Spectroscopy in the quark-gluon plasma

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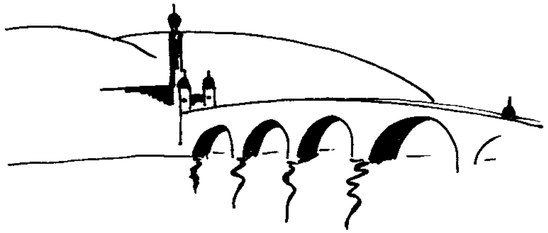

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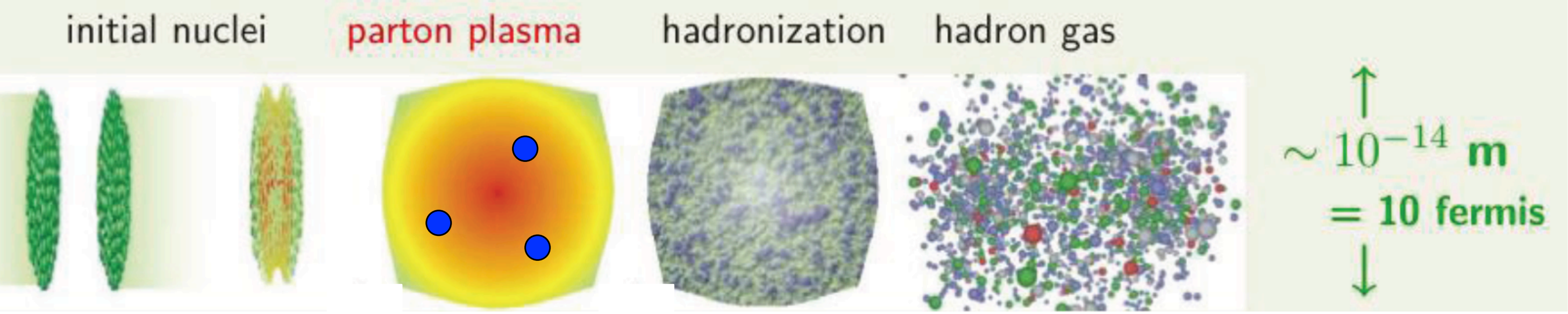
Quark-gluon plasma (QGP)

... was the state of the universe until ~ 10 microseconds following the t = 0 singularity in Friedman‘s equations (“big bang“)

... is being created in relativistic heavy-ion collisions for a very short time span of about 10^{-23} seconds

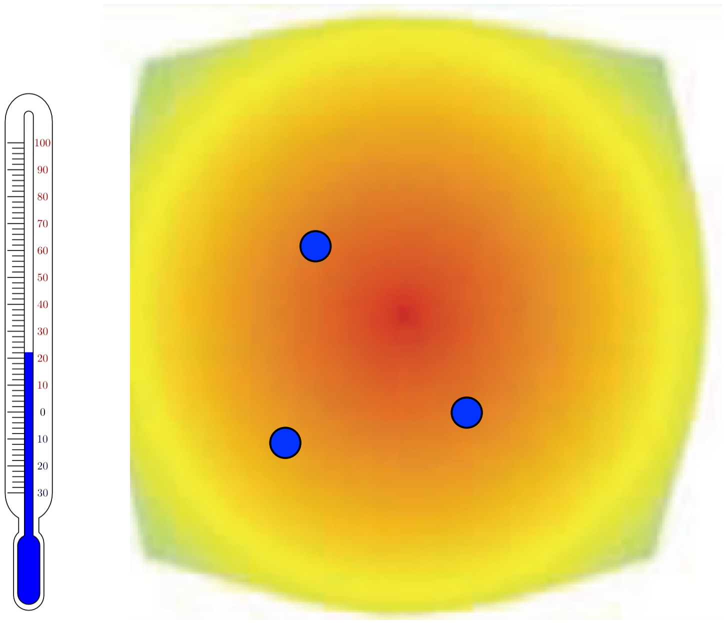


← ~ 10^{-23} s = 10 yoctoseconds →

● **Heavy mesons**

Artwork © Nikhef / S. Bass

Spectroscopy of heavy quarkonia in the QGP



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

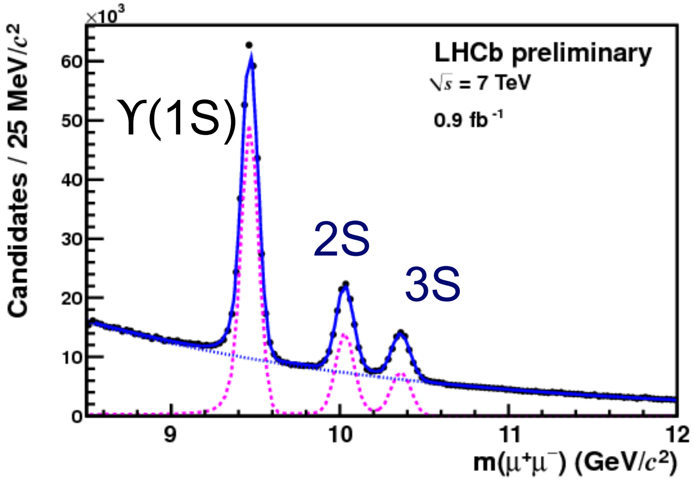
- **Investigate their spectroscopy in the QGP**

- **Deduce QGP properties such as the temperature T: "QGP-Thermometer"**

- **Expected central temperature in the $4\cdot10^2$ MeV range,**

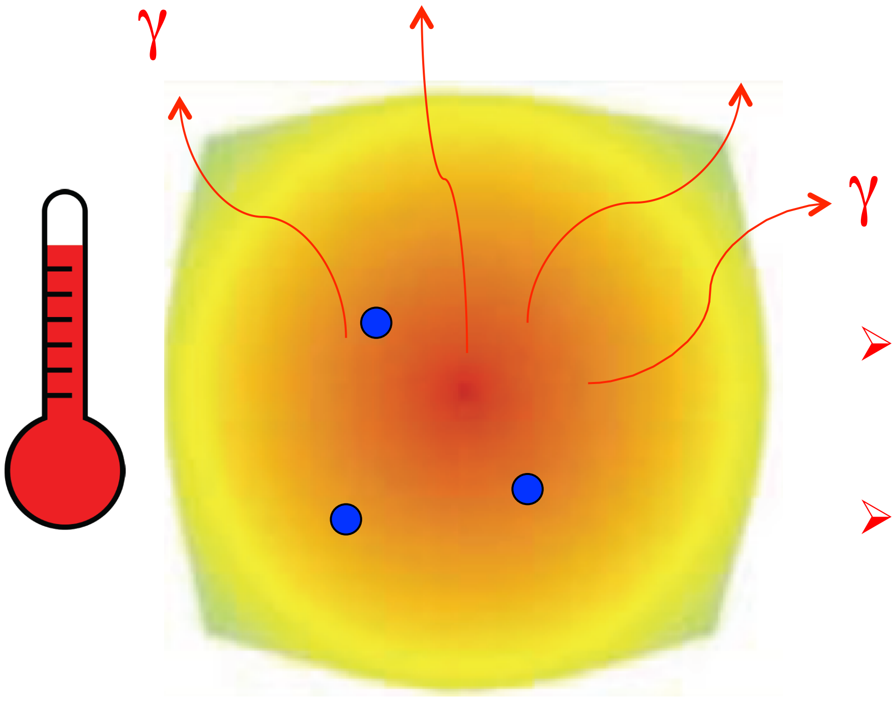
  100 MeV ≈ $1.16\cdot10^8$ Kelvin

- **Solar interior: $T_\odot \approx 1.57\cdot10^7$ K**



Υ spectrum in vacuum => in the QGP medium?

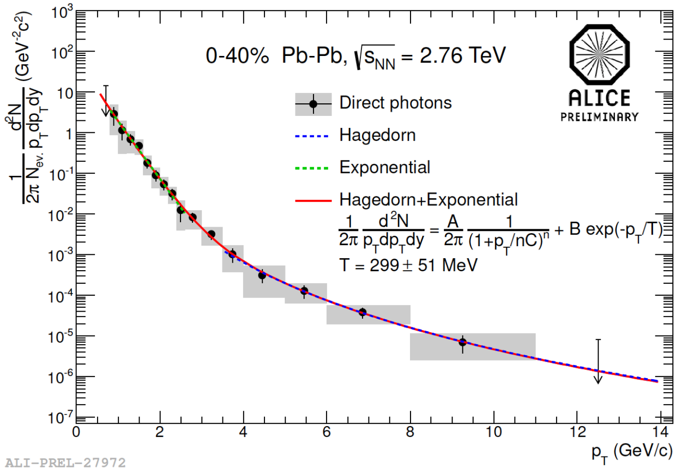
Continuum spectroscopy of the QGP with photons



- **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 $\approx 10^{9}\,T_{CMB}$



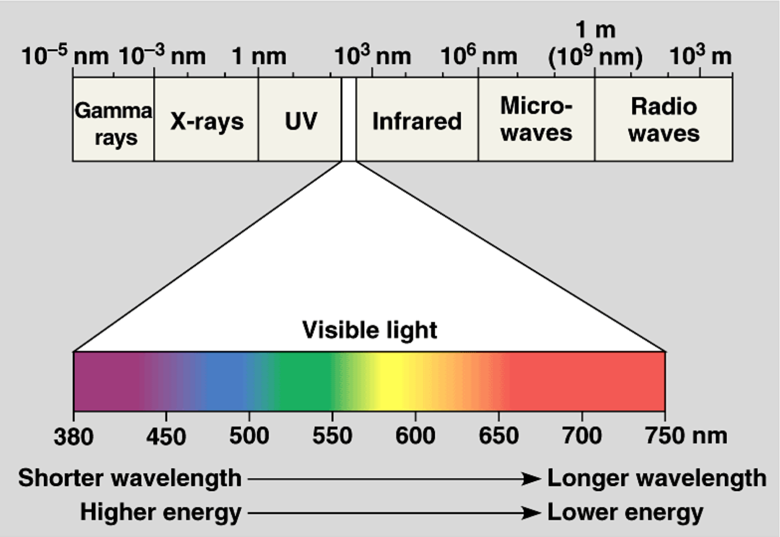
Continuum photons emitted from the QGP

Spectral analysis

Visible light as Bunsen and Kirchhoff used it for optical spectroscopy spans only a small fraction of the electromagnetic spectrum; the rest is quite significant: Stars emit IR, visible and UV light.

