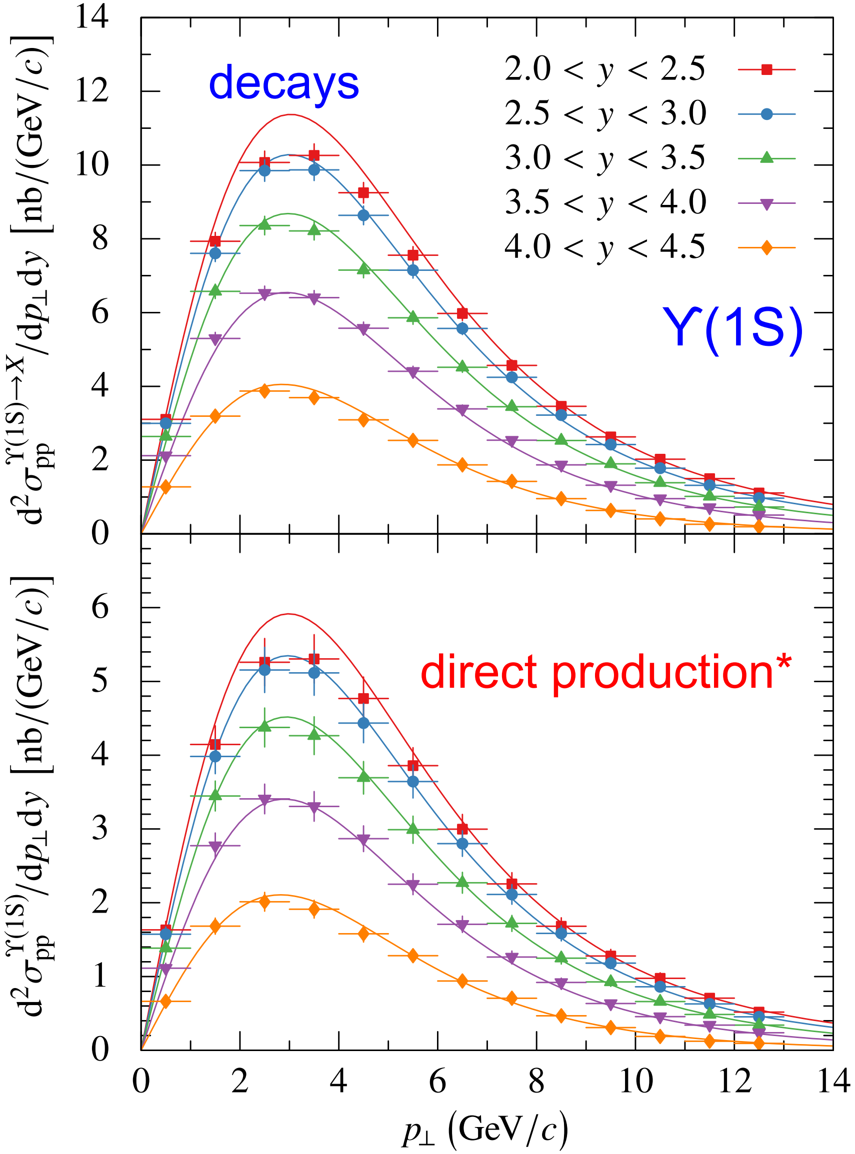
Modification factors R_{pPb} depend on rapidity *y*, transverse momentum p_T, and centrality / impact parameter *b*

$$R_{\mathrm{pPb}}(b, p_\perp, y) = \frac{1}{\langle N_{\mathrm{coll}}\rangle(b)} \frac{\frac{\mathrm{d}^2\sigma^{\Upsilon\to X}_{\mathrm{pPb}}}{\mathrm{d}p_\perp\,\mathrm{d}y}(b, p_\perp, y)}{\frac{\mathrm{d}^2\sigma^{\Upsilon\to X}_{\mathrm{pp}}}{\mathrm{d}p_\perp\,\mathrm{d}y}(p_\perp, y)}$$

with $\mathrm{d}^2\sigma^{\Upsilon\to X}/(\mathrm{d}p_\perp\mathrm{d}y)$ the Lorentz-invariant double-differential cross section for ϒ decays, calculated via the decay cascade from the corresponding production after applying CNM and QGP modifications.

The ϒ production cross section in pp is derived from the measured decay cross section in pp, applying an inverse feed-down cascade for every *y*- and p_T bin. The ϒ production cross section in pPb is scaled with the number of binary collisions from a Glauber calculation.

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



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

Fits:

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

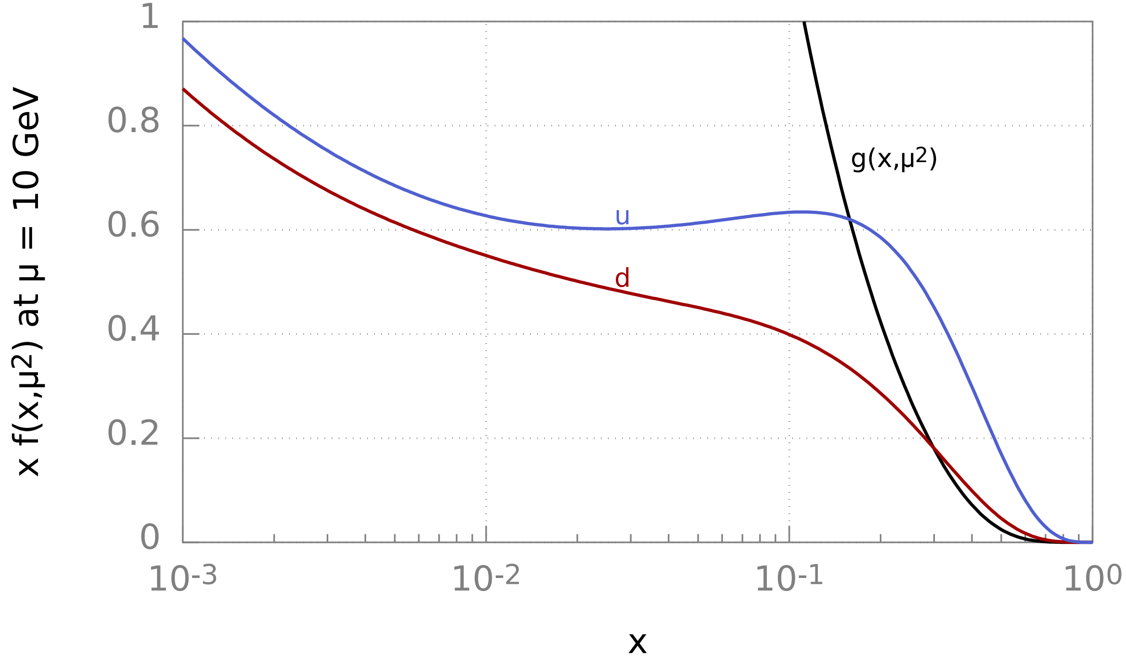
(4 parameters acc. to Arleo et al., JHEP 2013, 155 (2013))

