Theory overview of QGP

Georg Wolschin
Heidelberg University
Institut für Theoretische Physik
Philosophenweg 12-16
D-69120 Heidelberg

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Topics

1. QGP survey: Fluctuations, jet quenching, ridges, QGP photon continuum spectroscopy, charmonium suppression

2. Line spectroscopy in the QGP with quarkonia:

   Υ's in **Pb-Pb** @ LHC

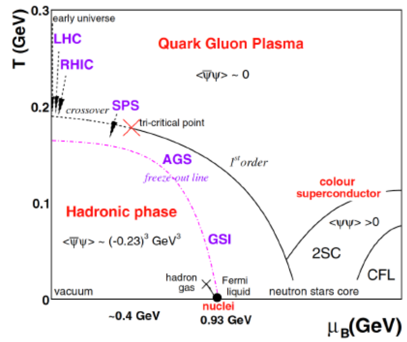
3. A model for quarkonia dissociation in the QGP

4. Cold nuclear matter (CNM) and QGP effects in 8.16 TeV **p-Pb**

5. Comparison of Υ's in p-Pb with LHCb and ALICE data

6. Conclusion

1. Quark-gluon plasma (QGP)...



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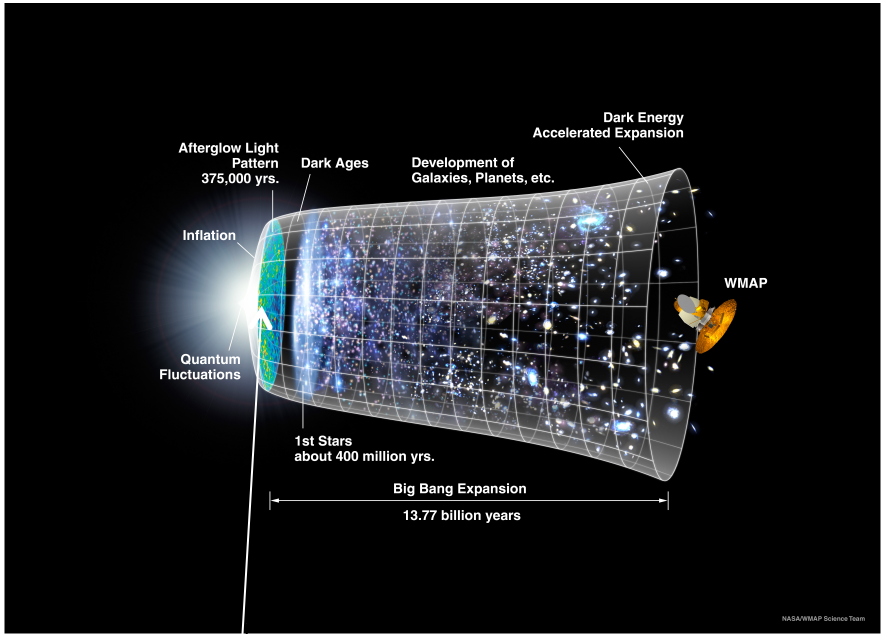
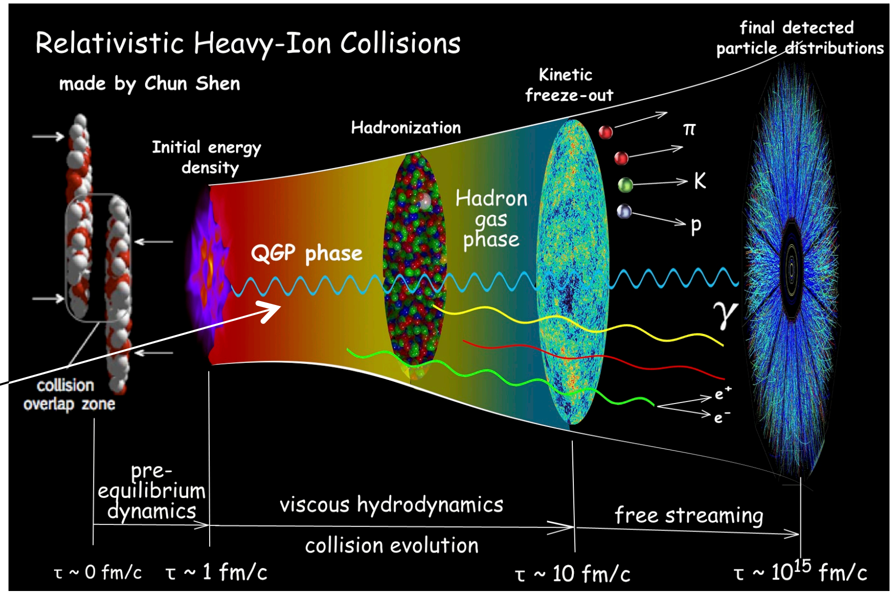
..was the state of matter in the early universe, t < 10μs



Big bang © **WMAP, NASA**

..is created in relativistic heavy-ion collisions, $t \approx 3\cdot10^{-23}$ s ≈ 9 fm/c



little bang © **C. Shen&P. Sorensen**

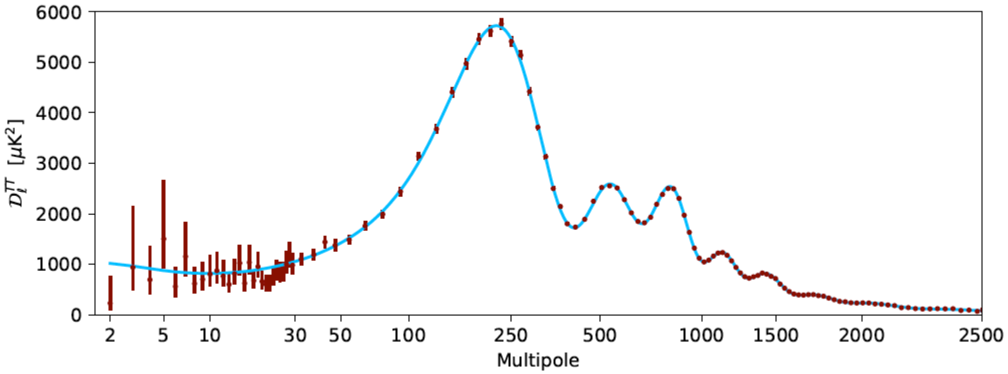
QGP:

hadronization occurs at an approximate energy density of $\varepsilon \approx 1$ GeV/fm^3 acc. to lattice gauge calculations

=> Study the phase transition in a non-abelian gauge theory

Analysis of the fluctuations...

..of the temperature (also, density) distribution in the early universe:
Light is released when p and e form hydrogen atoms

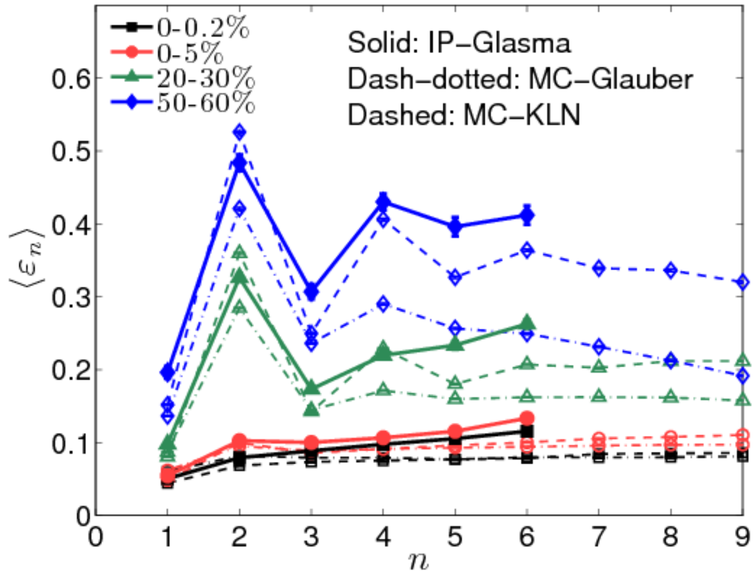


© Planck Collab./ ESA 2018

Very high multipoles due to negligible viscosity.
t ≈ $3.8 \cdot 10^5$ yrs after BB

(This provides no evidence for deconfined state of matter prior to hadronization/ recombination at t < 10 μs)

..of the primordial eccentricity power spectrum from the energy density distribution in relativistic heavy-ion collisions (2.76 ATeV Pb-Pb)

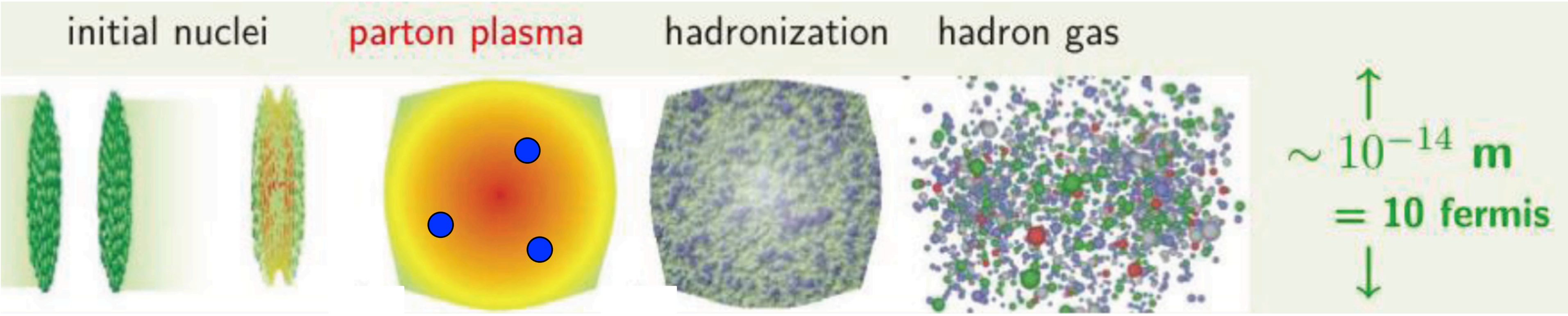


Higher multipoles damped out due to (small) η/s

© U. Heinz, R. Snellings, Annu. Rev. Nucl. Part. Sci. 63, 1056 (2013)

Quark-gluon plasma...