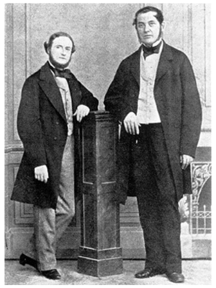
In cosmology the microwave part of the spectrum was essential for the discovery of the cosmic microwave background, CMB, by Penzias&Wilson 1964/65.

In the spectral analysis of the Quark-gluon plasma we use next to photons also other signatures:
'Particle radiation', such as lepton pairs (electrons or myons) from decaying heavy mesons like charmonium $J/\psi\ (c\bar{c})$ or bottomonium $\Upsilon(b\bar{b})$.

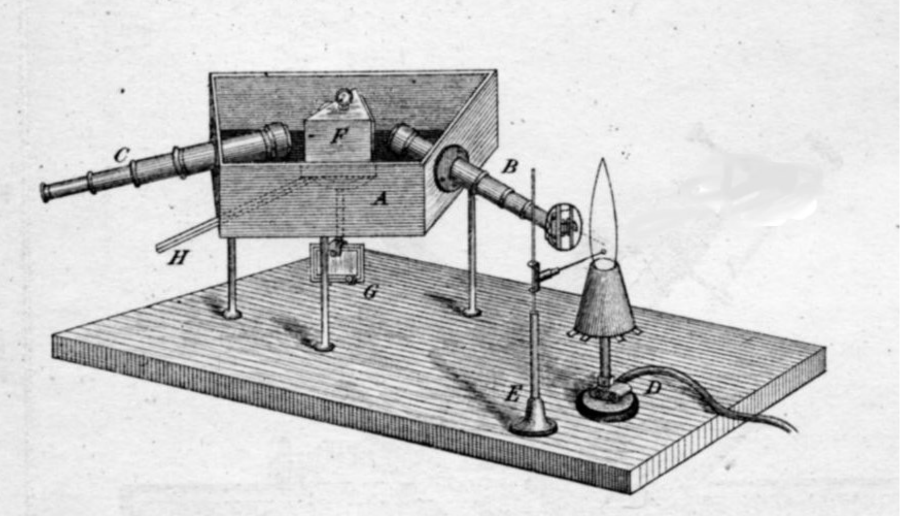


Optical spectroscopy: Bunsen and Kirchhoff

„Von allen Spectralreactionen ist die des **Natriums** am empfindlichsten. Die gelbe Linie Na α...fällt mit der Fraunhofer'schen Linie D zusammen...“



Discovery of new elements:
Cesium (2 blue lines) and Rubidium



G. Kirchhoff und R. Bunsen,
Annalen der Physik und Chemie, Bd. 110 No. 6, 1860, S. 161

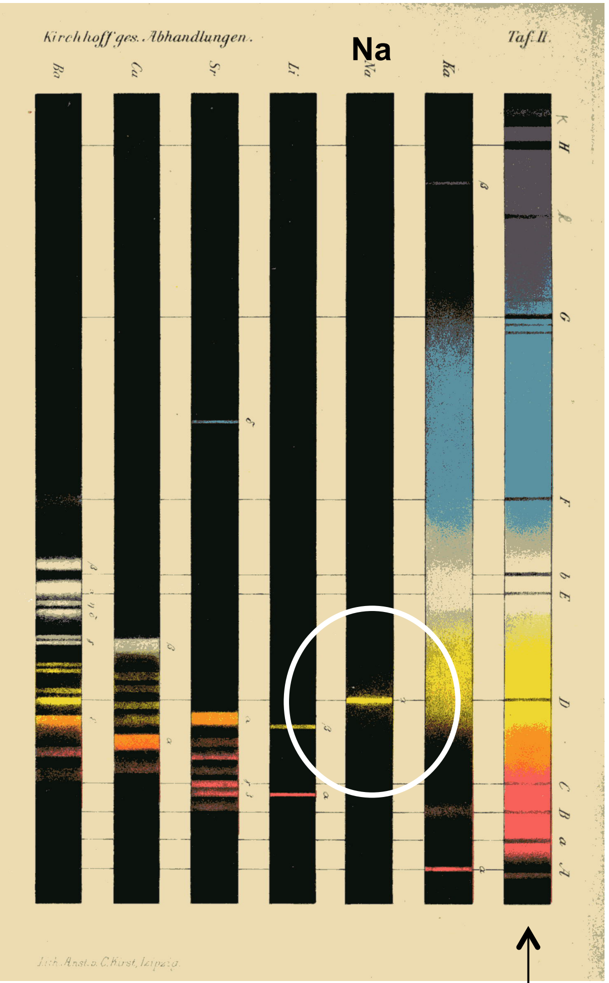
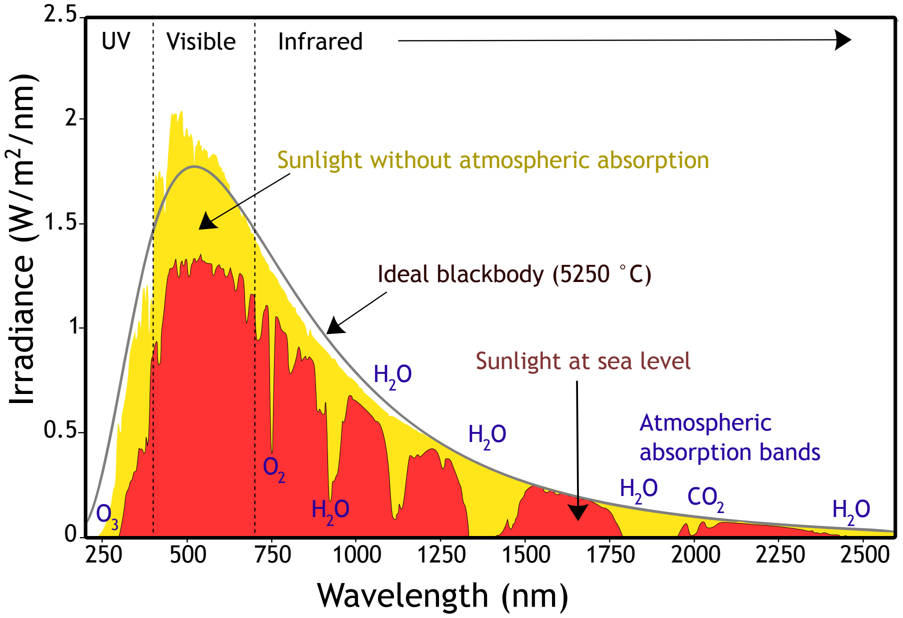


Abbildung 2: Spectren

(Heidelberg)

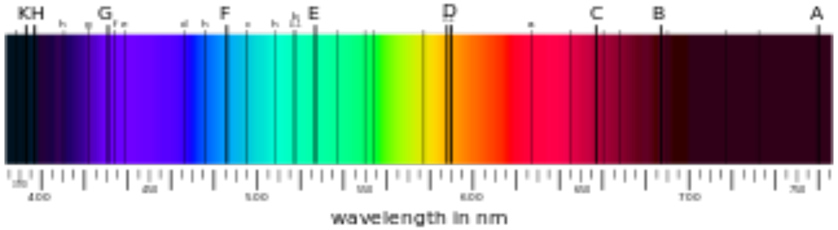
Fraunhofer lines
(absorption)

The sun and stars emit UV, visible and IR light


Spectrum of Solar Radiation (Earth)


J. v. Fraunhofer 1814
© R. Wimmer

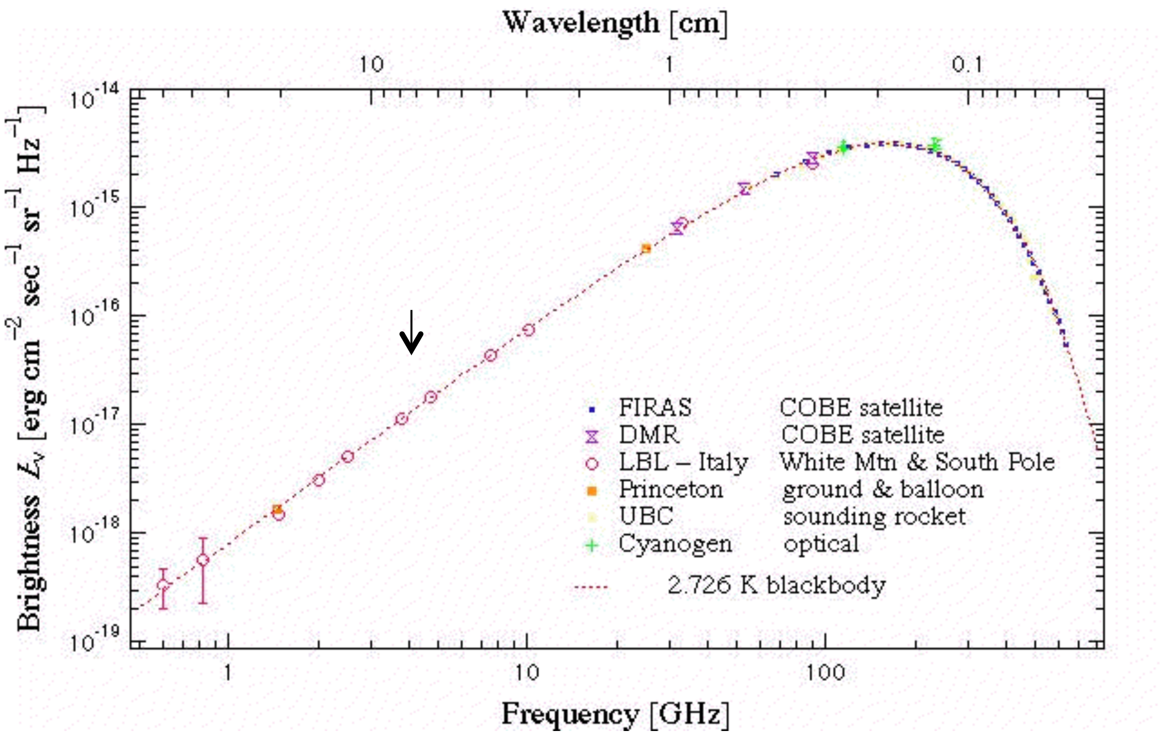
Fraunhofer absorption lines



W.H. Wollaston FRS, 1802 (independently; discovered Pd, Rh)