* from inverse feed-down cascade

V.H. Dinh, J. Hoelck and GW,
Phys. Rev. C, in press (2019)

CNM effects: Parton distribution functions (pdfs)

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



CT14NLO pdf set for u,d,g

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

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

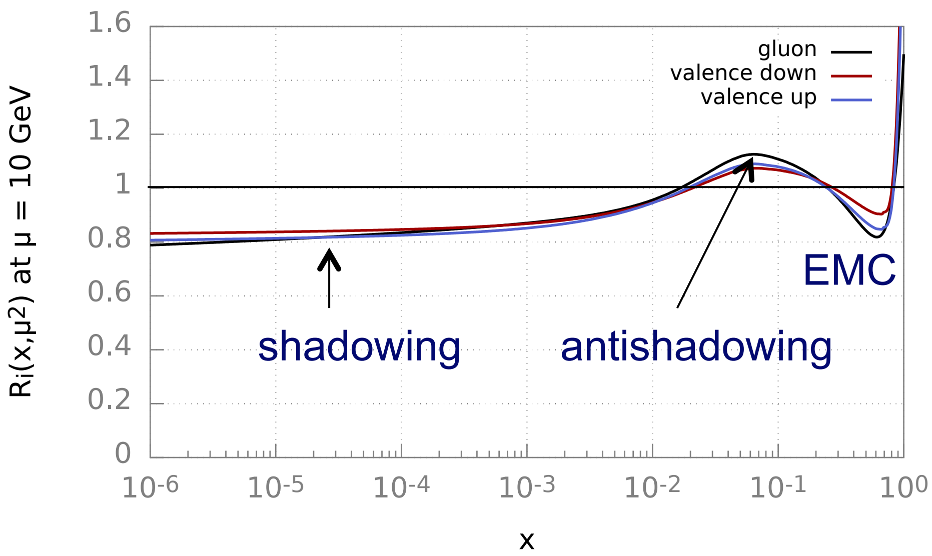
with λ = 0.2 - 0.3

- 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

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

$$x_2^{\rm shift} = x_2(p_\perp^{\rm shift}, y^{\rm shift})$$

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

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

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

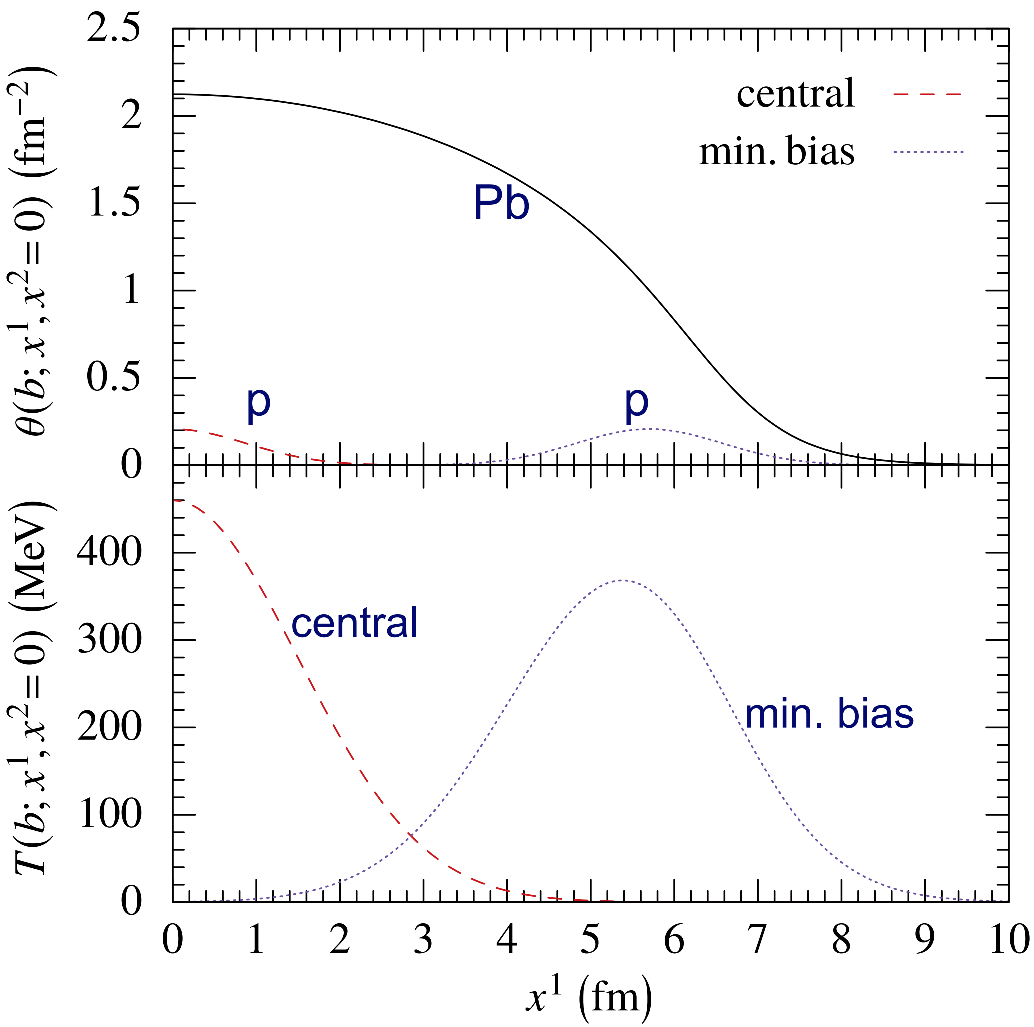
$$y^{\rm shift} = {\rm arcosh}\left[\frac{E(p_\perp, y)+\varepsilon}{M_\perp(p_\perp^{\rm shift})}\right] - y_{\rm beam}\,,$$

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

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

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.

QGP effects: Thickness functions and temperature profiles in relativistic pPb collisions