... created in relativistic heavy-ion collisions for a very short time span of about 10^{-23} seconds: Investigate experimental and theoretical signatures



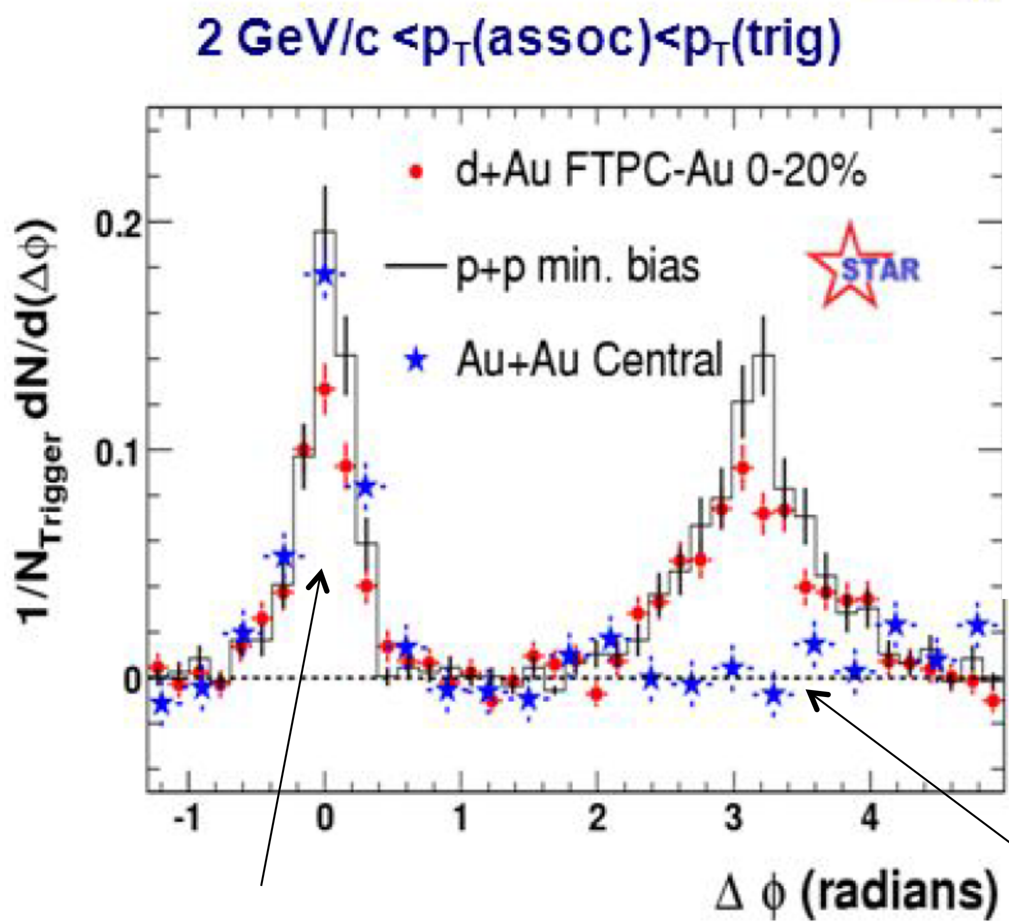
← $\sim 10^{-23}$ s = 10 yoctoseconds →

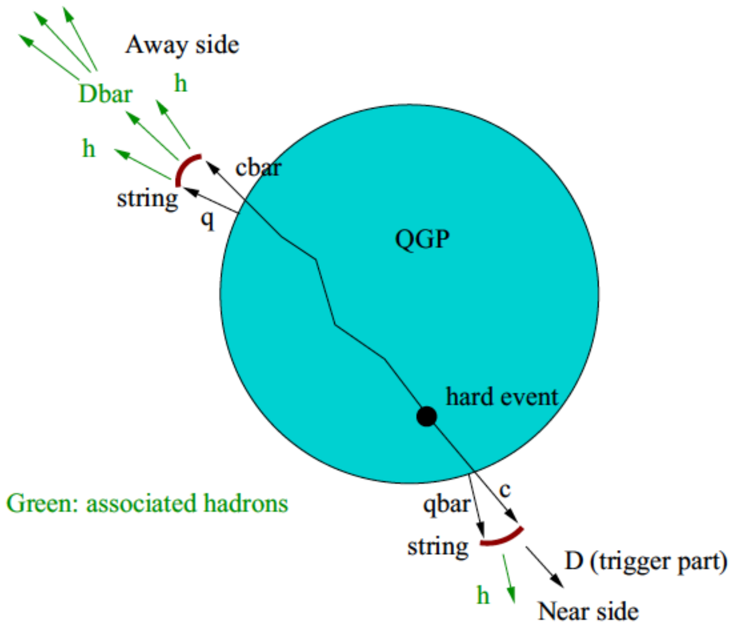
● **Heavy mesons**

Artwork © Nikhef / S. Bass

Early evidence for the QGP: Jet suppression found 2004 at RHIC in AuAu

Jets provide the most direct evidence for quarks and gluons in the system





© A. Beraudo et al., EPJC 75, 121 (2015)

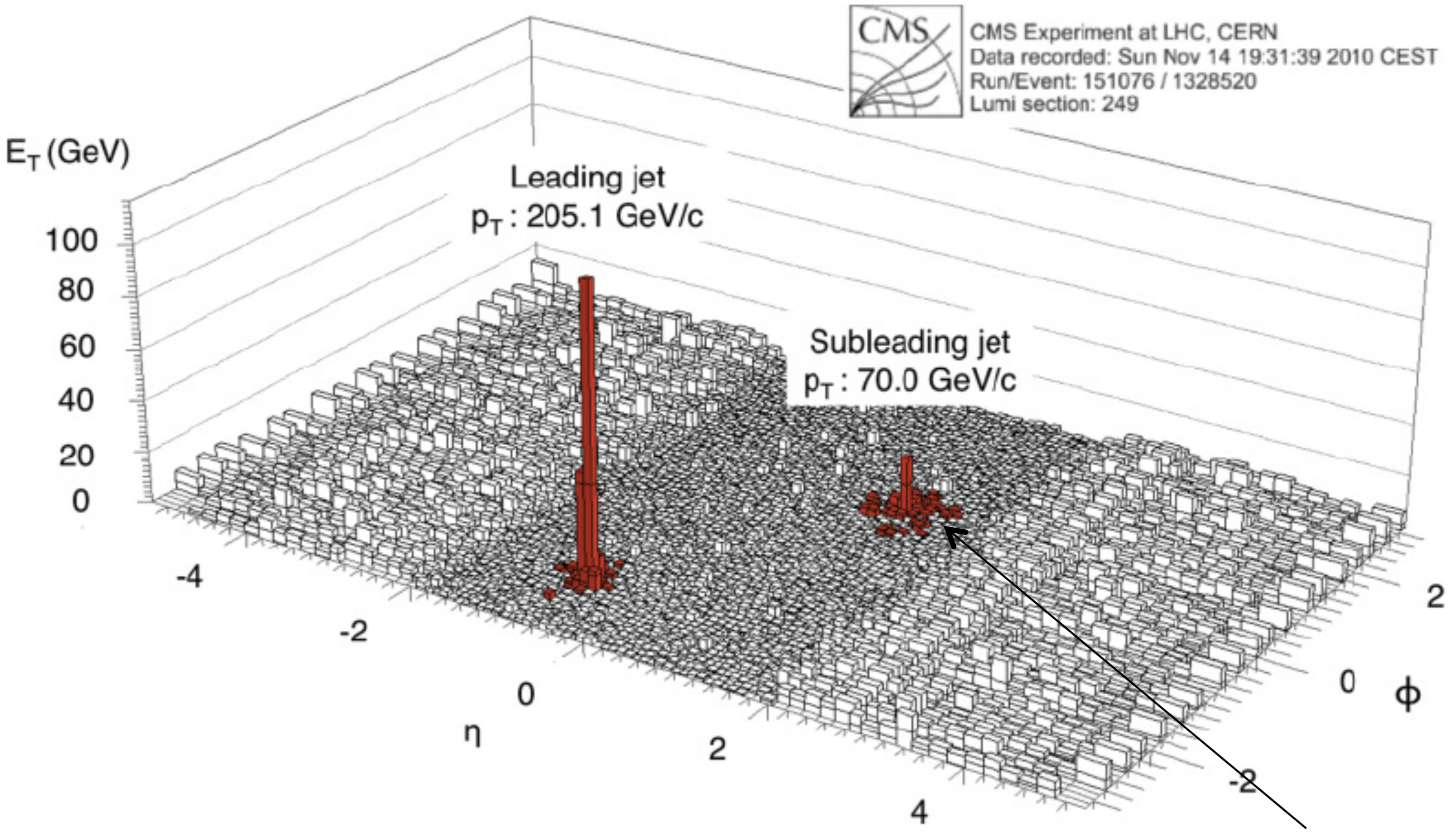
Near-side jet in two-particle correlations

Away-side jet: In AuAu suppressed in the QGP

© STAR PRL 91, 072304 (2004)

Predicted by J. D. Bjorken, FERMILAB-Pub-82/59-THY

Evidence for the QGP: Jet suppression in 2.76 TeV PbPb at the LHC (2011)



Away-side jet: In PbPb suppressed in the QGP

- The lost energy is in low-p_T particles at large angles
- Jet substructure measurements are sensitive to jet-medium interactions

© CMS Collab., PRC 84, 024906 (2011)

An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

bj 1982

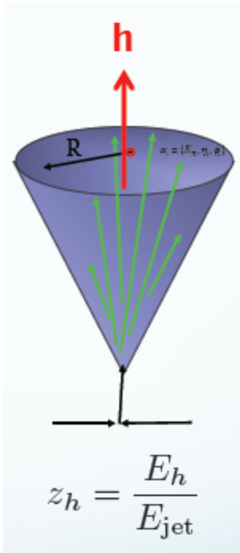
Jet quenching at RHIC and LHC is a very active field of research

- Space-time structure of jet quenching → indications about QGP properties
- Momentum broadening and LPM effect decisive for jet quenching
- The medium response to the jets accounts for the soft components
- Color decoherence of jet substructure