The continous stellar spectrum is close to a blackbody spectrum,
it is in thermal equilibrium.
Note however, that many astrophysical processes are not -

Continuum spectroscopy: the cosmic microwave background radiation



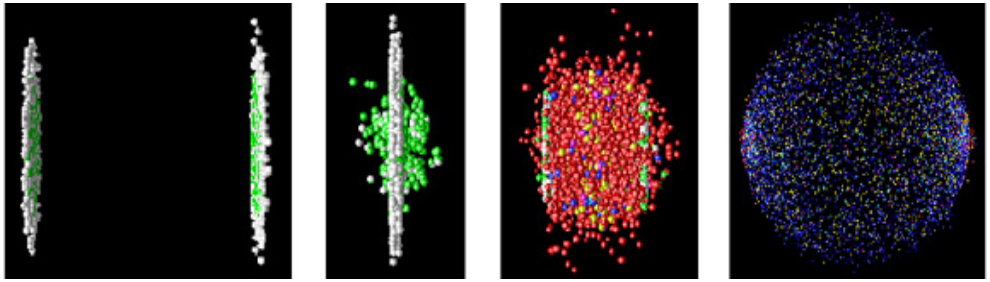
- Discovered by Arno Penzias und Robert Wilson 1964/5 at 4.1 GHz. Physics Nobel Prize 1978
- Due to expansion, the temperature has dropped to 2,73 Kelvin today
- It is a **Planck-spectrum**

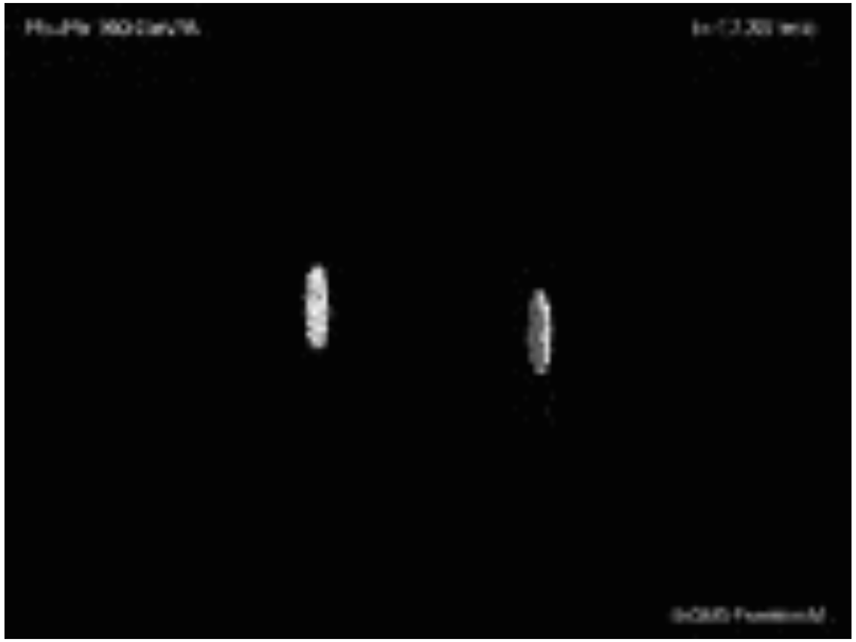
The most precise blackbody spectrum realized in nature. Temperature at emission ≈ 3000 Kelvin (0.25 eV)

$$U_\nu^o(\nu, T)\,\mathrm{d}\nu = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{\left(\frac{h\nu}{kT}\right)} - 1}\,\mathrm{d}\nu$$

Source: COBE-Collaboration, 1992

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



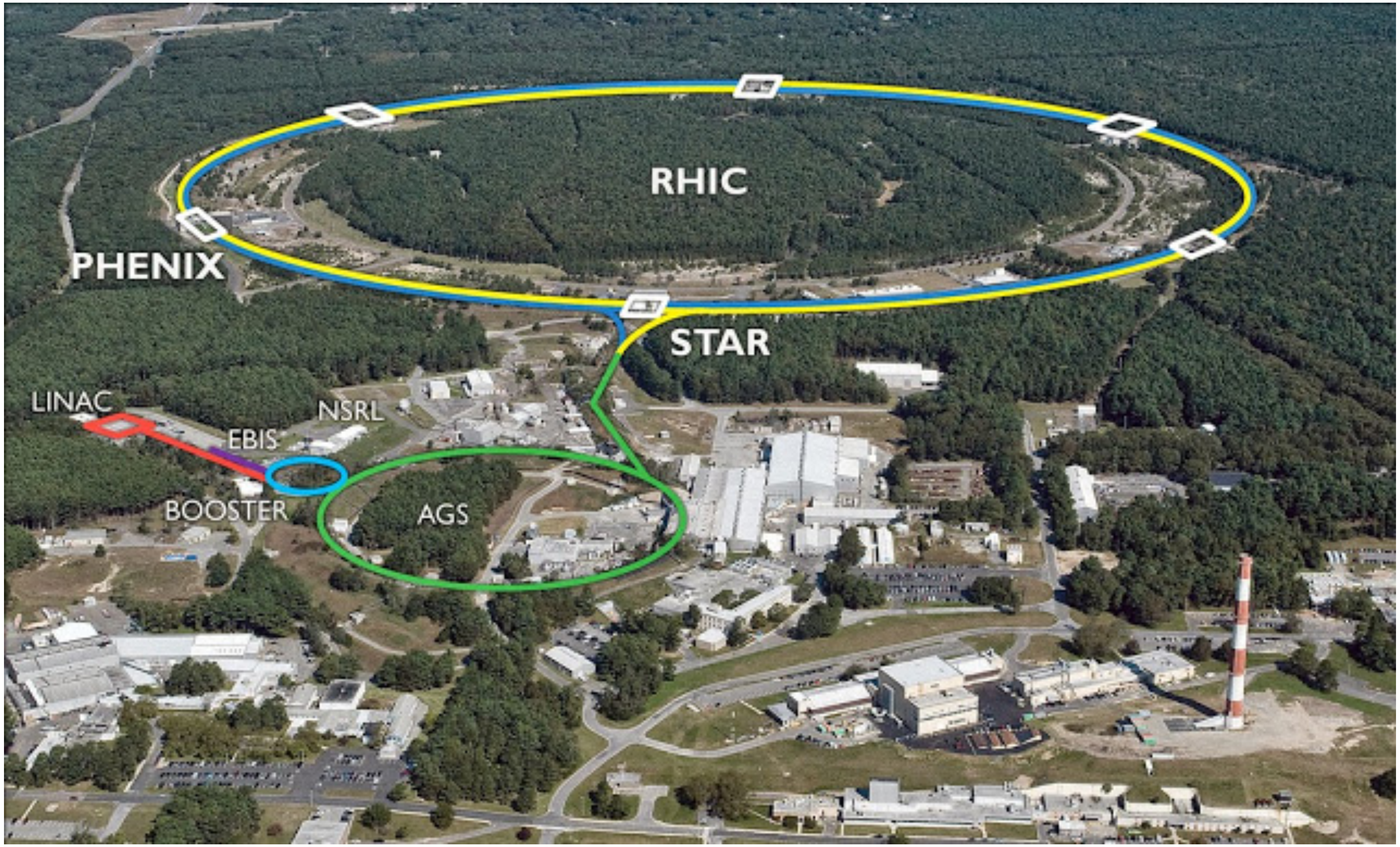


© CERN

In the first stages of the collision, gluons equilibrate, quarks and heavy mesons 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.

Relativistic Heavy Ion Collider (RHIC), BNL



e.g. Au+Au collisions @ $\sqrt{s_{NN}}$= 200 GeV center of mass energy

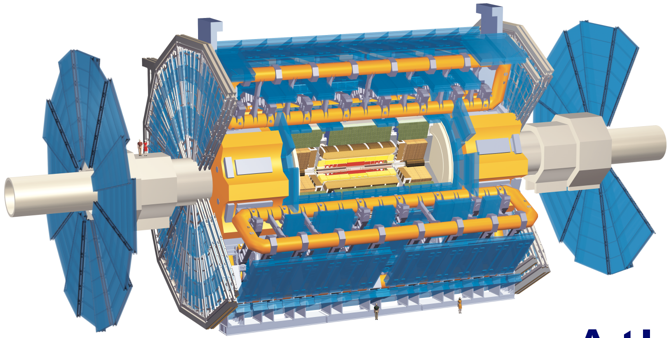
Large Hadron Collider (LHC) / CERN

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

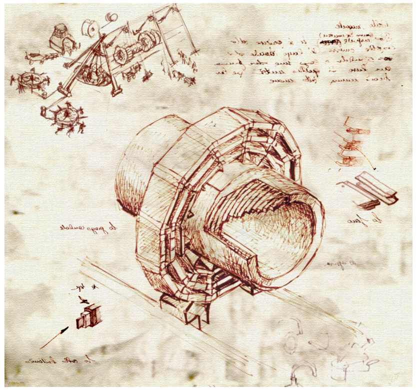
p+Pb @ 5.02 TeV 2012/13
@ 5.02, 8.16 TeV 2016

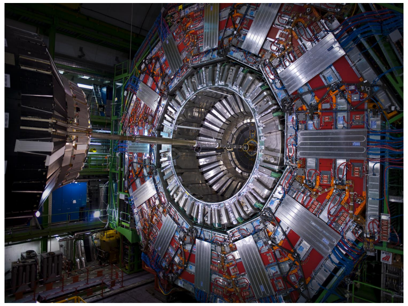
Pb+Pb @ 2.76 TeV 2011/12 Run 1
@ 5.02 TeV Oct. 2015 Run 2
(design energy 5.52 TeV)