top: thickness functions

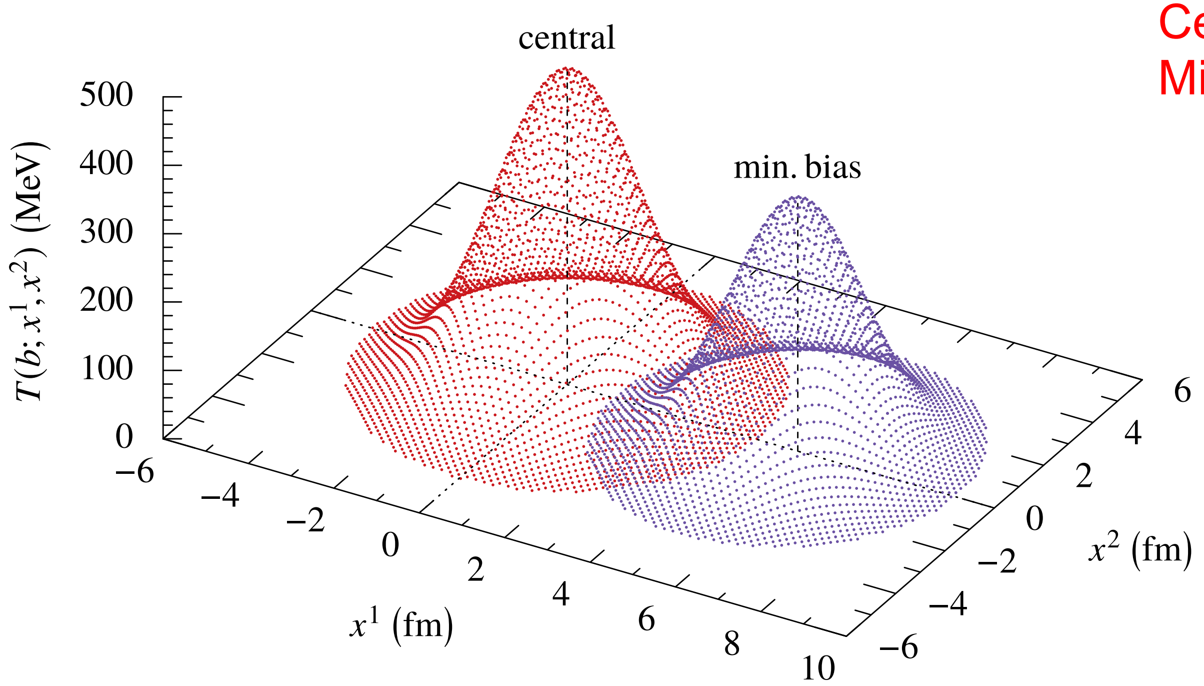
$\theta_{\mathrm{Pb}}(x^1, x^2=0)$ for Pb (solid curve),

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

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

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

Initial temperature profiles in 8.16 TeV pPb collisions



Transverse plane (x^1, x^2)

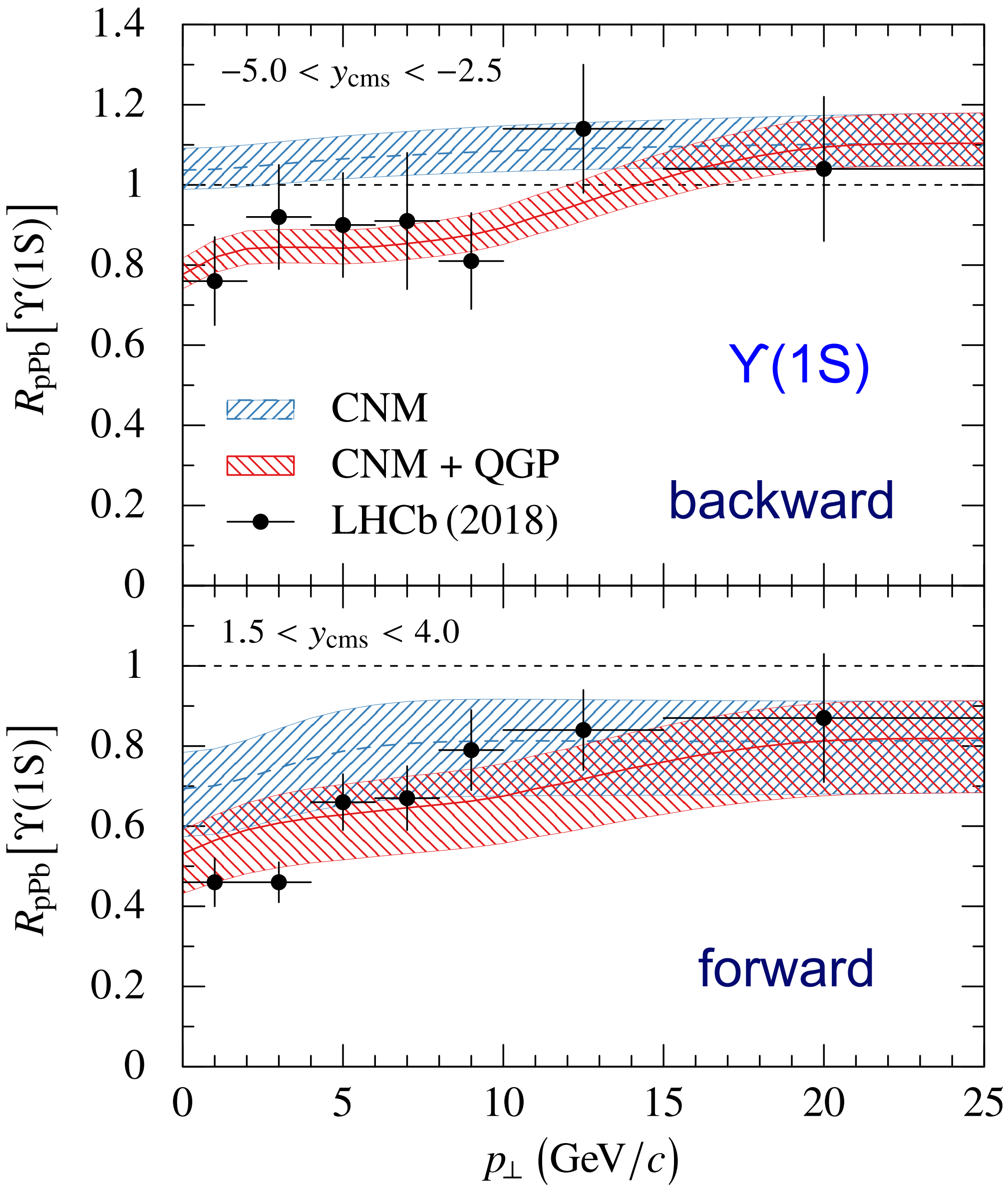
Central collisions: $\langle N_{coll} \rangle \approx 15.6$
Min. bias: $\langle N_{coll} \rangle \approx 7$