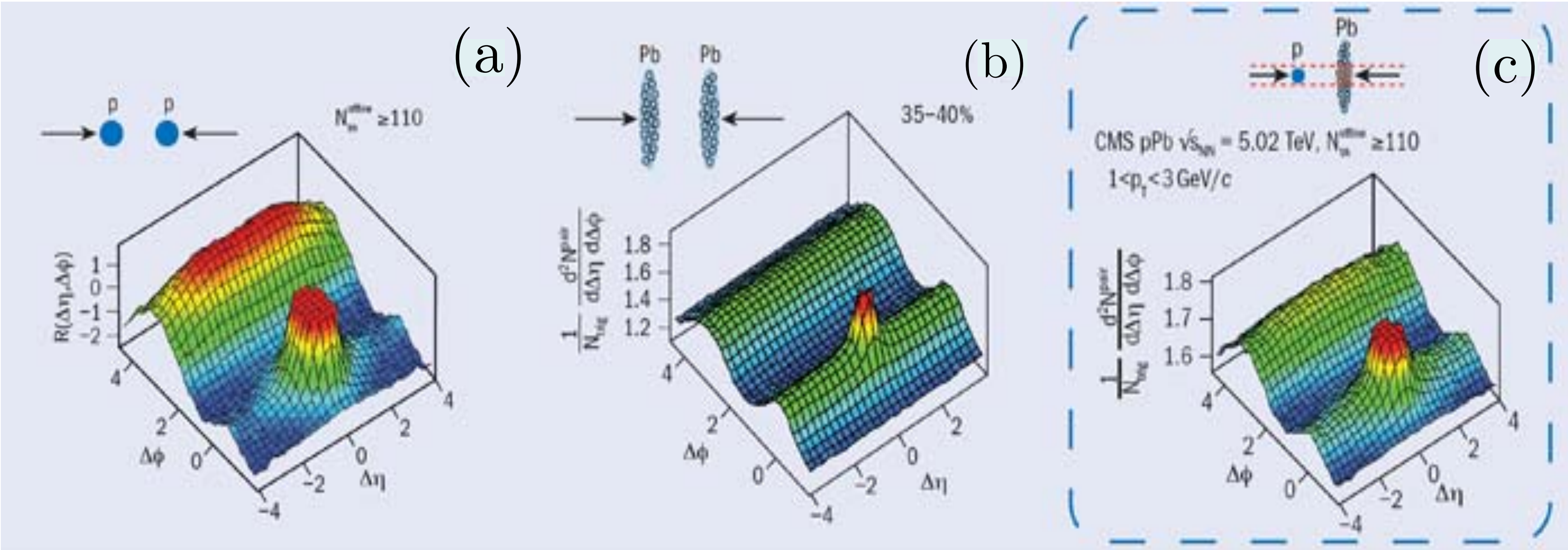
Strong final-state interactions cause high-p_T jets to loose energy to the plasma

$$\frac{\mathrm{d}P}{\mathrm{d}z\,\mathrm{d}q_\perp^2} \sim \alpha_s^2\, C_R\, \frac{n}{q_\perp^4}$$

Since the dominant collisions are soft, jet broadening is essentially a diffusion process in transverse momentum space.



Long-range correlations in symmetric and asymmetric systems @ LHC



Ridges: correlations indicate collective behaviour in pp, Pb-Pb,p-Pb

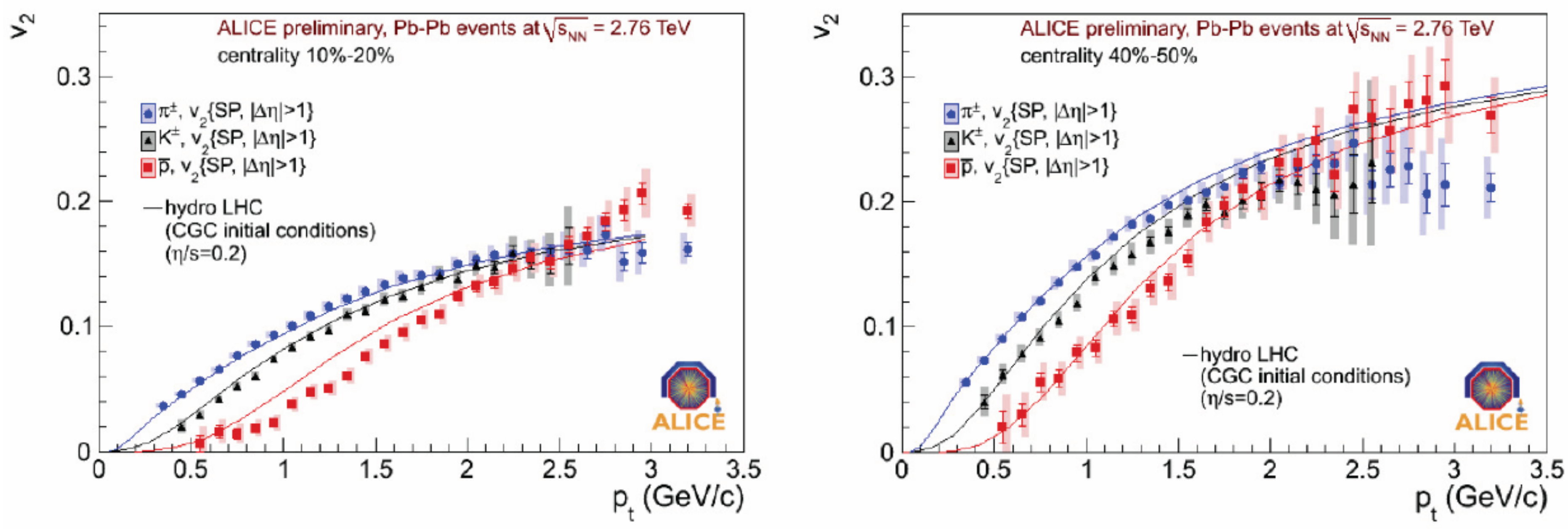
(a) Correlations between pairs of particles in high-multiplicity pp collisions produce a ridge-like enhancement at small relative azimuthal angle $\Delta\phi$.
(b) A similar effect was observed in Pb-Pb collisions, and
(c) in p-Pb collisions.

© **CMS 2012**, confirmed in the 2013 p-Pb run

Anisotropic flow compared to viscous hydrodynamics @ LHC

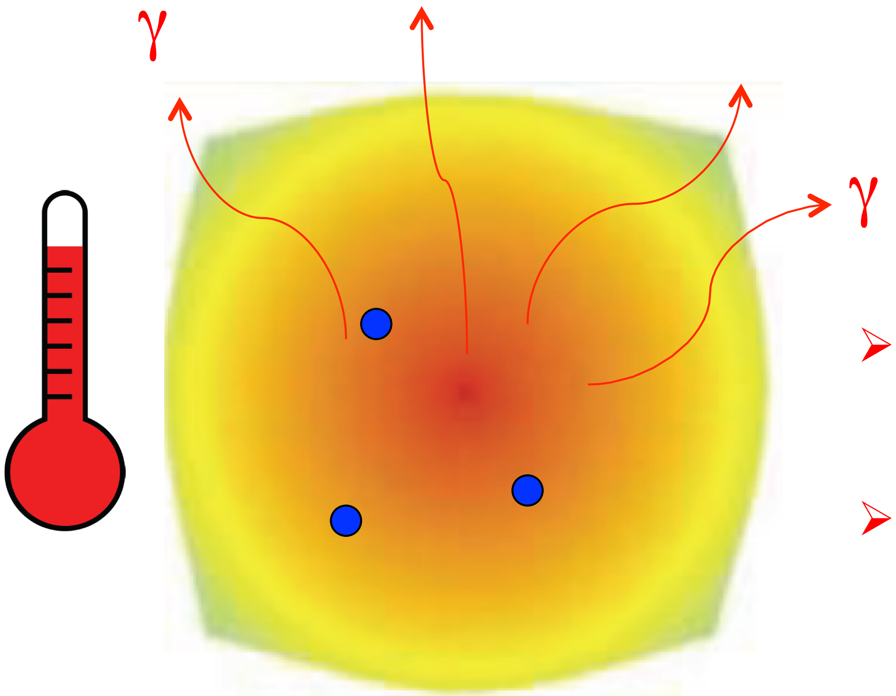
Particle momentum distributions are correlated with the flow symmetry plane Ψ_n.
Fourier expansion of the event-averaged azimutal particle distribution:

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n e^{in(\phi-\psi_n)}$$, anisotropic flow: $$v_n = \langle \cos n(\phi - \psi_n) \rangle$$



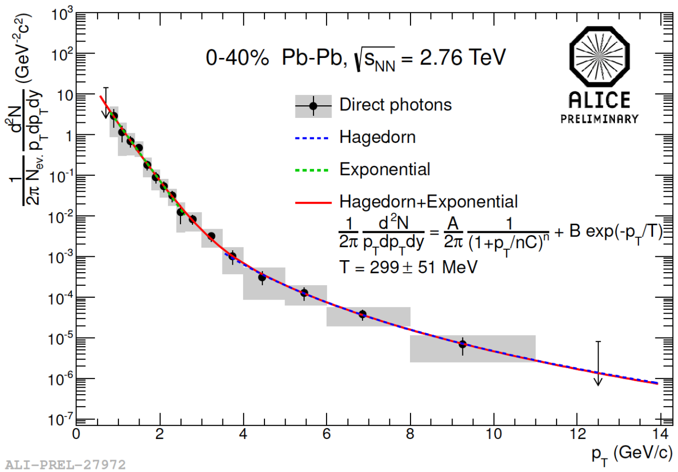
© ALICE; hydro predictions from C. Shen et al., PRC84, 044903 (2011)