LHC Detectors: pp,
plus Relativistic heavy-ion physics: PbPb



Higgs boson





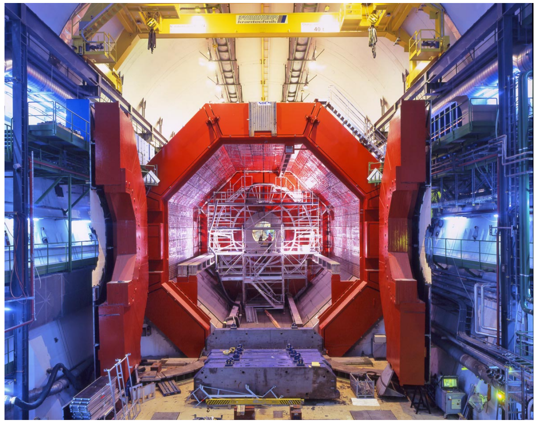
CMS

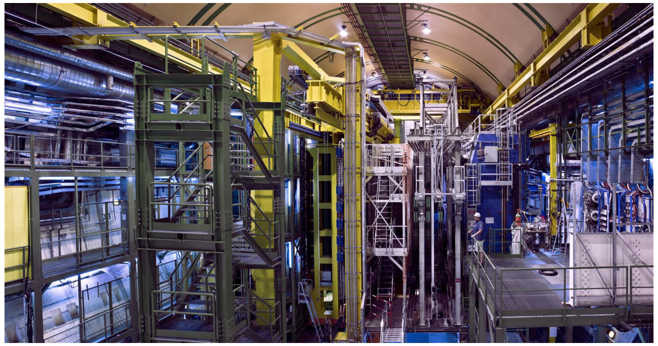
da Vinci style

≈ 60 HI people

Atlas

≈ 35 HI people





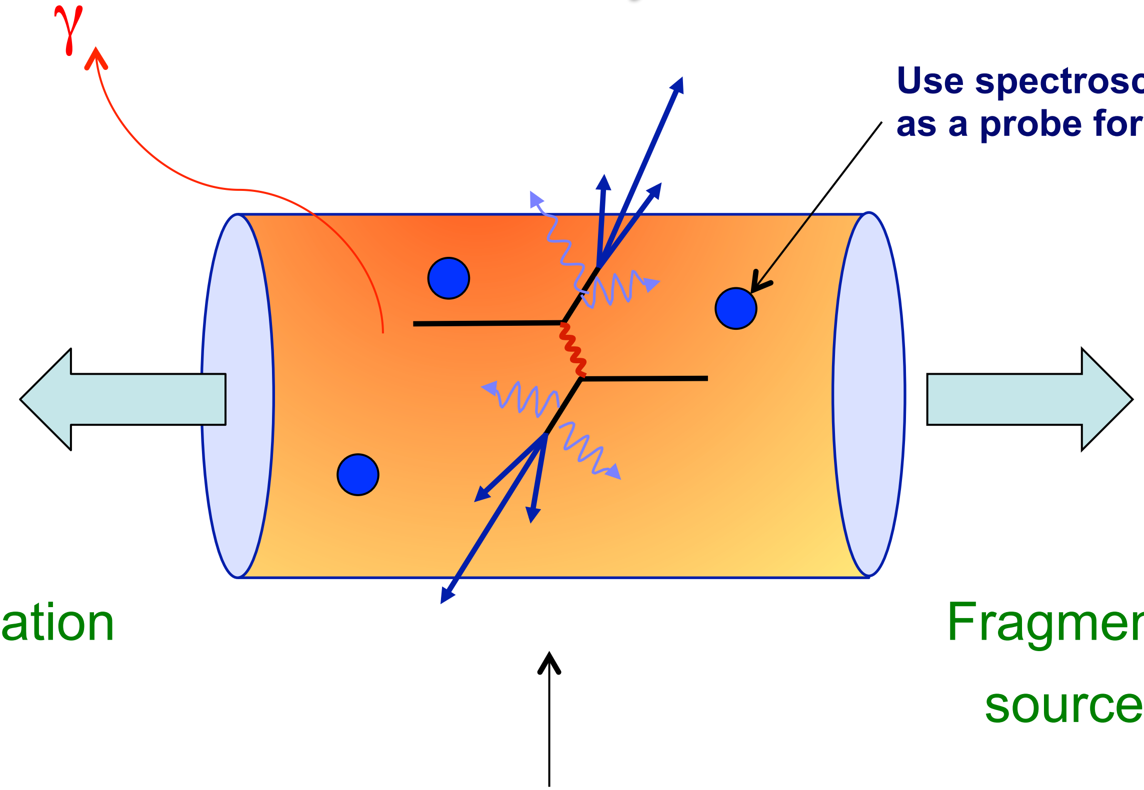
LHCb

p-Pb; peripheral PbPb

Alice: L3 magnet

≥ 1,000 HI people

Three sources for particle production in a relativistic heavy-ion collision



Use spectroscopy of heavy mesons as a probe for the QGP properties

Fragmentation source 1

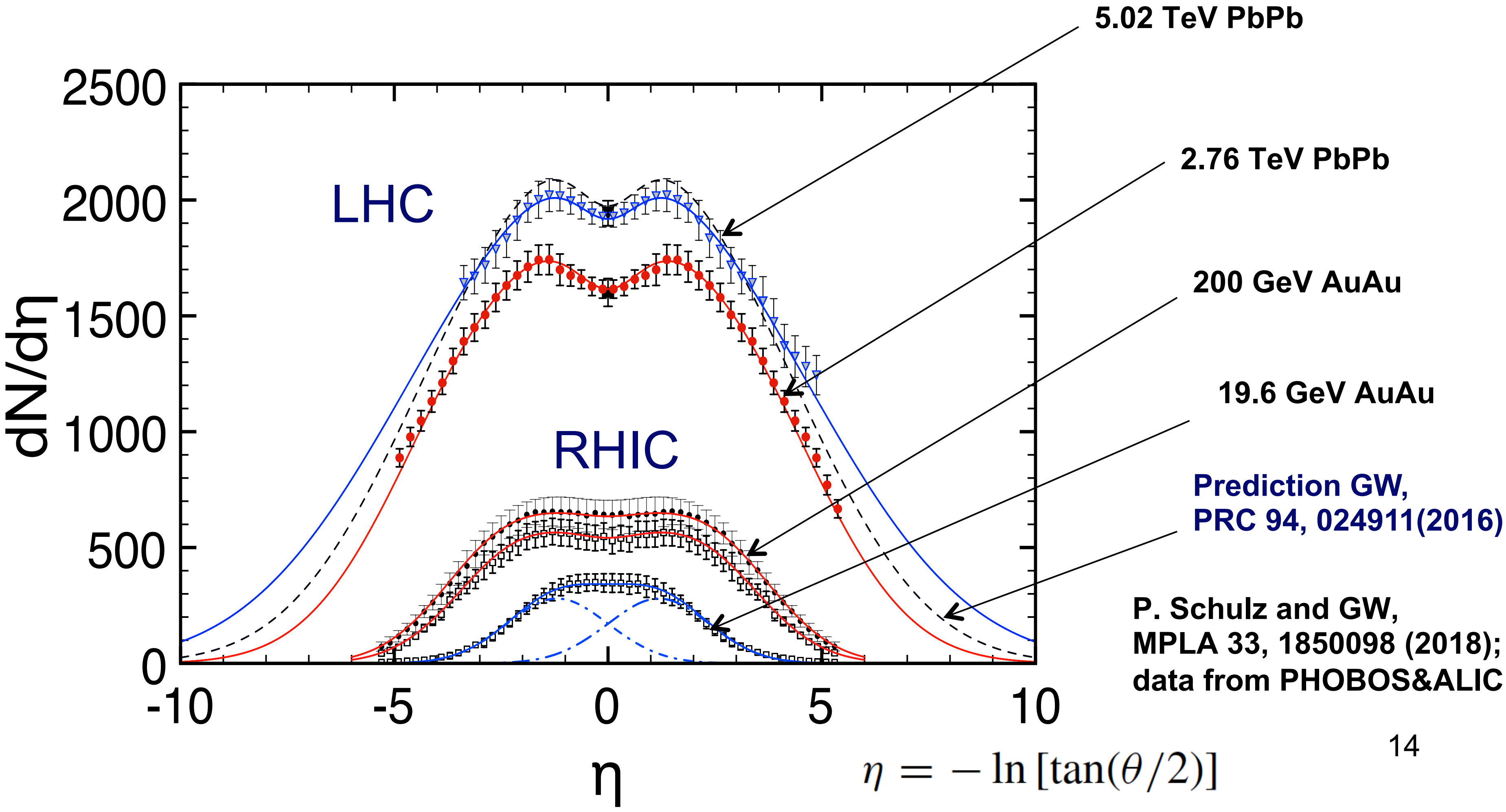
Fragmentation source 2

Fireball: low-x gluonic source, close to equilibrium

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 ~10^{-23} s

Produced charged hadrons in central collisions

New ALICE data from **central 5.02 TeV Pb-Pb** collisions included