T_0 = 460 MeV

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

6. Comparison with LHC data:

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



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

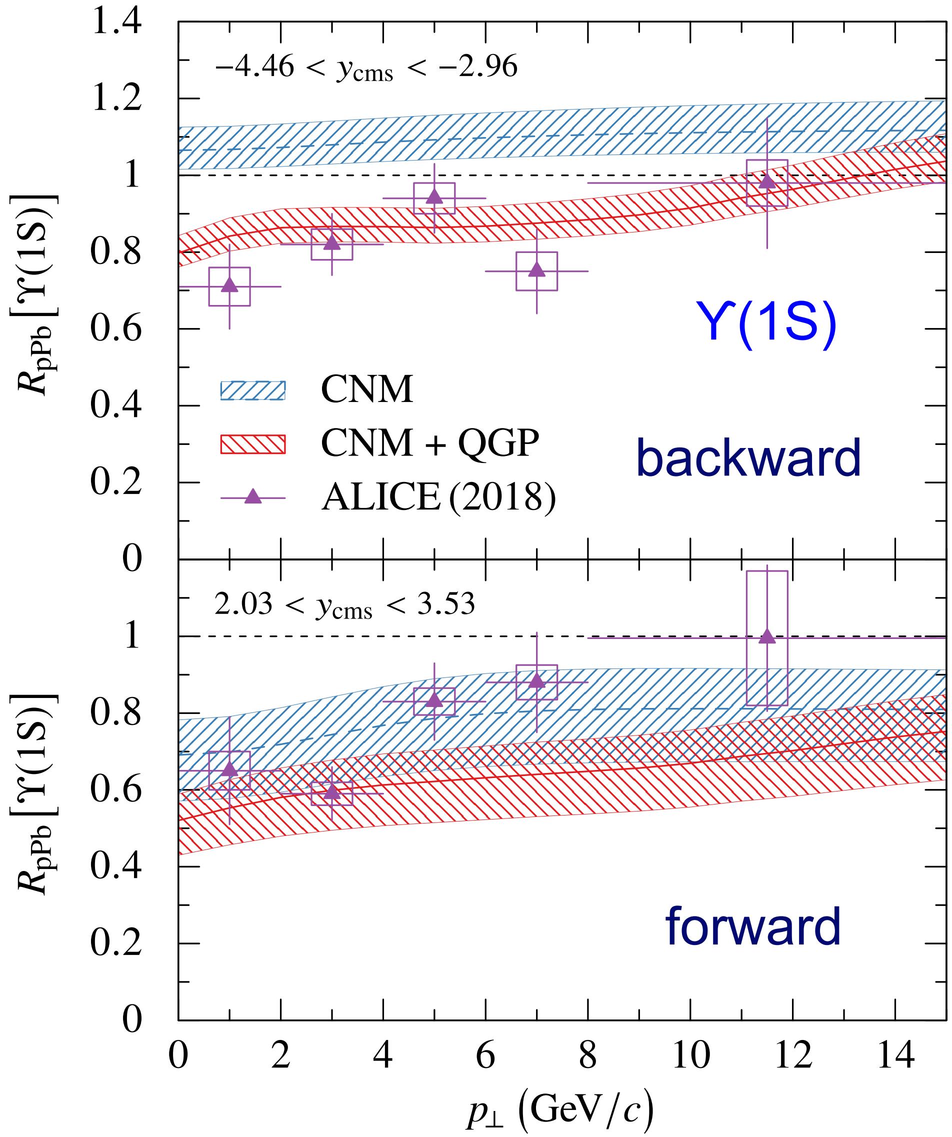
Energy-loss effects pronounced at
$p_T \leq 8$ GeV/c

Red: With hot-medium suppression
(T_0= 460 MeV; t_F= 0.4 fm/c)

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

V.H. Dinh, J. Hoelck and GW,
Phys. Rev. C, in press (2019)