Continuum spectroscopy *of* the QGP with photons



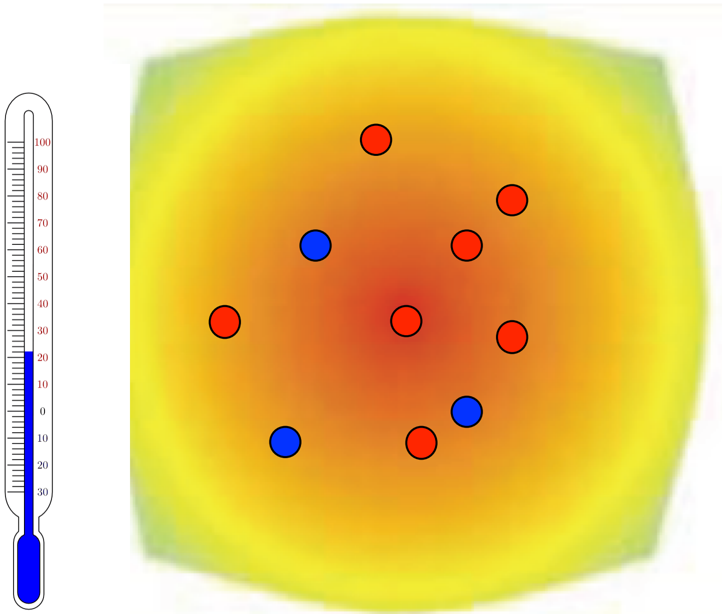
- **Deduce QGP properties such as the temperature T: "QGP-Thermometer"**
- **Direct photons determine the mean temperature in the fireball as**

$\langle T_{QGP} \rangle \approx (299 \pm 51)$ MeV $\approx 10^9\, T_{CMB}$ in 2.76 TeV PbPb



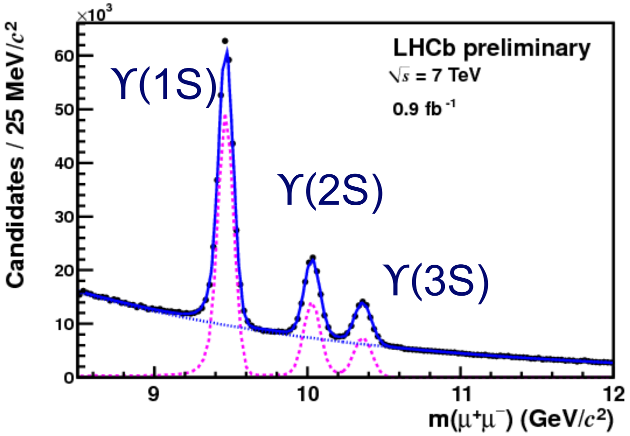
Continuum photons emitted from the QGP

2. Line spectroscopy *in* the QGP with heavy quarkonia



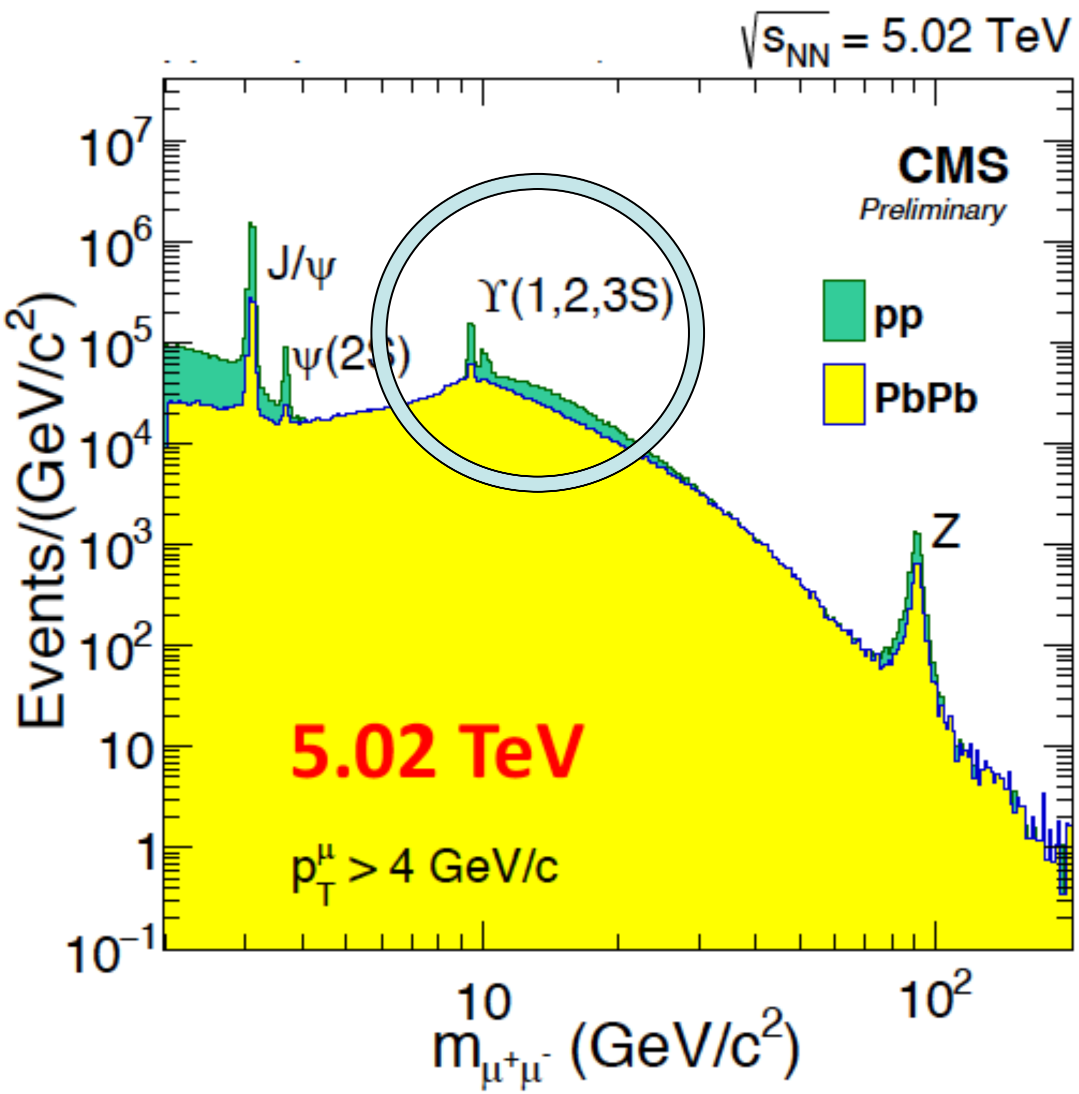
- $J/\psi\ (c\bar{c})$ Recombination @ low p_T!
- $\Upsilon\ (b\bar{b})$

- Investigate their spectroscopy in the QGP: **Colorless states in the colored 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 PbPb @ LHC



© CMS Collab.

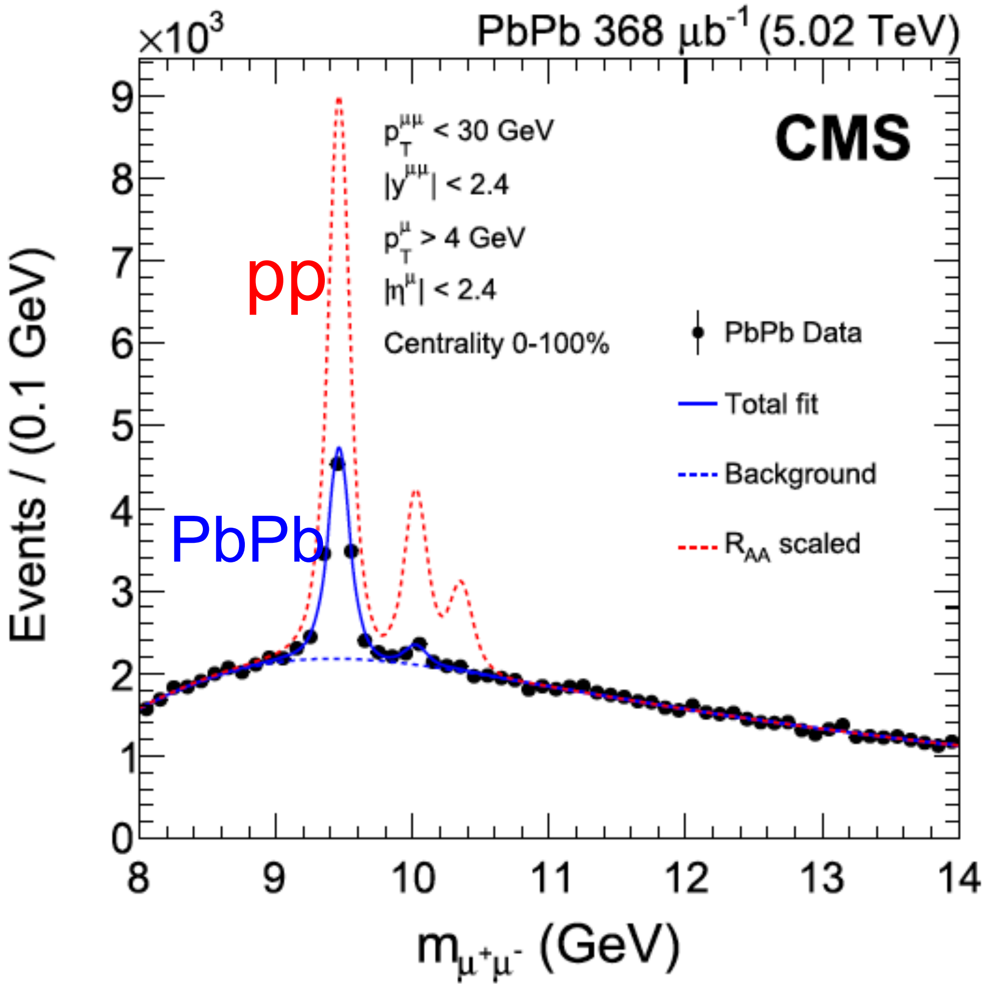
ϒ suppression as a sensitive probe for the QGP

- 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:



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 Y(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. Our 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

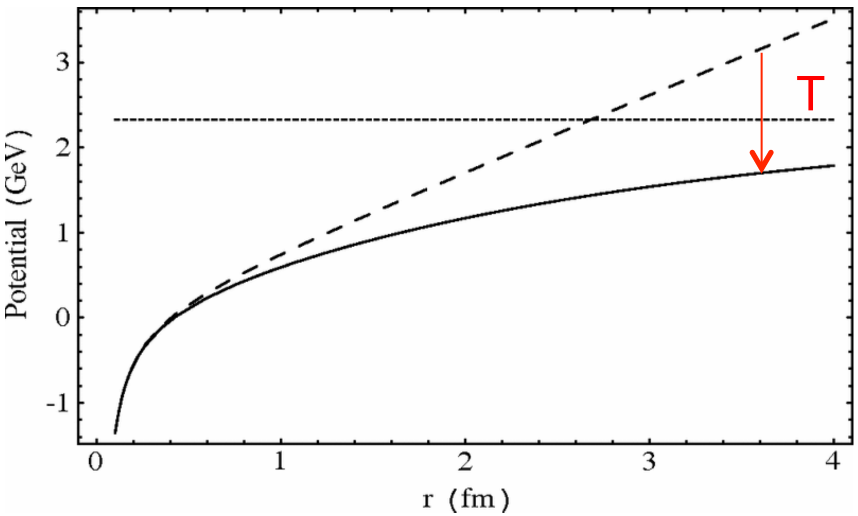
③ Gluon-induced dissociation: dynamic suppression, in particular of the $\Upsilon(1S)$ ground state due to the large thermal gluon density