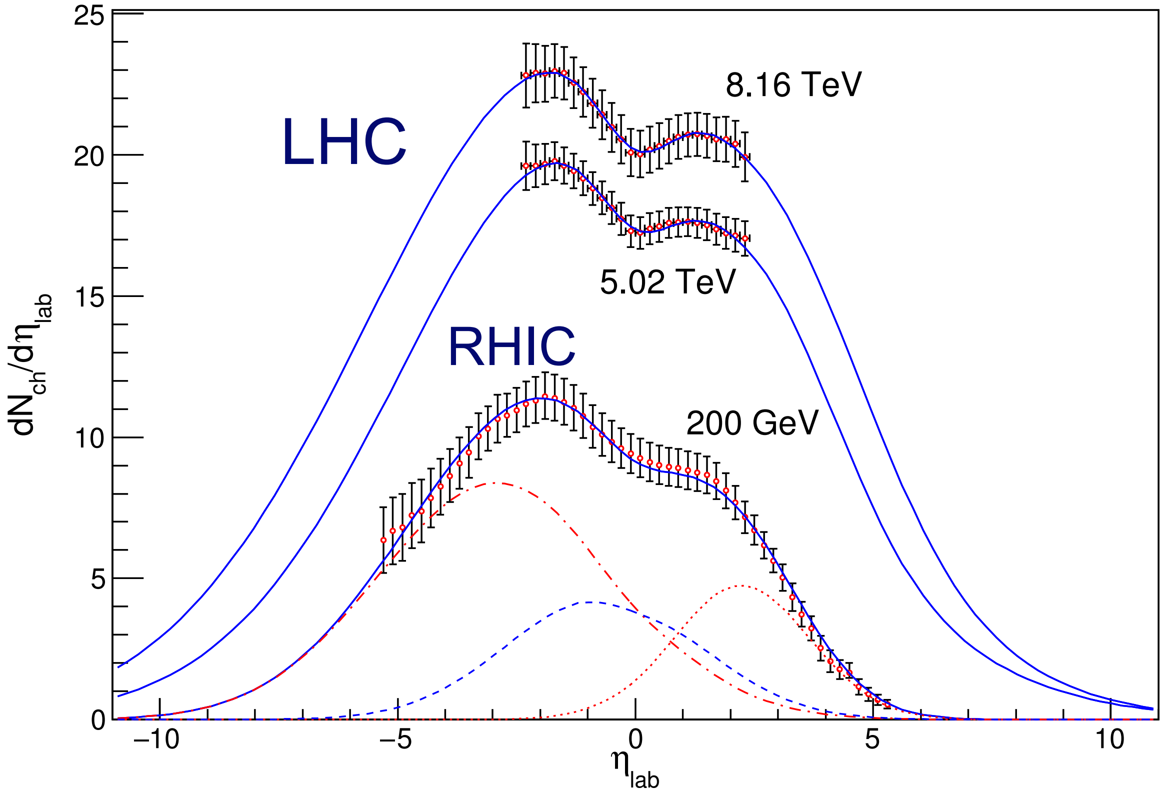


P. Schulz and GW,
MPLA 33, 1850098 (2018);
data from PHOBOS&ALICE

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

Produced charged hadrons in central collisions

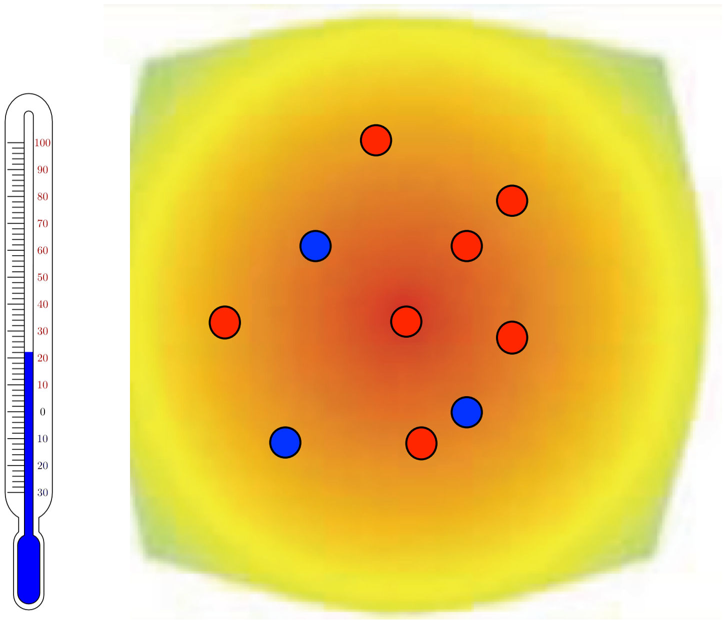
CMS data from min. bias **5.02/ 8.16 TeV p-Pb**,
PHOBOS data from **200 GeV d-Au**



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

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

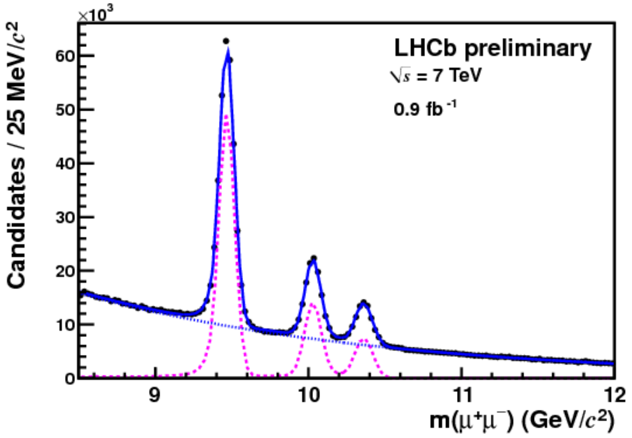
Produced heavy quarkonia in the QGP



● $J/\psi\ (c\bar{c})$

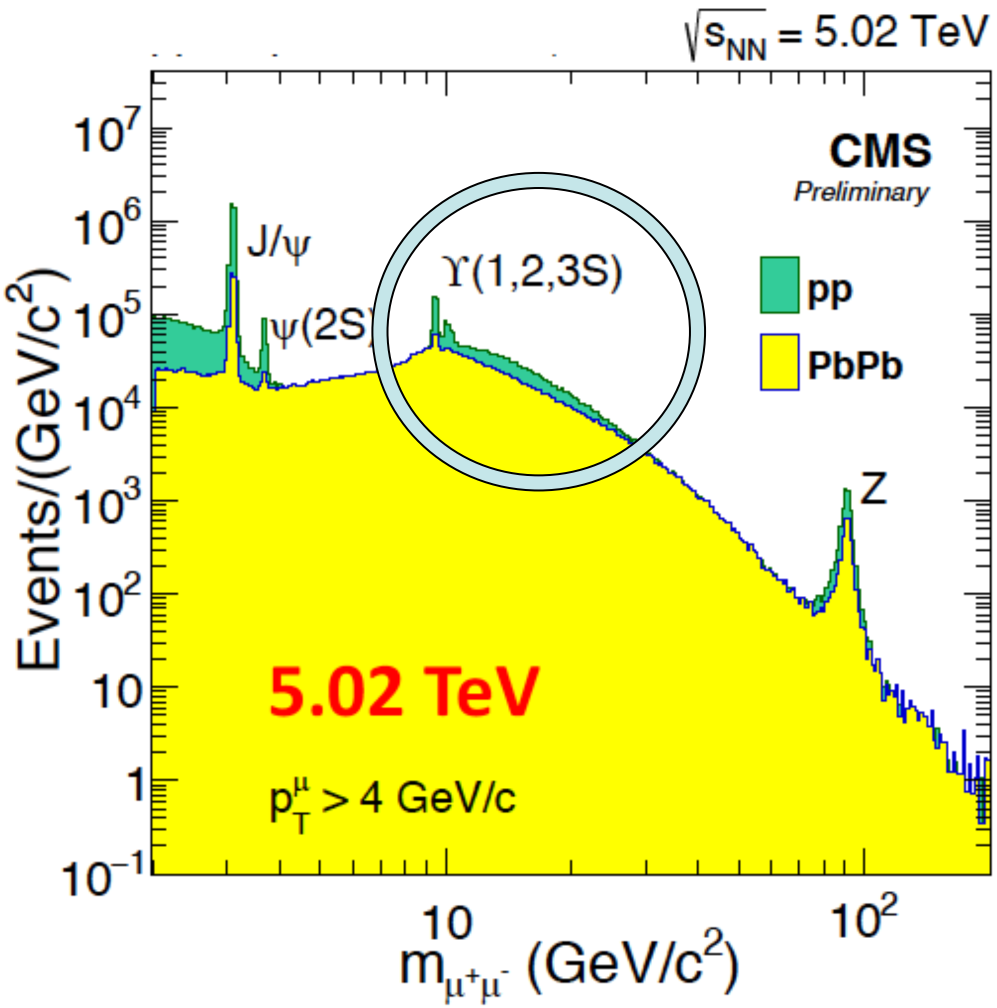
● $\Upsilon\ (b\bar{b})$

- **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

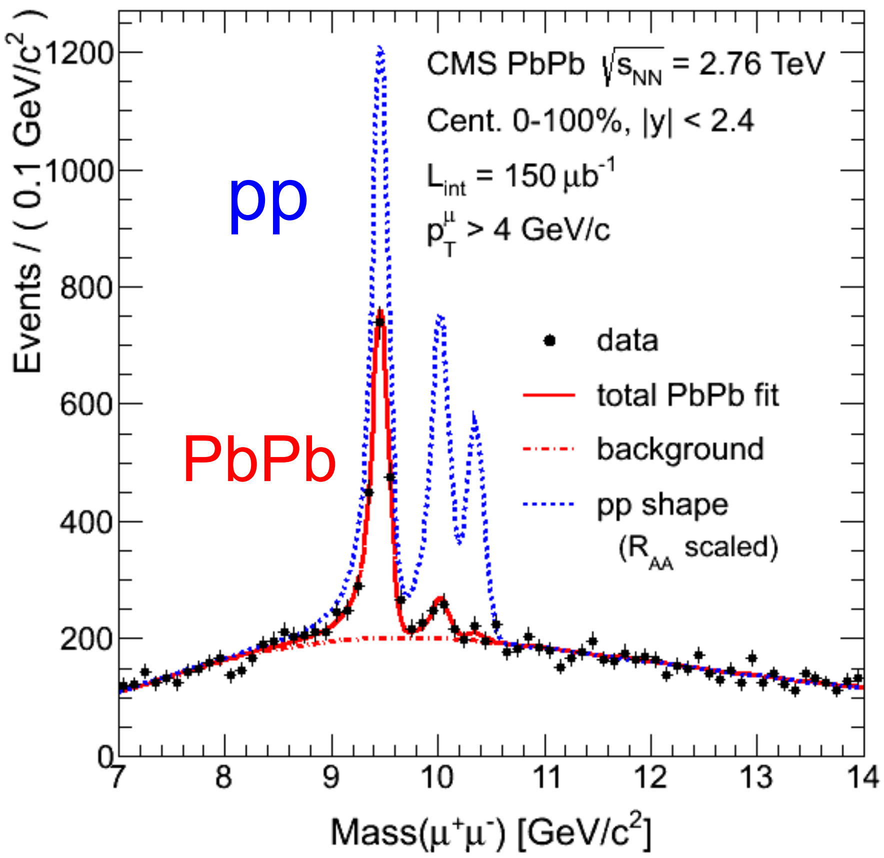
- No significant effect of regeneration
- $m_b \approx 3m_c$ ⇨ cleaner theoretical treatment
- More stable than J/ψ