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



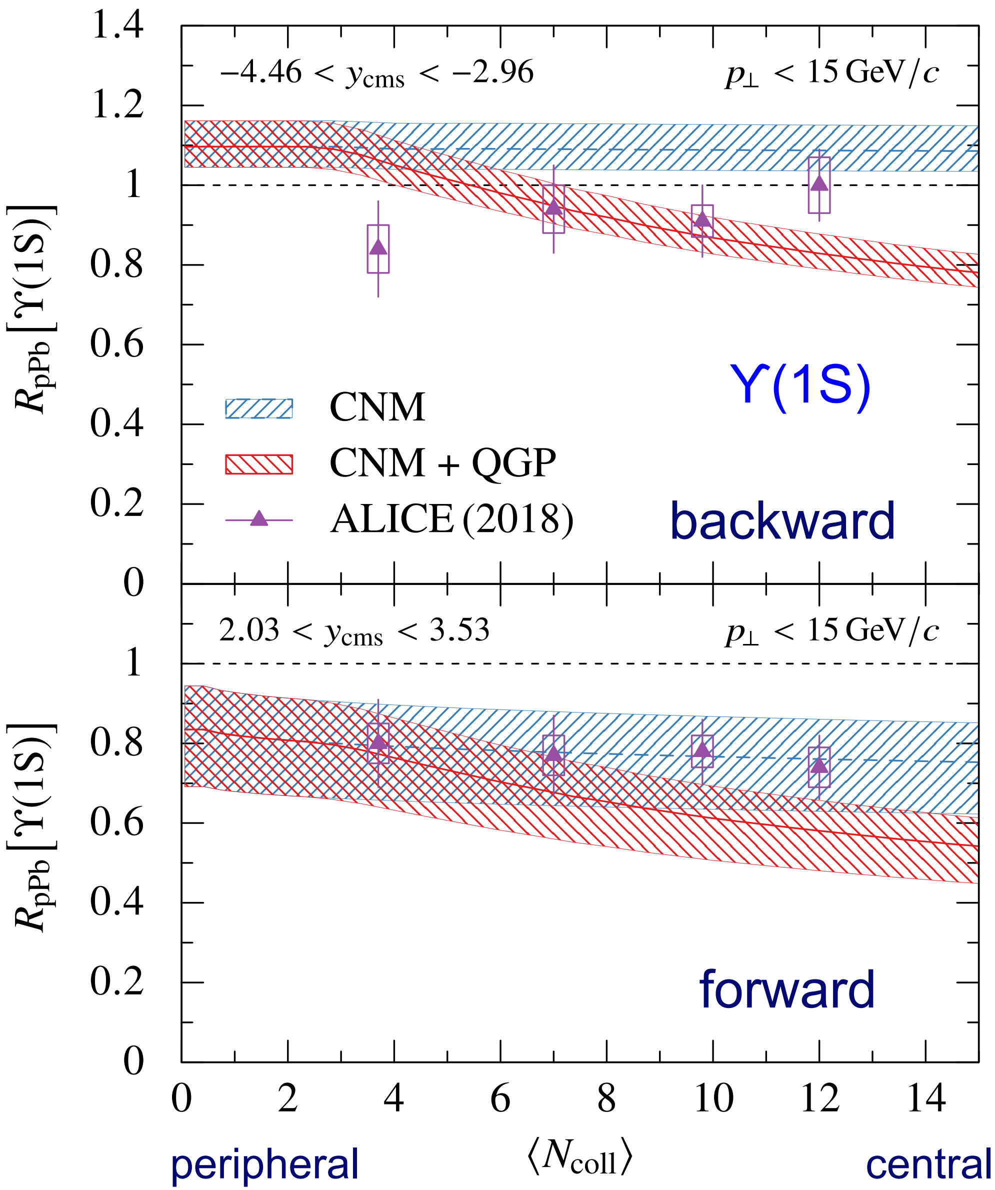
Blue: CNM effects only

Red: With hot-medium suppression

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

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

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



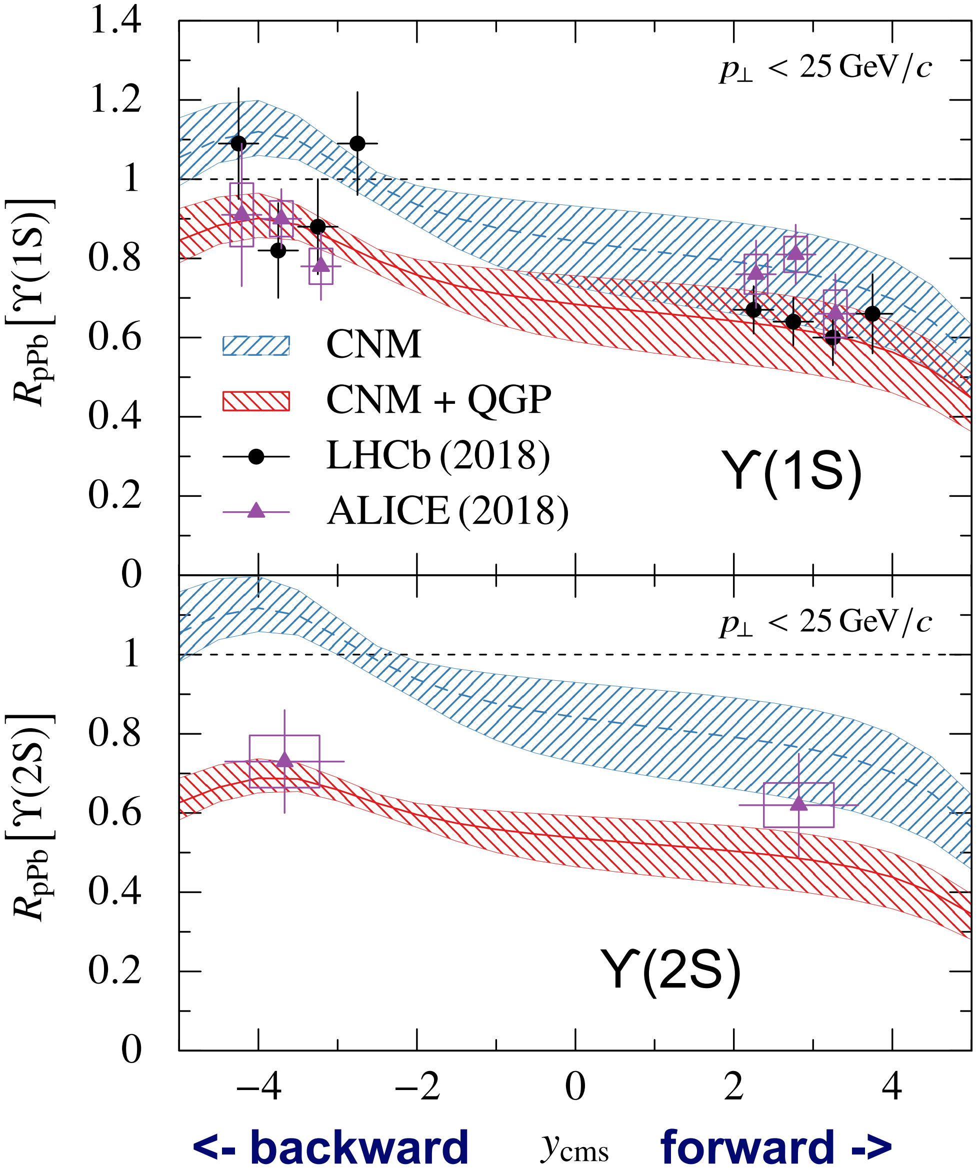
Blue: CNM effects only

Red: With hot-medium suppression

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

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

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

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

data: LHCb: JHEP 2018, 194 (2018)

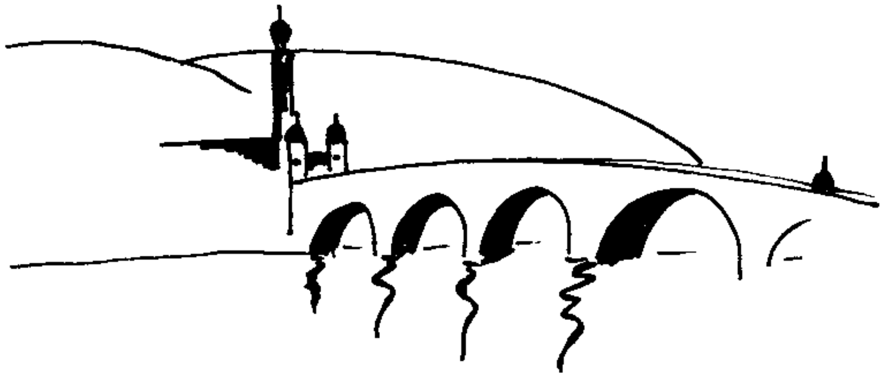
(T_0= 460 MeV; t_F= 0.4 fm/c)

V.H. Dinh, J. Hoelck and GW,
Phys. Rev. C, in press (2019);
arXiv:1903.12594v2

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.
- The theoretical model with CNM and QGP effects is found to be in agreement with the LHCb and ALICE results for Υ(1S) in p_T and rapidity dependence; discrepancies remain for the centrality dependence.
- The hot-medium (QGP) effects play a decisive role in the measured Υ suppression in p-Pb, which cannot be understood with CNM effects alone.
- 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 !



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Extra slides: Glauber calculation, number of binary collisions

TABLE II. Results of our Glauber calculation for the expected numbers of binary collisions $\langle N_{\mathrm{coll}} \rangle$ and participants $\langle N_{\mathrm{part}} \rangle$, the differential and integrated inelastic pPb cross sections $\mathrm{d}\sigma^{\mathrm{inel}}_{\mathrm{pPb}}/\mathrm{d}b$ and $\sigma^{\mathrm{inel}}_{\mathrm{pPb}}$, and the corresponding centrality c in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ for different impact parameters b.

b (fm)	$\langle N_{\mathrm{coll}} \rangle$	$\langle N_{\mathrm{part}} \rangle$	$\mathrm{d}\sigma^{\mathrm{inel}}_{\mathrm{pPb}}/\mathrm{d}b$ (fm)	$\sigma^{\mathrm{inel}}_{\mathrm{pPb}}$ (fm^2)	c (%)
0	15.6	16.6	0	0	0
1	15.4	16.4	6.3	3	1.6
2	4.8	15.8	12.6	13	6.0
3	3.7	14.7	18.8	29	13.3
4	2.0	12.9	25.1	52	23.5
5	9.3	10.3	31.4	80	36.6
6	6.0	6.9	37.6	115	52.4
7	2.8	3.6	41.4	155	70.8
8	0.9	1.4	30.6	192	87.7
9	0.2	0.4	11.4	212	96.7
10	0.0	0.1	2.7	218	99.3
11	0.0	0.0	0.5	219	99.9