④ Reduced feed-down from the excited Υ/χ_b states to $\Upsilon(1S)$ 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



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

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

σ string tension, κ Coulomb-parameter

λ_D = Debye length, T = temperature

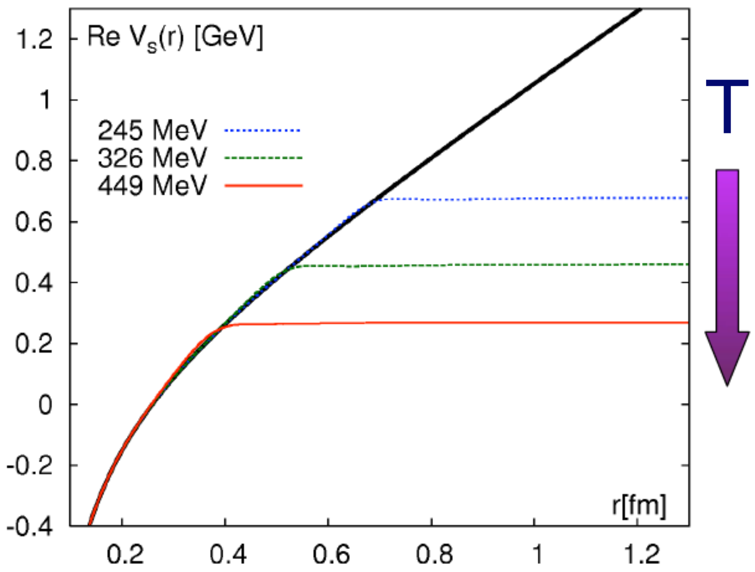
=> Heavy mesons can “melt” in the hot medium

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

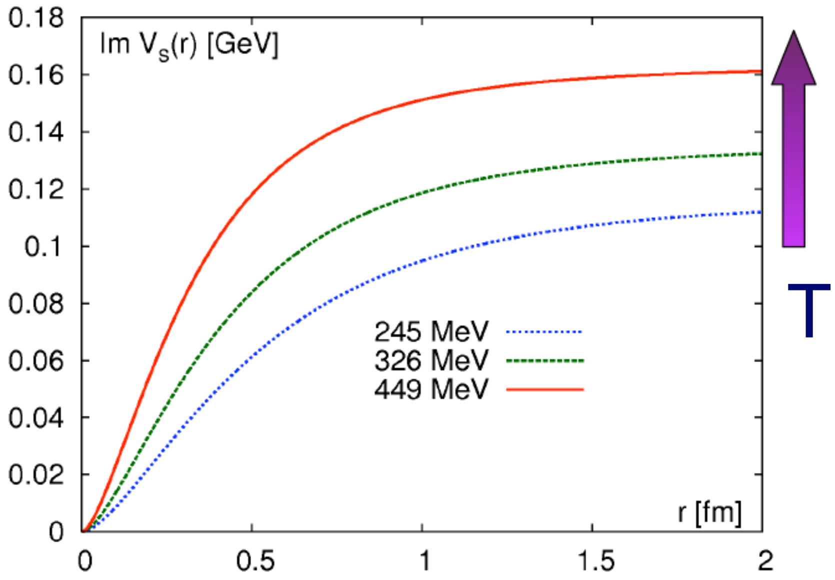


Mócsy, Petreczky, PRL 99 (07) 211602

Screening

Take Im$V_s(r)$ from pQCD calculations

Minimal value



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

Damping

From: A. Mocsy et al.

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

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. Average over thermal gluons.

Add gluodissociation and damping widths for each T and space-time point,

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

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).

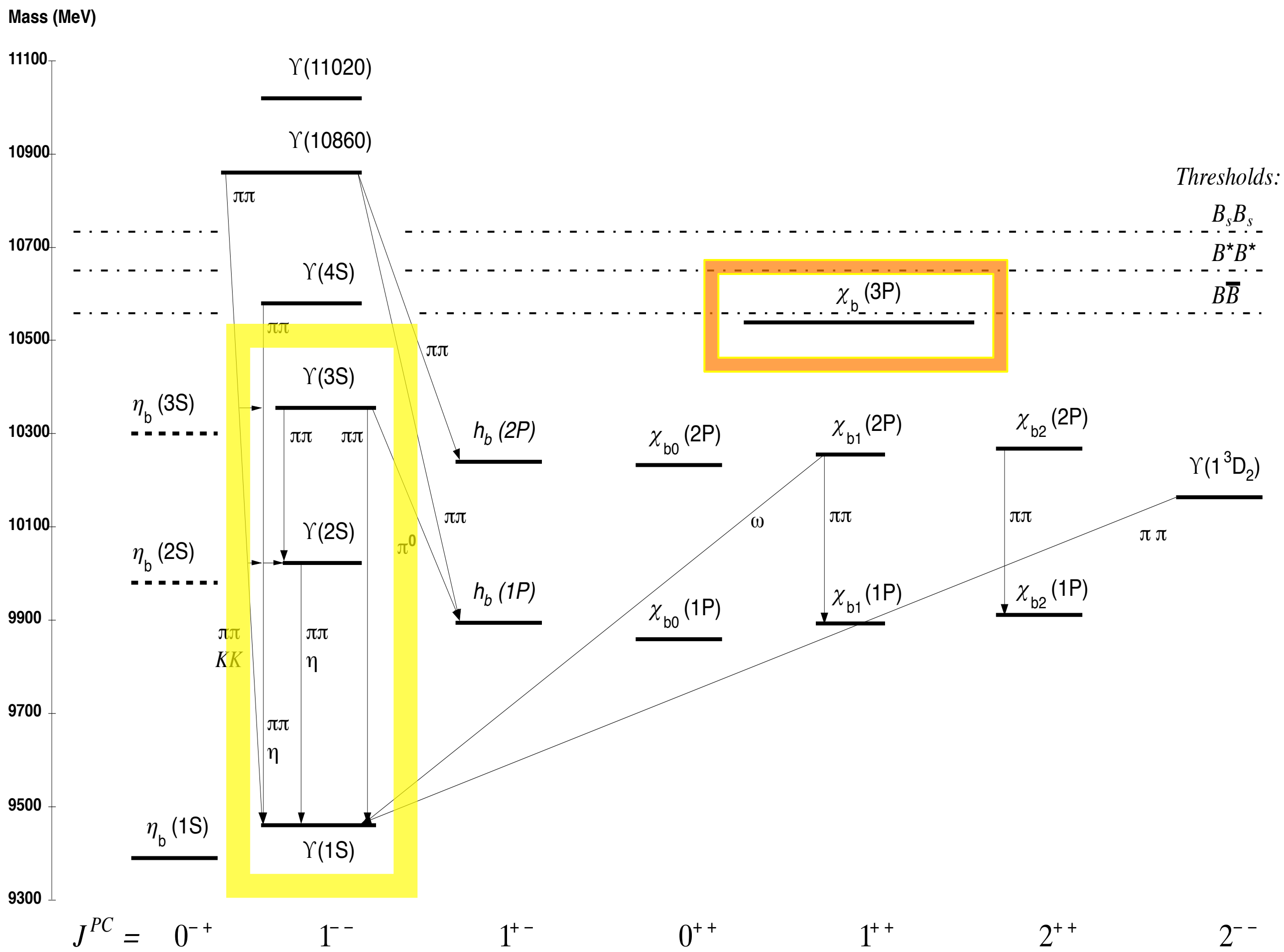
Feed-down is reduced if excited states are screened or depopulated