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

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

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 Y(1S)

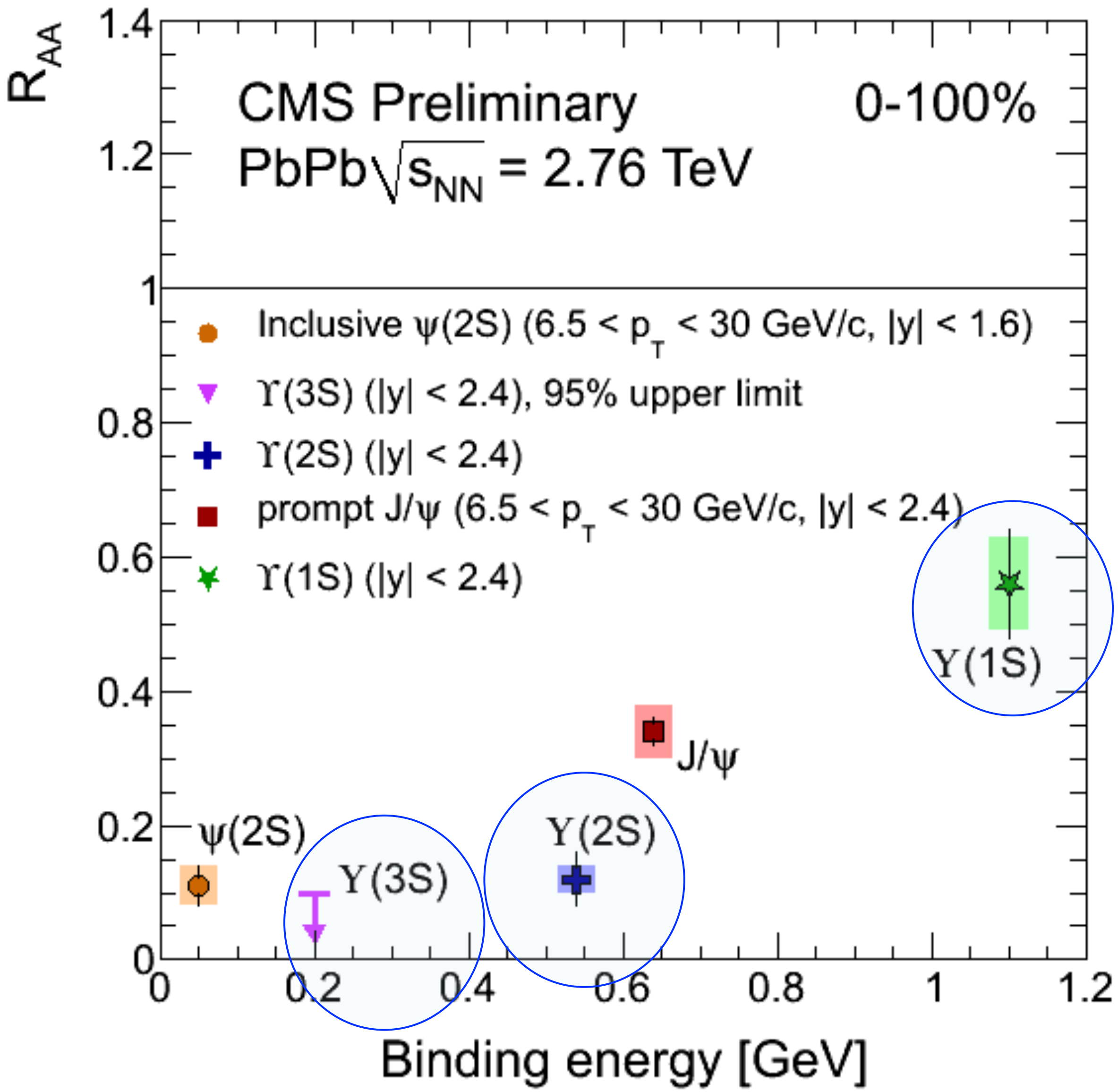
R_{AA}(Υ(2S)) = 0.12 ± 0.04 (stat.) ± 0.02 (syst.)

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]

Successive suppression of ϒ(nS) and J/y states



Min. bias

© G. Roland / CMS

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

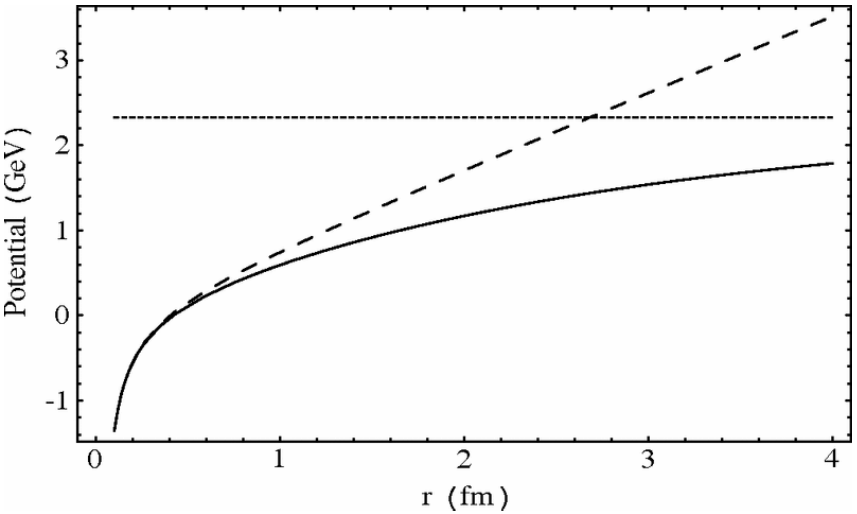
③ Gluon-induced dissociation: dynamic suppression, in particular of the Υ(1S) ground state due to the large thermal gluon density

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

F. Vaccaro, F. Nendzig and GW, Europhys.Lett. 102, 42001 (2013); J. Hoelck and GW, EPJA 53, 37 (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)

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

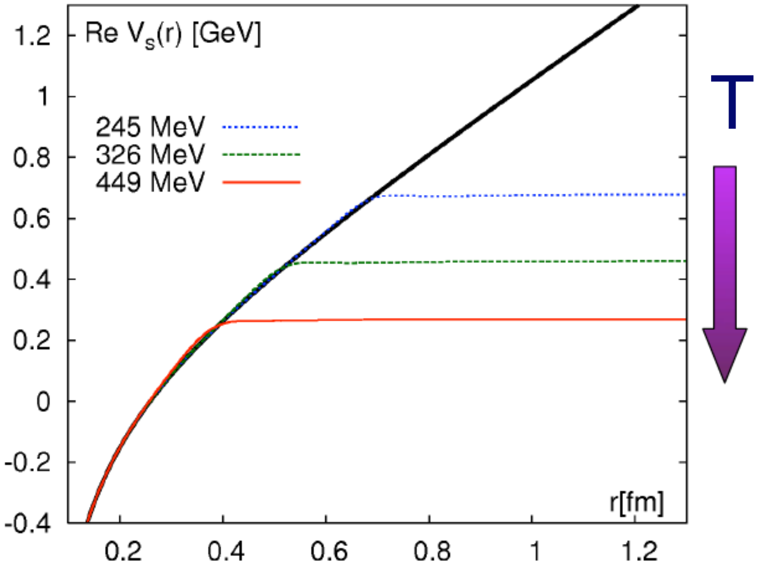
=> Heavy mesons can “melt” in the hot medium