Bottomonium cross sections in pp and p-Pb

$$\sigma_{\mathrm{pp}} = \sum_{ij} \int \mathrm{d}x_1 \mathrm{d}x_2 \; f_i^{\mathrm{p}}(x_1, \mu_{\mathrm{F}}^2) f_j^{\mathrm{p}}(x_2, \mu_{\mathrm{F}}^2) \sigma_{ij}(p_1, p_2, \mu_{\mathrm{R}}^2, \mu_{\mathrm{F}}^2),$$

$$\sigma_{\mathrm{pPb}} = \sum_{ij} \int \mathrm{d}x_1 \mathrm{d}x_2 \; f_i^{\mathrm{p}}(x_1, \mu_{\mathrm{F}}^2) f_j^{\mathrm{Pb}}(x_2, \mu_{\mathrm{F}}^2) \sigma_{ij}(p_1, p_2, \mu_{\mathrm{R}}^2, \mu_{\mathrm{F}}^2).$$

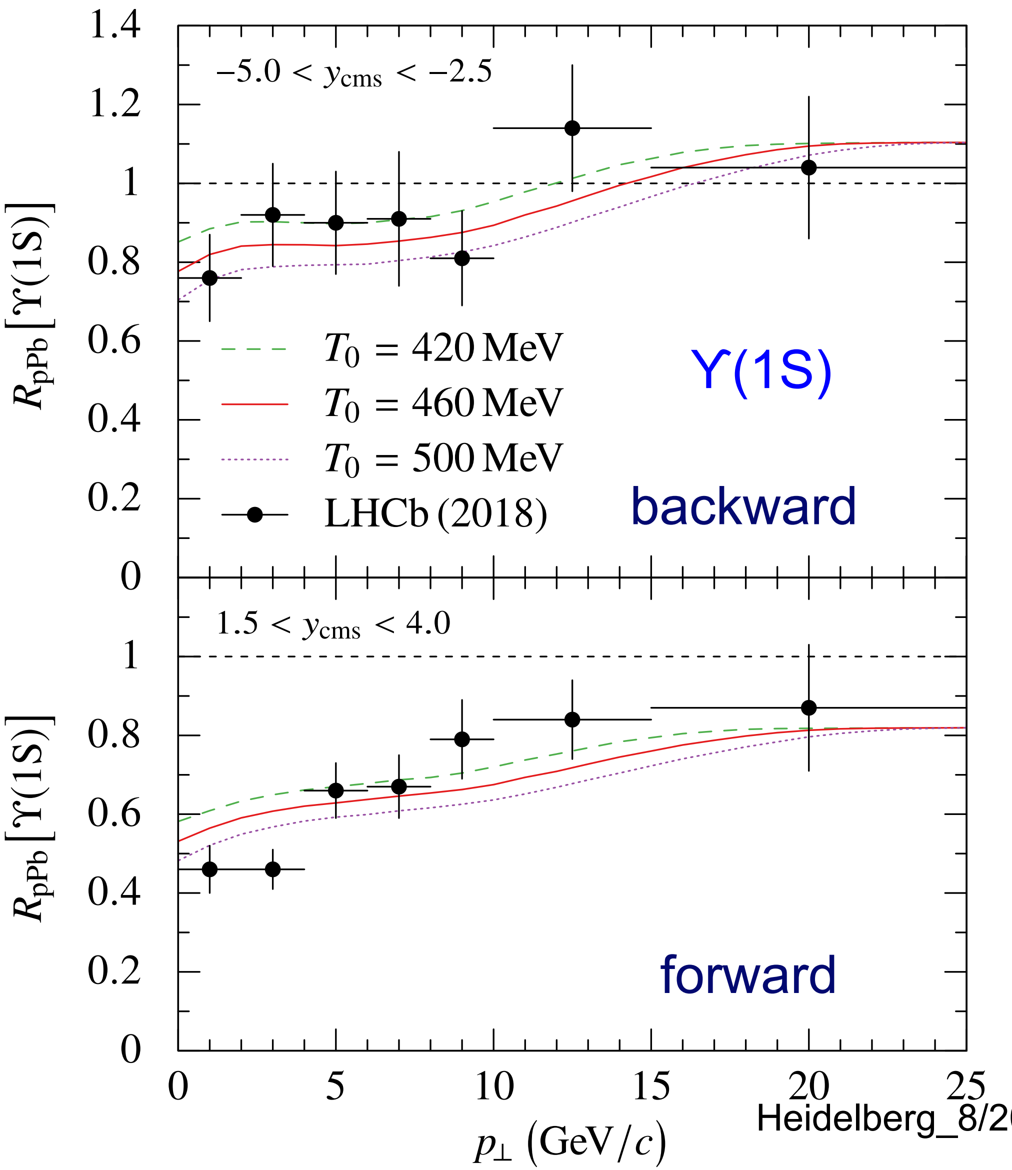
Nuclear modification in Pb parametrized by a shadowing factor

$$R_i^{\mathrm{Pb}}(x, \mu_{\mathrm{F}}^2) = \frac{f_i^{\mathrm{Pb}}(x, \mu_{\mathrm{F}}^2)}{f_i^{\mathrm{p}}(x, \mu_{\mathrm{F}}^2)} \qquad \mu_R \simeq \mu_F \simeq p_\perp$$

For ϒ production arising from gluon fusion, the diff. cross section in p-Pb becomes

$$\frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}\sigma_{\mathrm{pPb}}}{\mathrm{d}y \mathrm{d}p_\perp}(y, p_\perp) = R_g^{\mathrm{Pb}}(x_2, \mu_{\mathrm{F}}^2) \frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}y \mathrm{d}p_\perp}(y, p_\perp)$$