$N_{initial}$

3S: 0.324

2S: 0.367

1S: 0.373

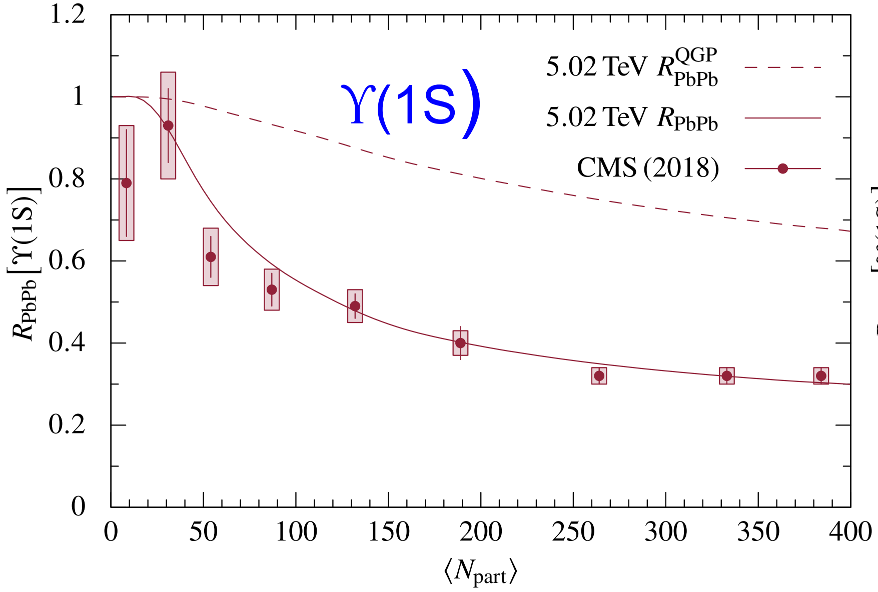


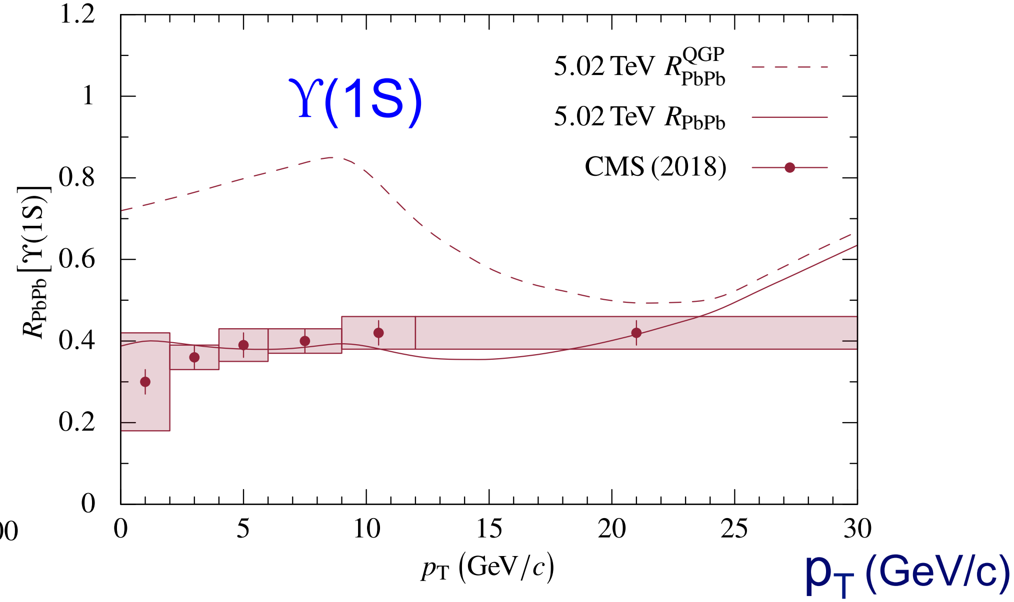
$N_{initial}$

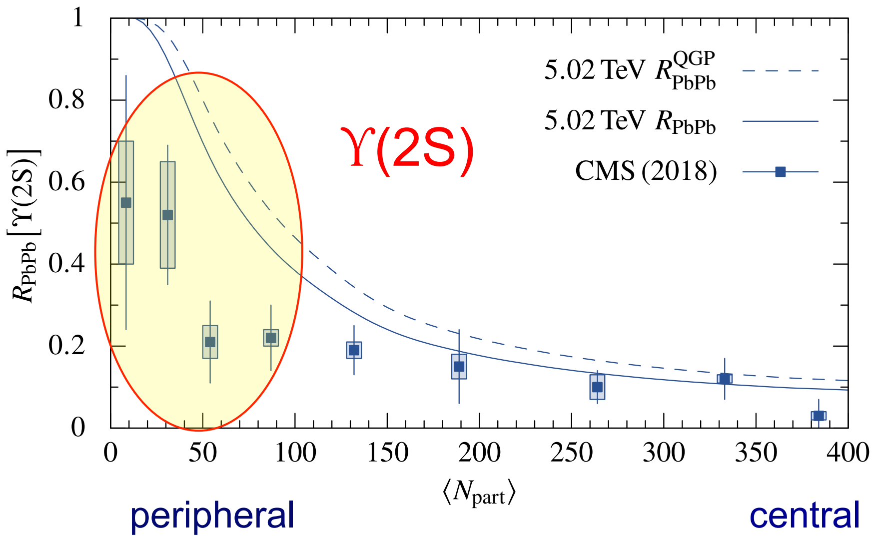
2P: 0.881

1P: 1.084

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)

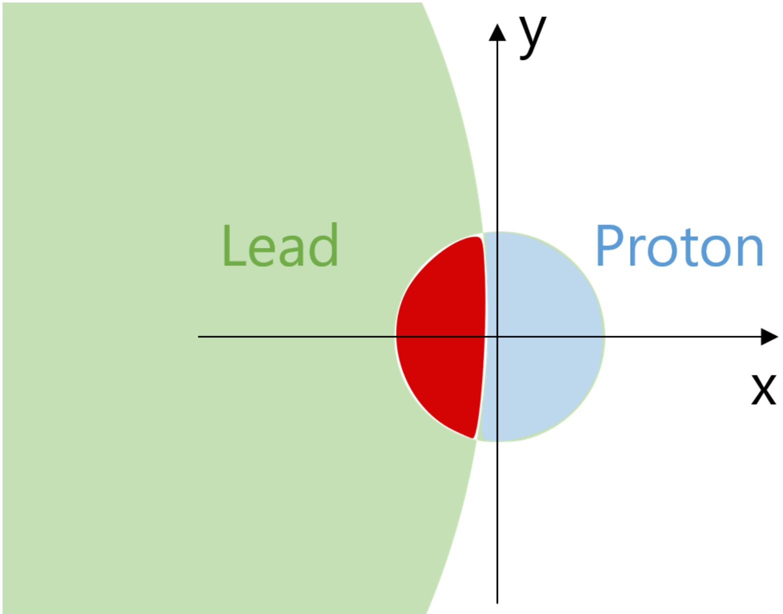
CMS data: Phys. Lett. B 790, 270 (2019)

(T_0= 513 MeV; t_F= 0.4 fm/c)

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.

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



transverse plane

Thickness functions

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

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

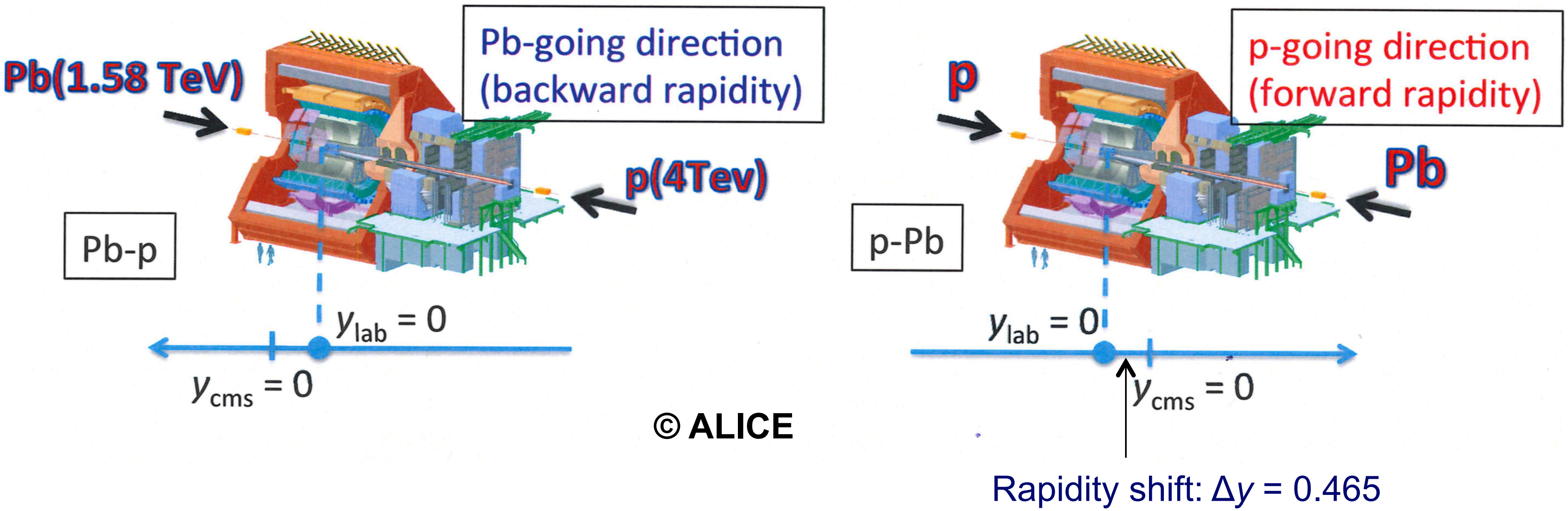
Overlap function

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

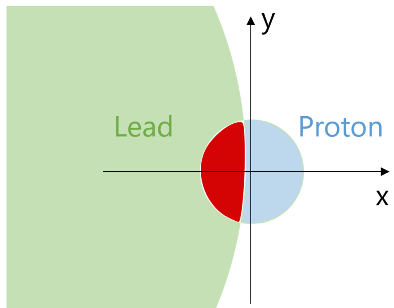
graphic from: V.H. Dinh, MSc thesis, Heidelberg (2019)

Most of the system remains 'cold': $T \ll T_H$
$\Rightarrow$ Consider CNM effects on Υ yields,
plus suppression in the hot QGP

CNM and QGP in asymmetric collisions: p-Pb @ LHC energies



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



CNM and QGP effects in asymmetric collisions

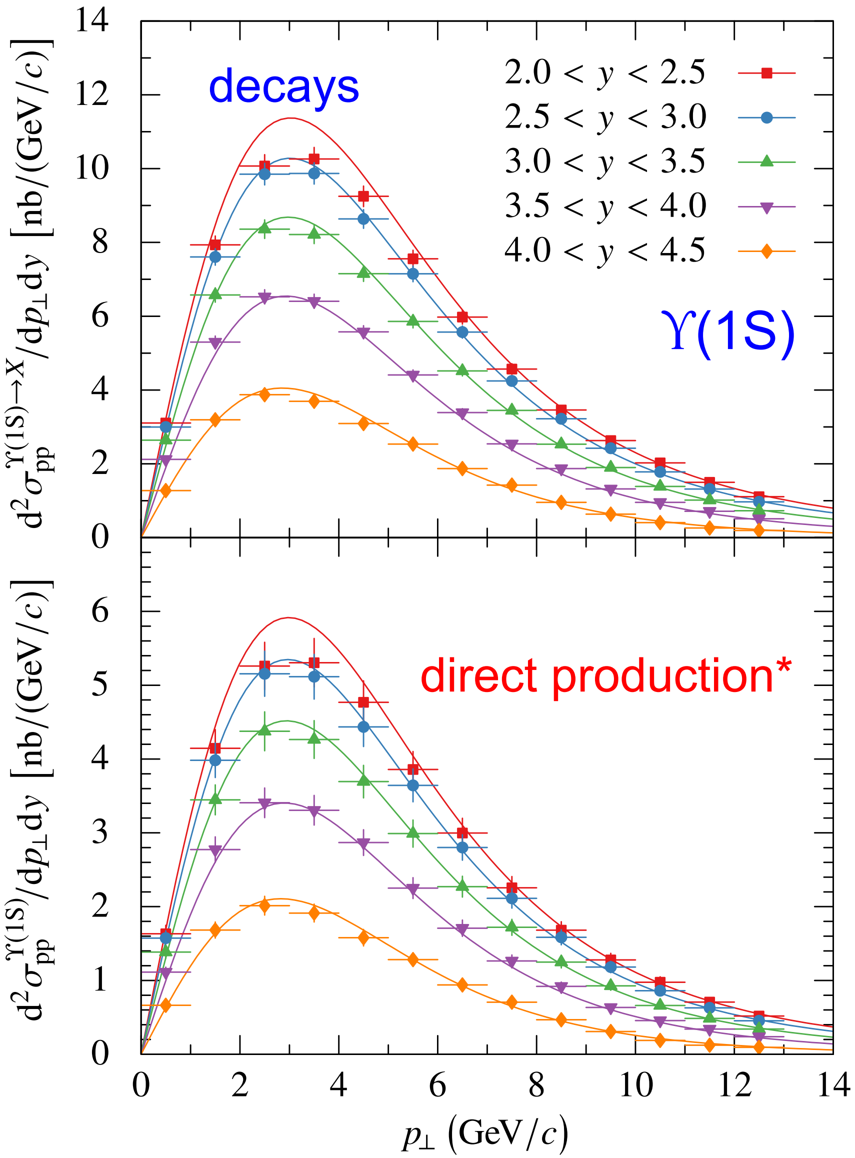
Bottomonia yields are influenced by the presence of nuclear matter: Cold nuclear matter (CNM) effects.