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

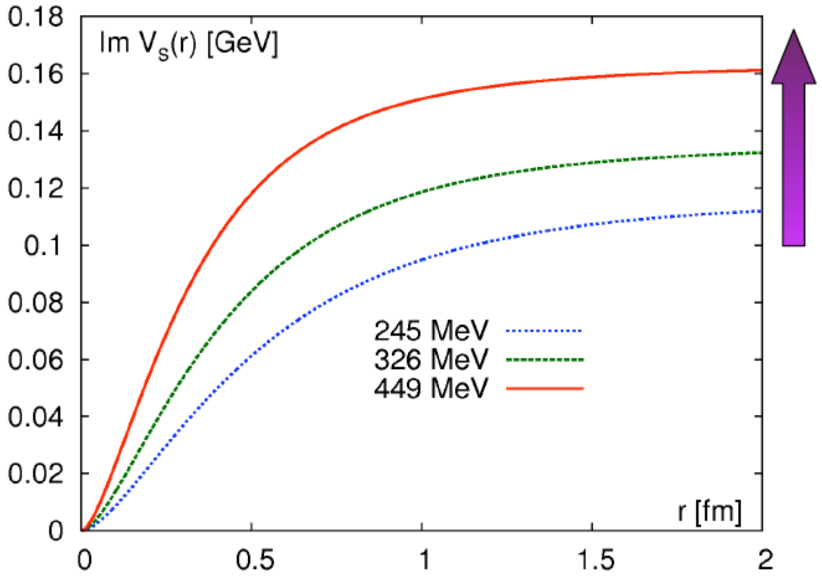
Maximal value



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

Screening and damping in a nonrelativistic potential model

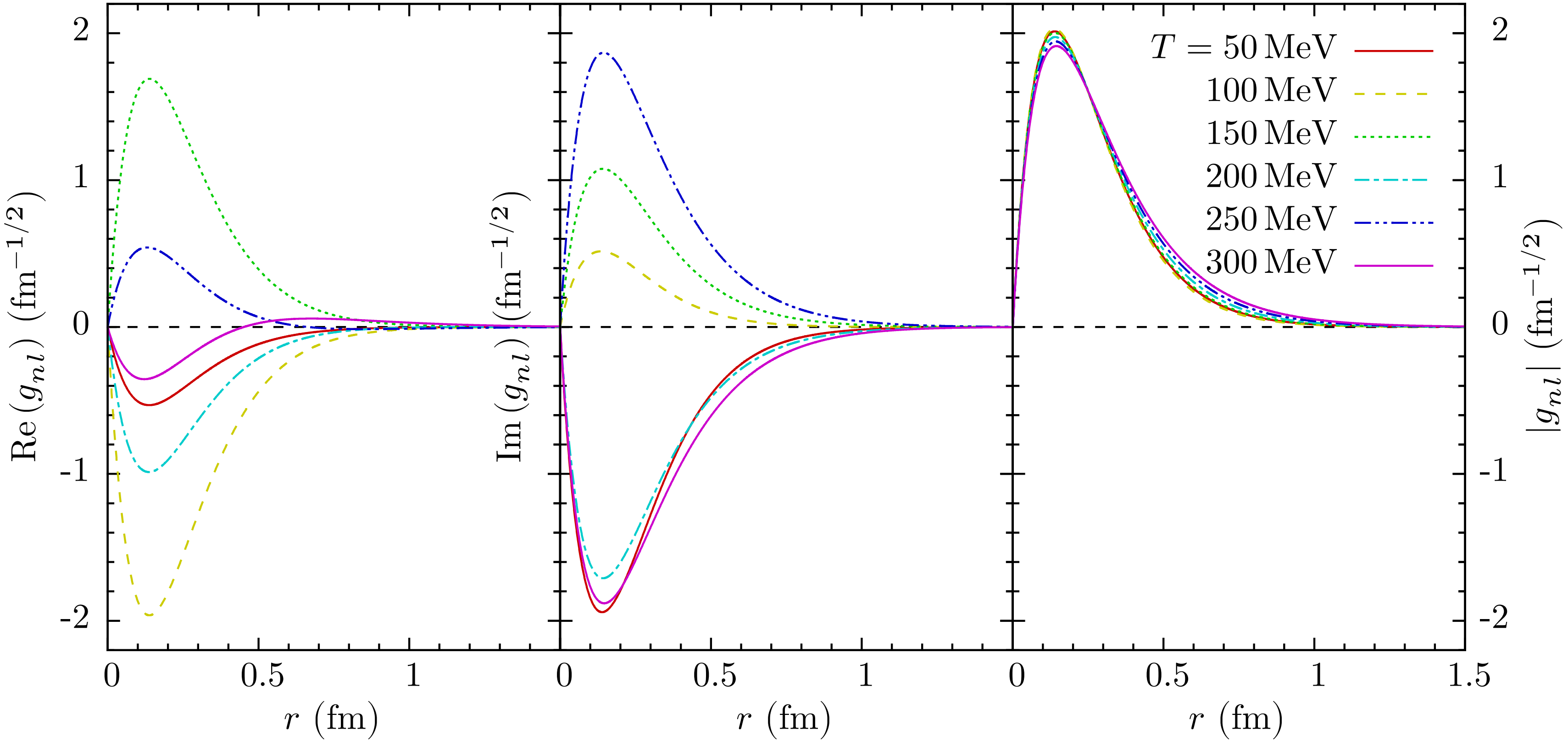
$$V_{nl}(r,T) = -\frac{\sigma}{m_D(T)} e^{-m_D(T)r} - C_F\alpha_{nl}(T)\left(\frac{e^{-m_D(T)r}}{r} + iT\phi(m_D(T)r)\right)$$

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

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

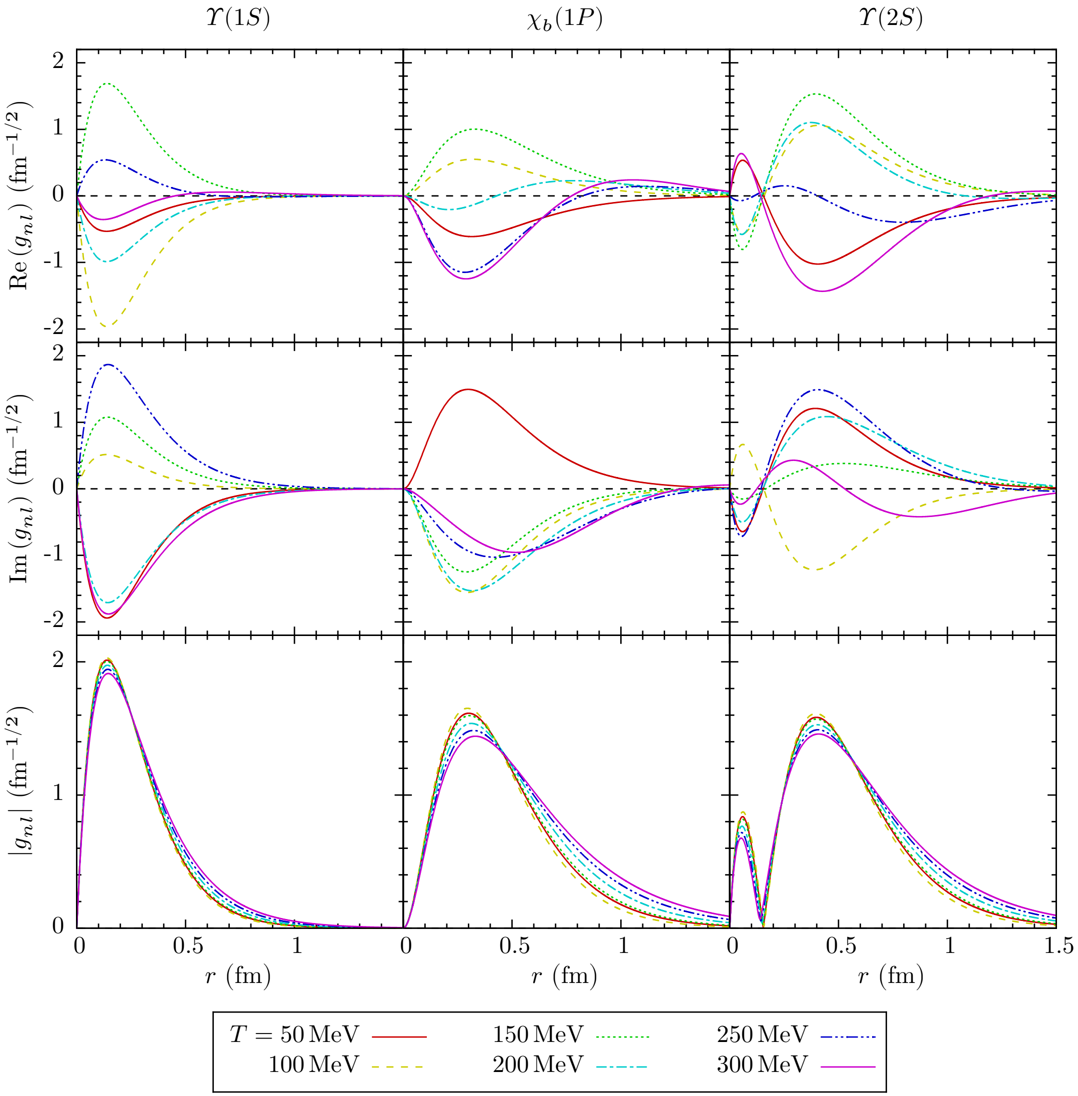
Radial wave function of $\Upsilon(1S)$ at temperatures T

Solutions of the Schödinger equation with complex potential V(r,T,α_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

Radial wave functions of Υ(nS), X_b(nP) states



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

Υ(nS), χ_b (nP), n = 1, 2, 3

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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)

$$\sigma^{nS}_{diss}(E) = \frac{2\pi^2\alpha_s E}{9}\int\limits_0^\infty dk\,\delta\left(\frac{k^2}{m_b} + \epsilon_n - E\right)|w^{nS}(k)|^2$$

$$w^{nS}(k) = \int_0^\infty dr\, r\, g^s_{n0}(r) g^a_{k1}(r)$$

for the Gluodissociation cross section of the Y(nS) states, and correspondingly for the χ_b(nP) states.