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



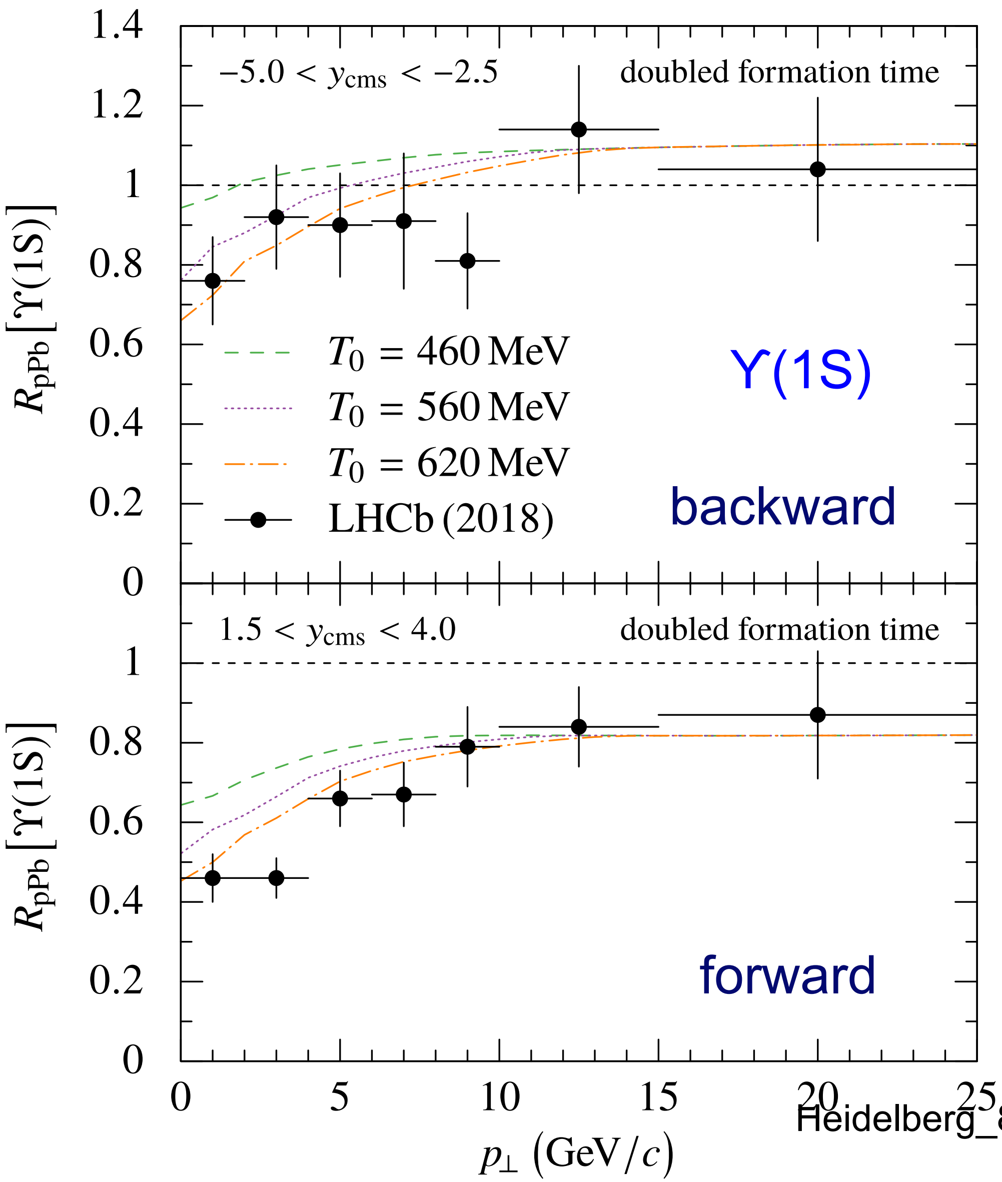
T_0 = 420, 460, 500 MeV

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

(t_F= 0.4 fm/c)

Heidelberg_8/2019

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)**

① ,② Screening and damping in a nonrelativistic potential model

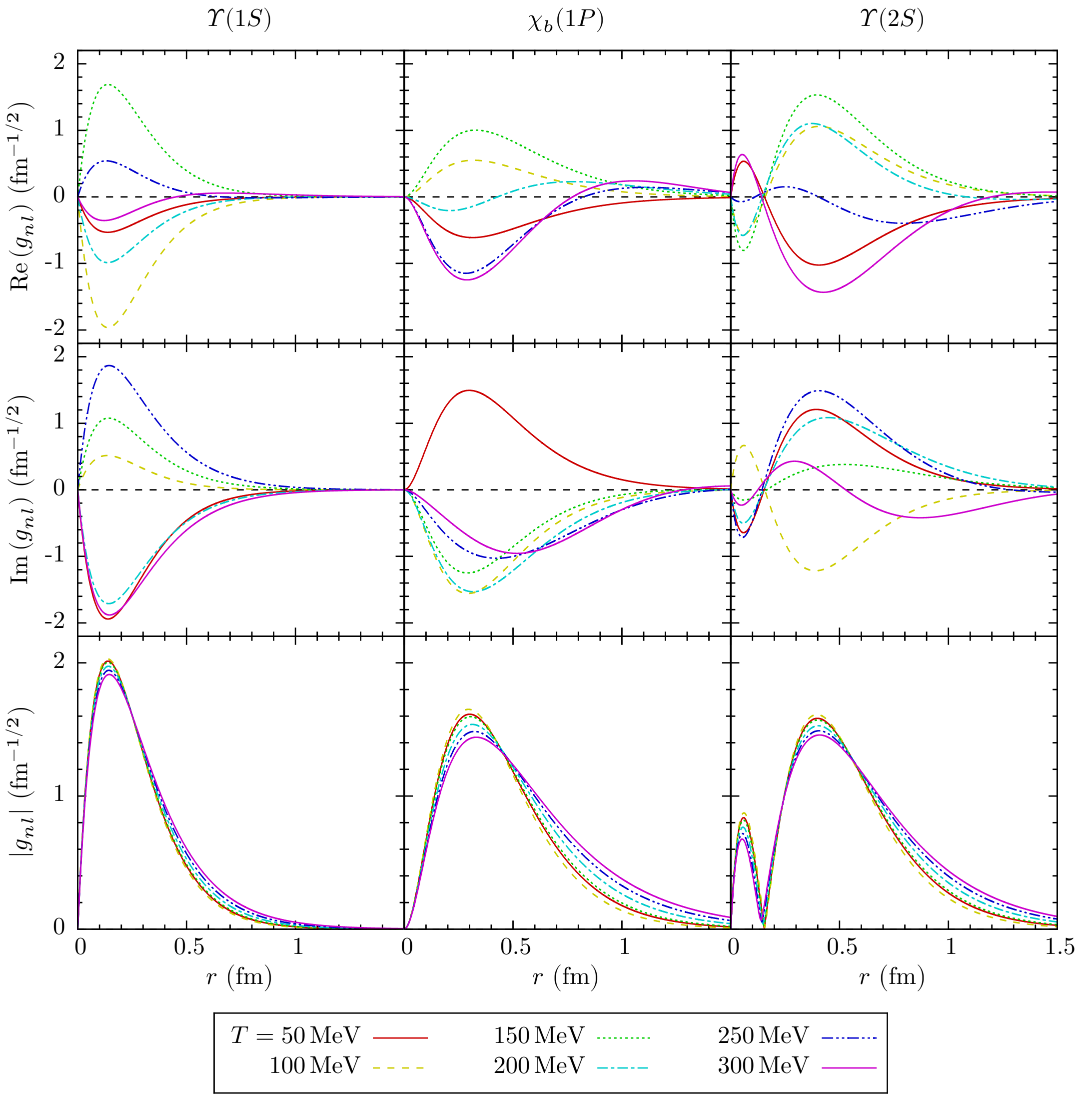
$$V_{nl}(r,T) = -\frac{\sigma}{m_D(T)}e^{-m_D(T)r} - C_F\alpha_{nl}(T)\left(\frac{e^{-m_D(T)r}}{r} + iT\phi(m_D(T)r)\right)$$

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

Screened potential: m_D = Debye mass,
α_{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 functions of ϒ(nS), X_b(nP) states