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

We consider the well-established CNM effects [1,2] together with the Υ suppression in the hot quark-gluon plasma [3], as in Pb-Pb.

[1] F. Arleo,et al., JHEP 05, 155 (2013);
[2] R. Vogt, Phys. Rev. C 92, 034909 (2015).
[3] V.H. Dinh, J. Hoelck and GW, Phys. Rev. C 100, 024906 (2019)

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



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

Fits:

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

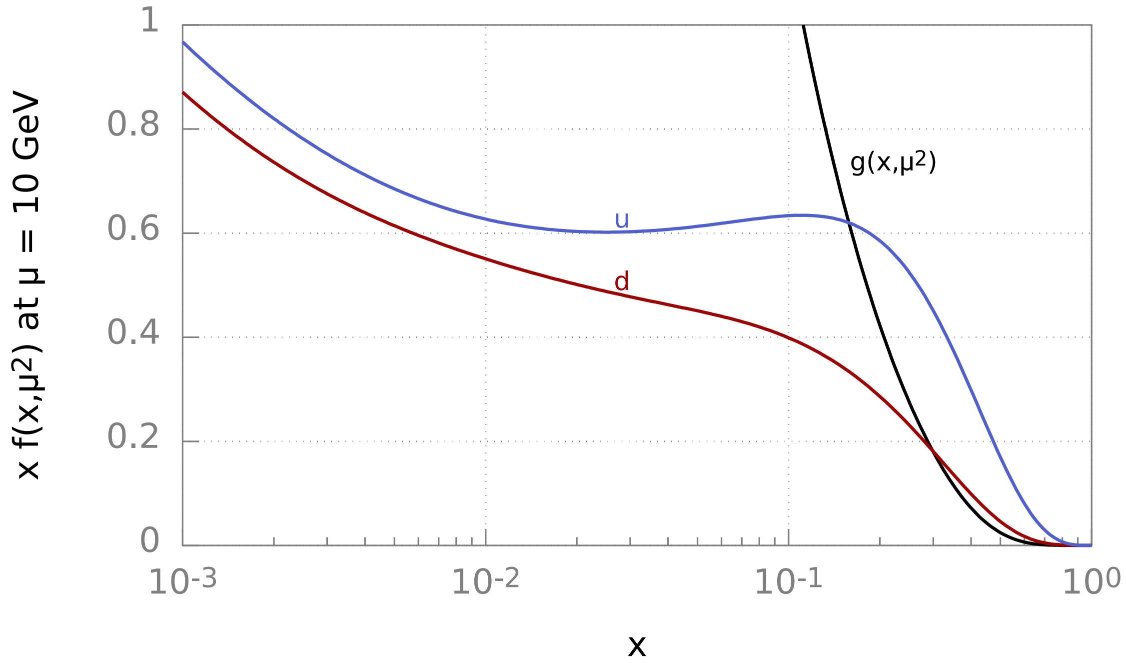
(4 parameters acc. to **Arleo et al., JHEP 2013, 155 (2013)**)

* from inverse feed-down cascade:

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

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

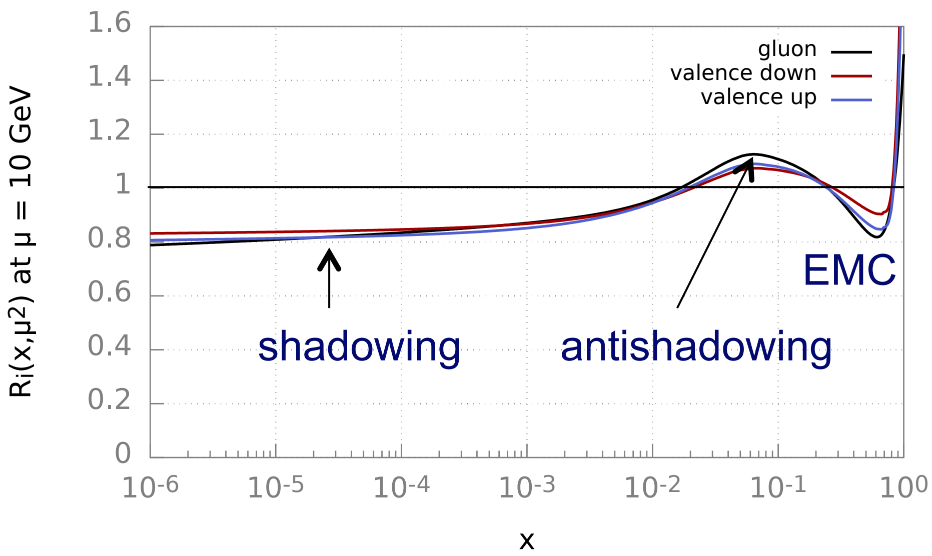
with λ = 0.2 - 0.3

- 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

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

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)

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)

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

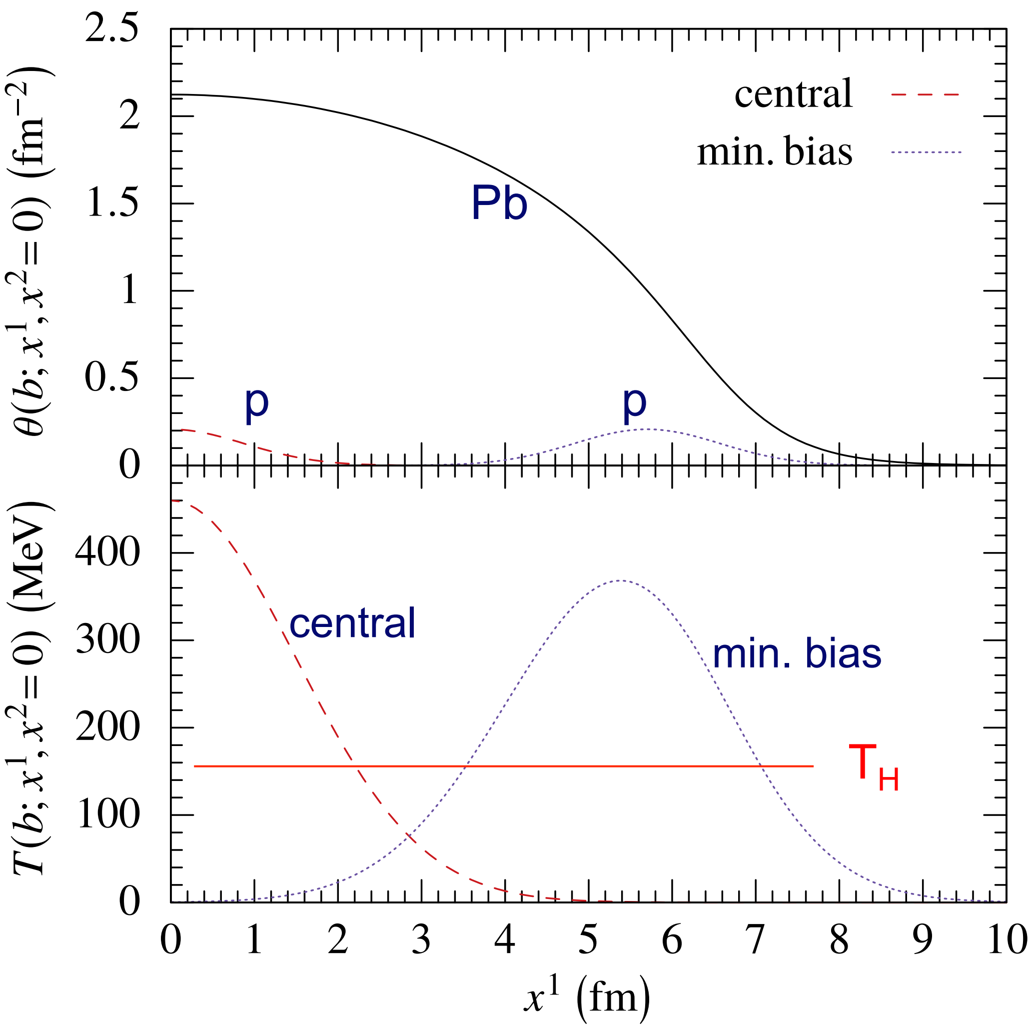
$$p_\perp^{\rm shift} = \sqrt{p_\perp^2 + \Delta p_\perp^2 + 2p_\perp\Delta p_\perp\cos\varphi}\,,$$

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

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.

See **F. Arleo,et al., JHEP 05, 155 (2013);**
R. Vogt, Phys. Rev. C 92, 034909 (2015).