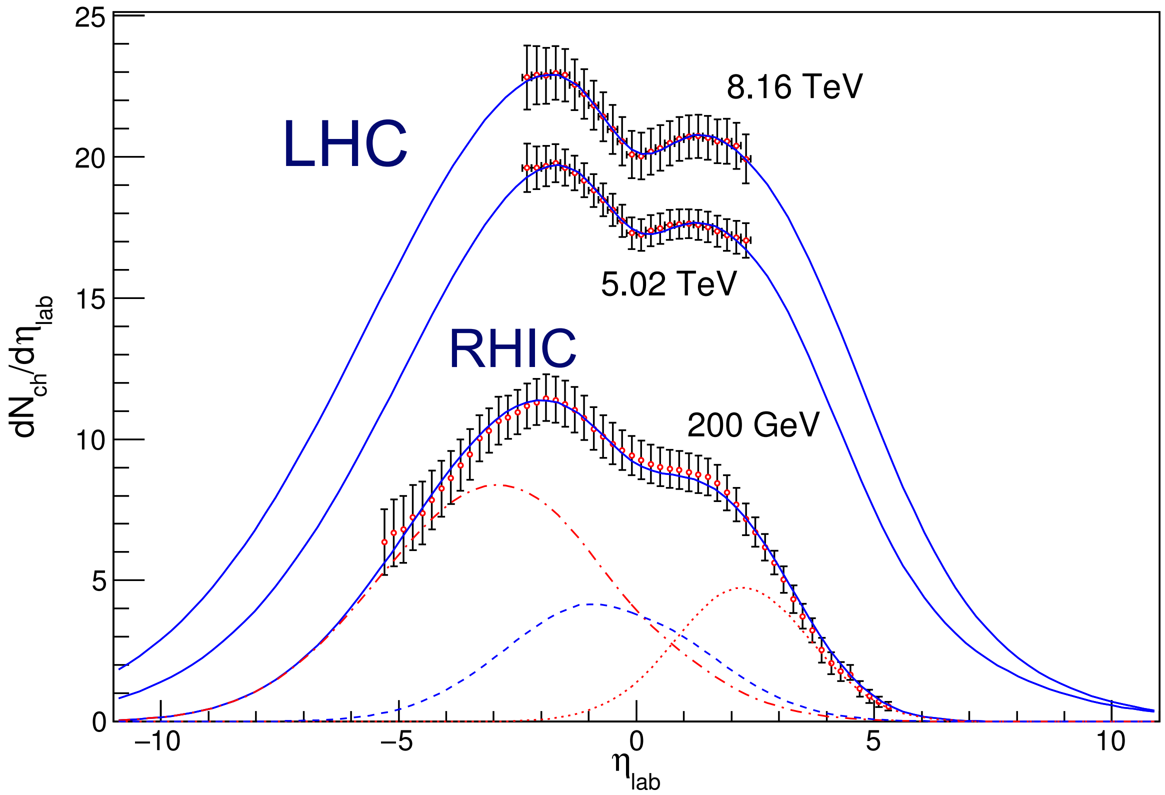


Calculate the damping widths $\Gamma_{damp}(T)$ for all six states

ϒ(nS), χ_b (nP), n = 1, 2, 3

Produced charged hadrons in central collisions: 3 sources for particle production

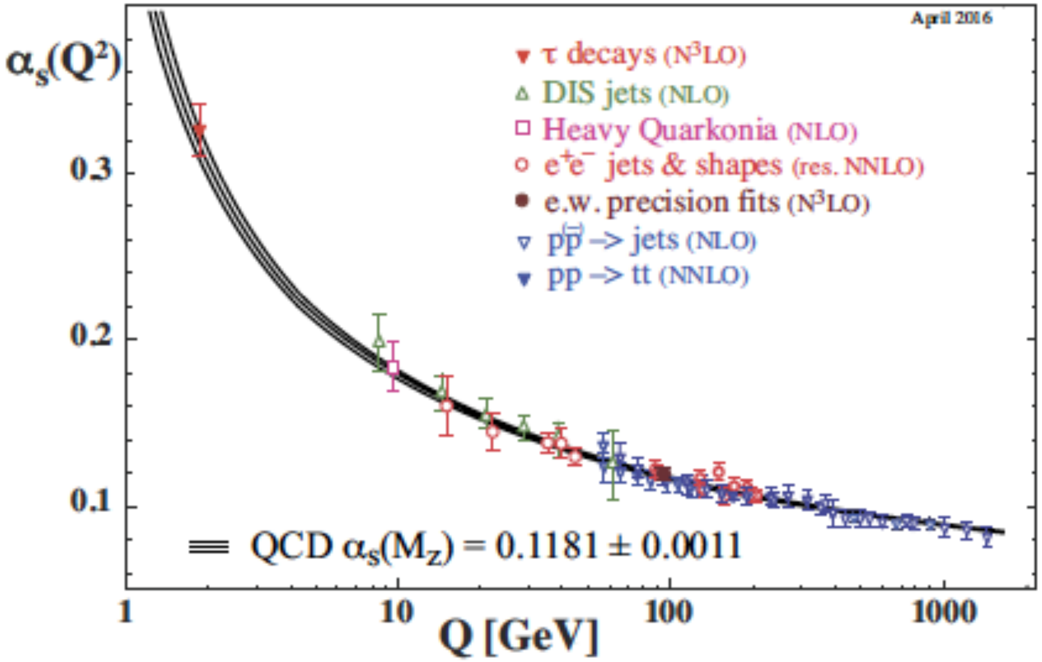
CMS data from min. bias **5.02/ 8.16 TeV p-Pb**,
PHOBOS data from **200 GeV d-Au**



P. Schulz and GW, MPLA 33, 1850098 (2018); data from PHOBOS&CMS

$$\eta = -\ln\left[\tan(\theta/2)\right]$$

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

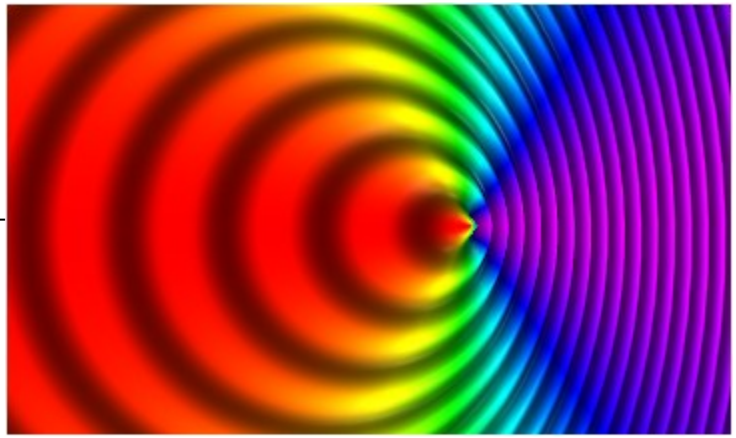
For a finite relative velocity between the expanding QGP and the bottomium states the relativistic Doppler shift results in an angle-dependent effective temperature

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

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 Y's.