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),

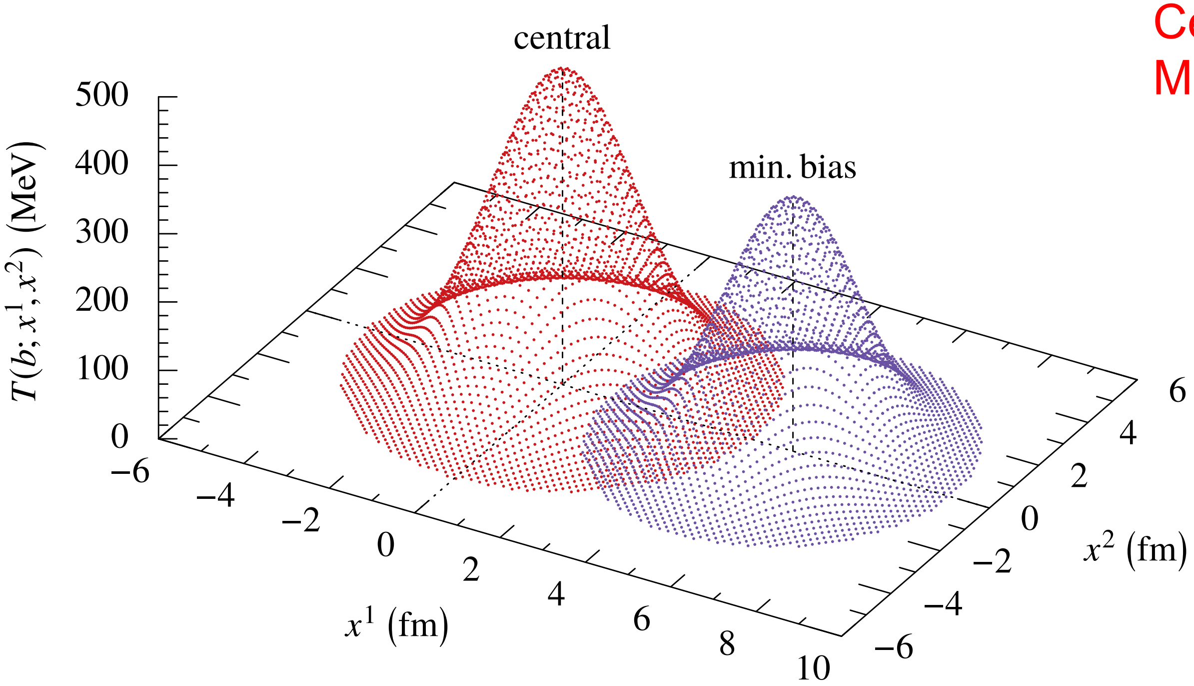
$\theta_{\rm p}(x^1, x^2 = 0)$ for p

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 pPb collisions



Transverse plane (x^1, x^2)

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

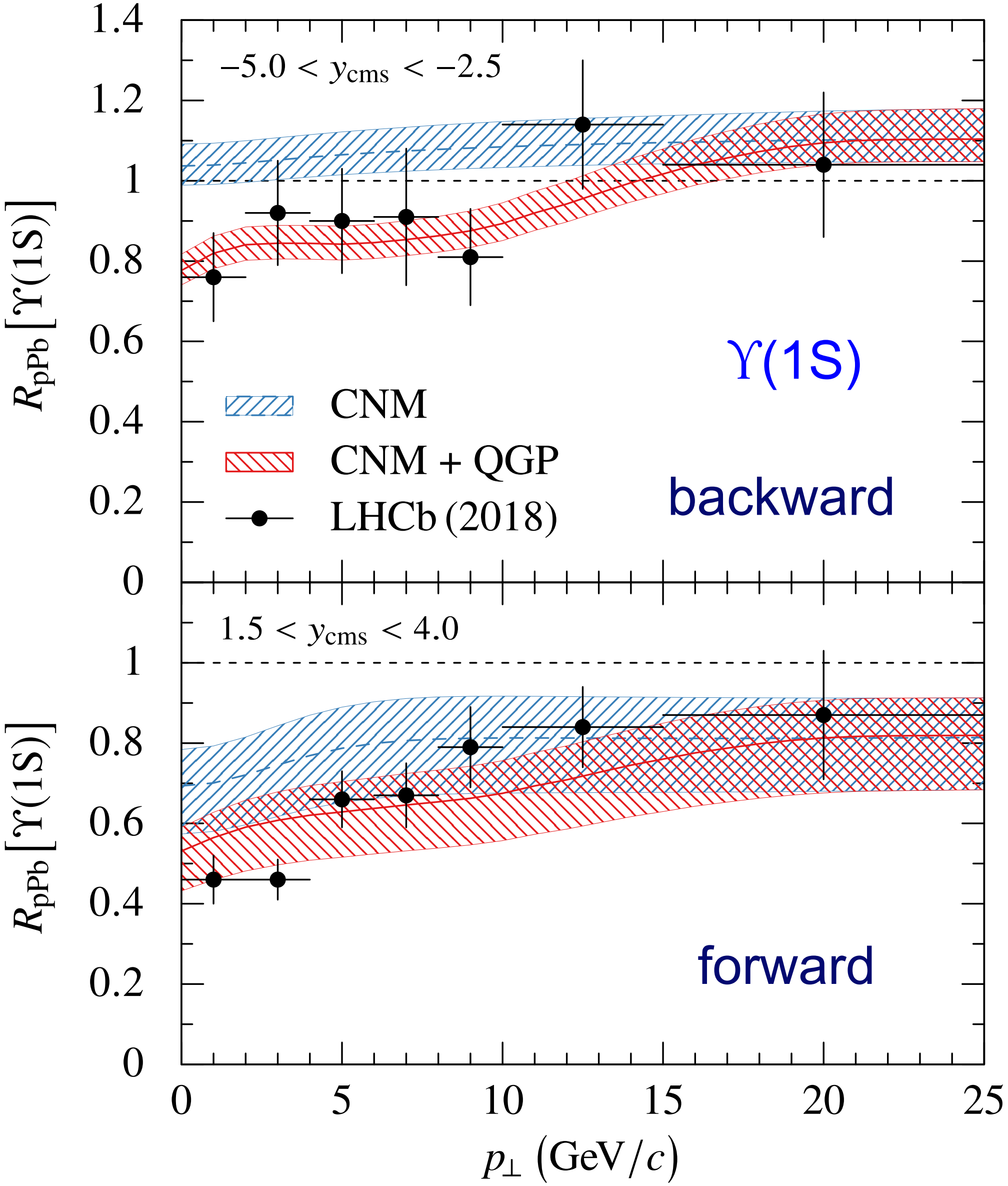
$T_0 = 460$ MeV

Deconfined for
$T > T_H \approx 160$ MeV

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

5. 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

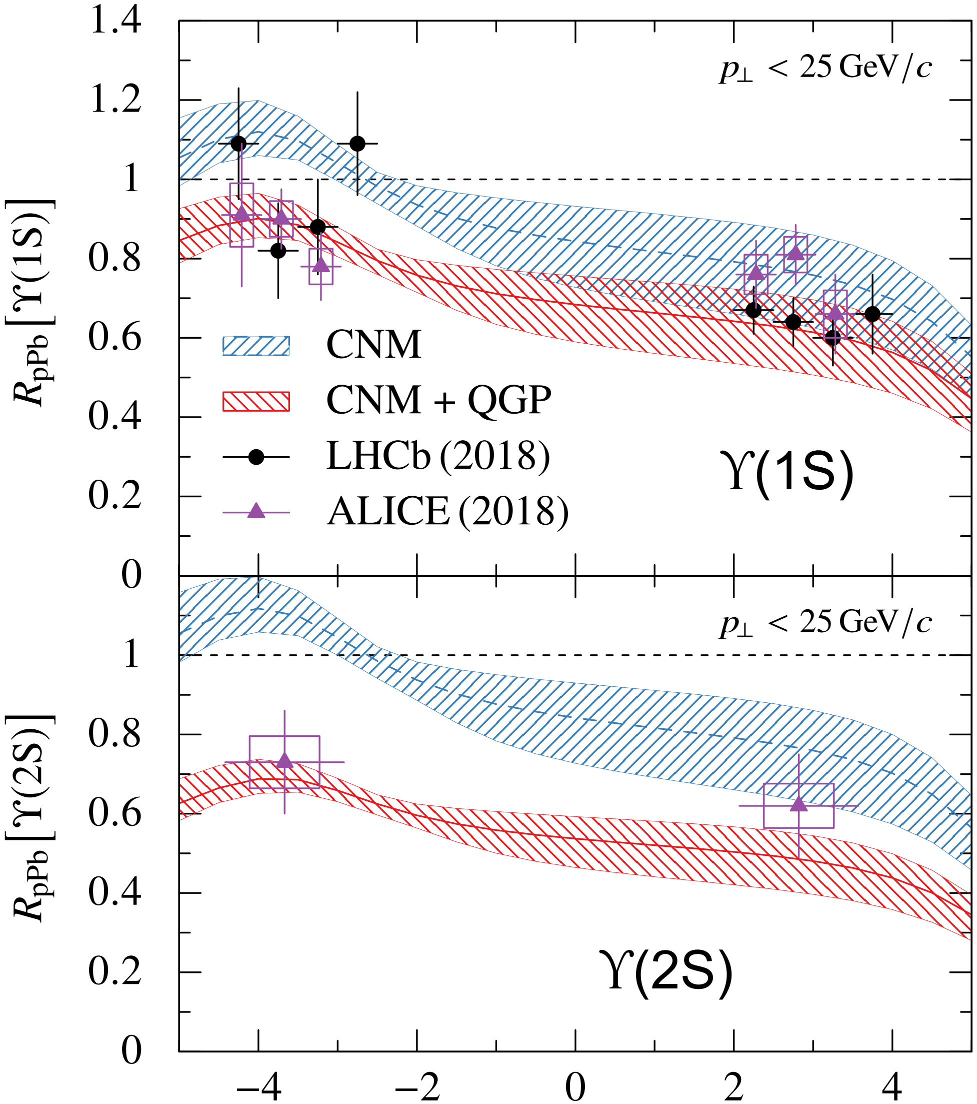
Energy-loss effects pronounced at
$p_T \leq 8$ GeV/c

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

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

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

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



Pb-going **<- backward** **forward ->** p-going

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 100, 024906 (2019); arXiv:1903.12594v2

6. 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 !