Gluodissociation cross section

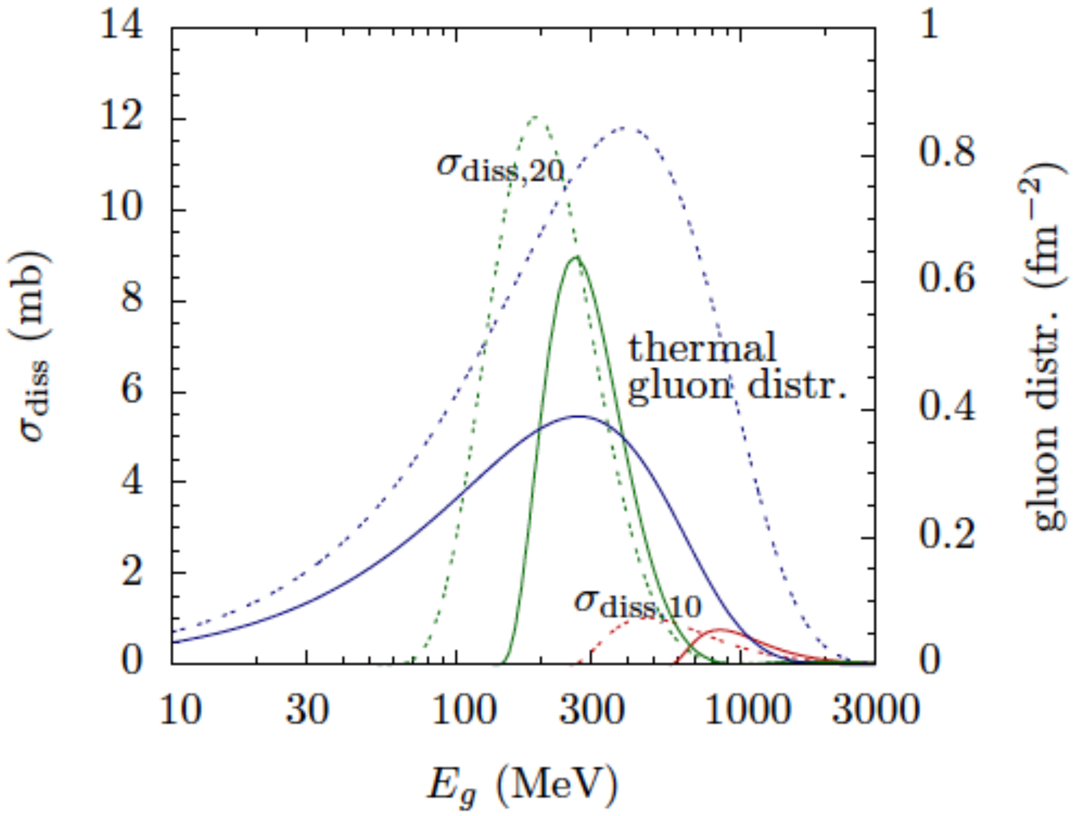


Figure 3. Gluodissociation cross section σ_{diss} (left scale) of the $\Upsilon(1S)$ and $\Upsilon(2S)$ and the thermal gluon distribution (right scale) plotted for temperature $T = 170$ (solid curves) and 250 MeV (dotted curves) as functions of the gluon energy E_g.

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

Thermal gluodissociation cross section

Average the gluodissociation cross section over the Bose-Einstein distribution of the thermal gluons in the QGP to obtain the dissociation width at temperature T for each of the six bottomia states involved

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

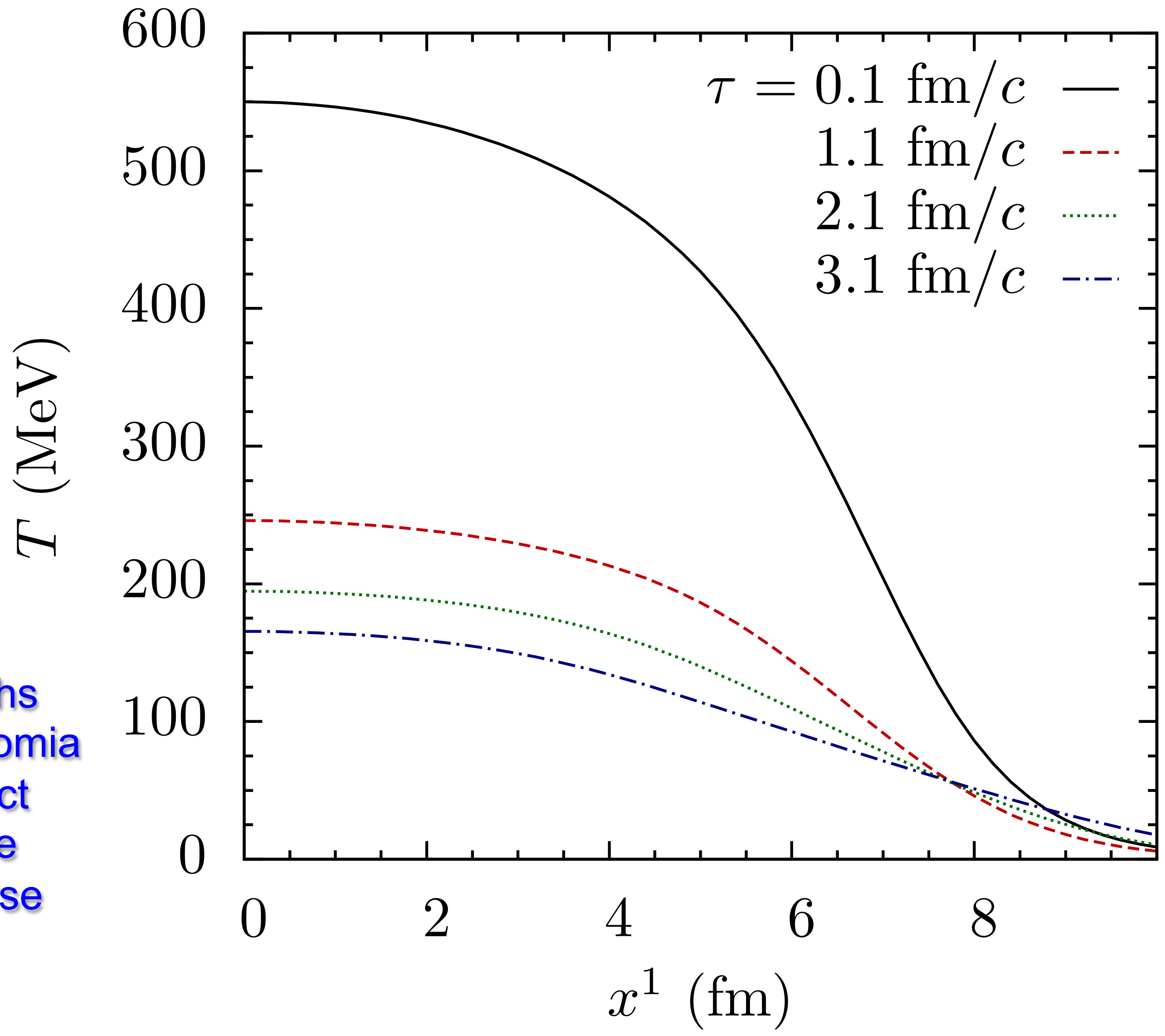
($g_d = 16$)

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

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

Hydrodynamic expansion (ideal)

Temperature profile for central collisions at different times τ



Use total decay widths $\Gamma_{tot}(b,x,y)$ of the bottomia states for each impact parameter b and time step t in the transverse (x^1,x^2) plane

Dynamical fireball evolution

Dependence of the local temperature T on impact parameter b, time t, and transverse coordinates x, y evaluated in ideal hydrodynamic calculation with transverse expansion

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

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

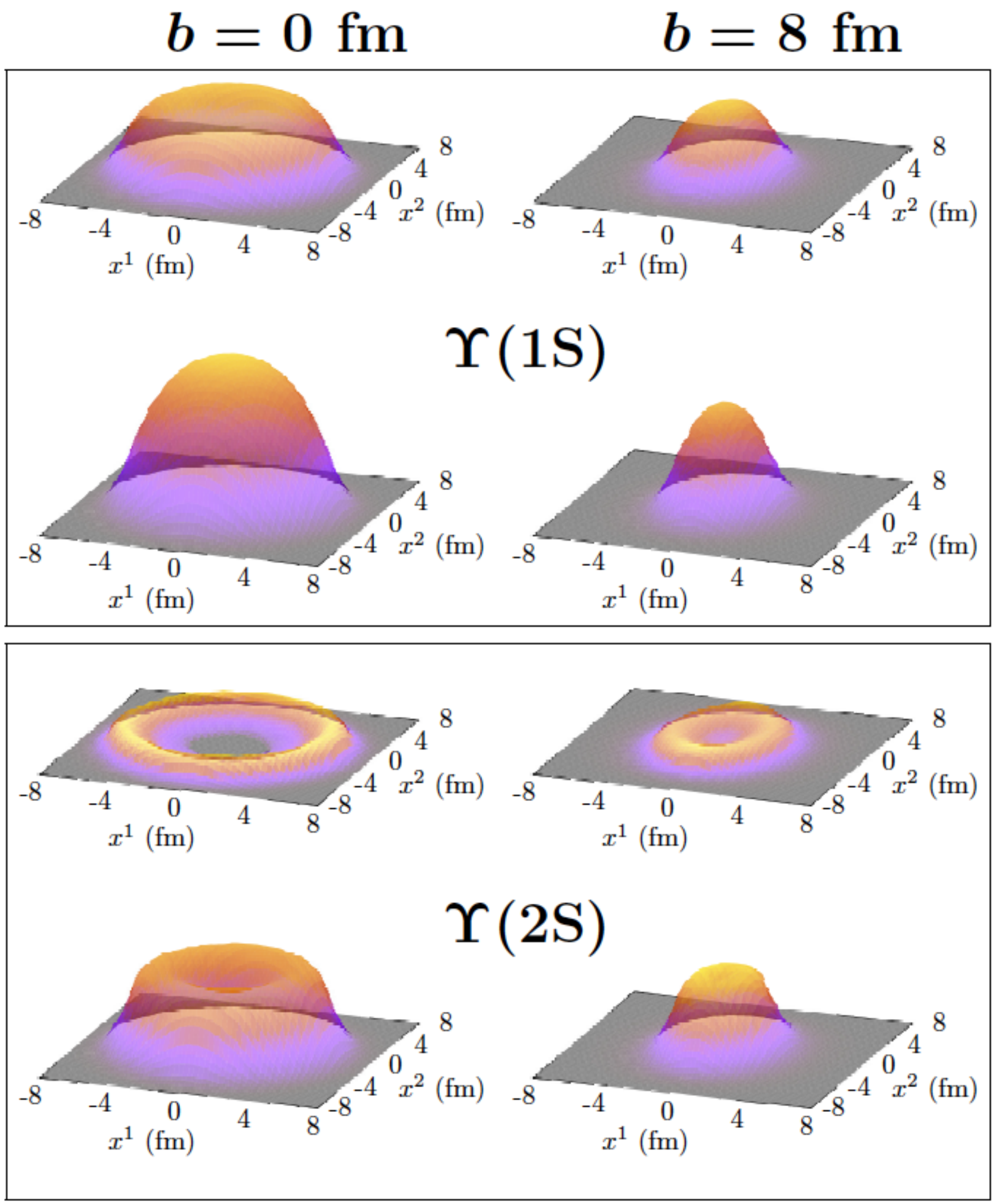
The number of produced $b\bar{b}$ -pairs is proportional to the number of binary collision, and the nuclear overlap

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

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

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

Integrand in the transverse plane



$p_T = 0$

$p_T = 12$ GeV/c

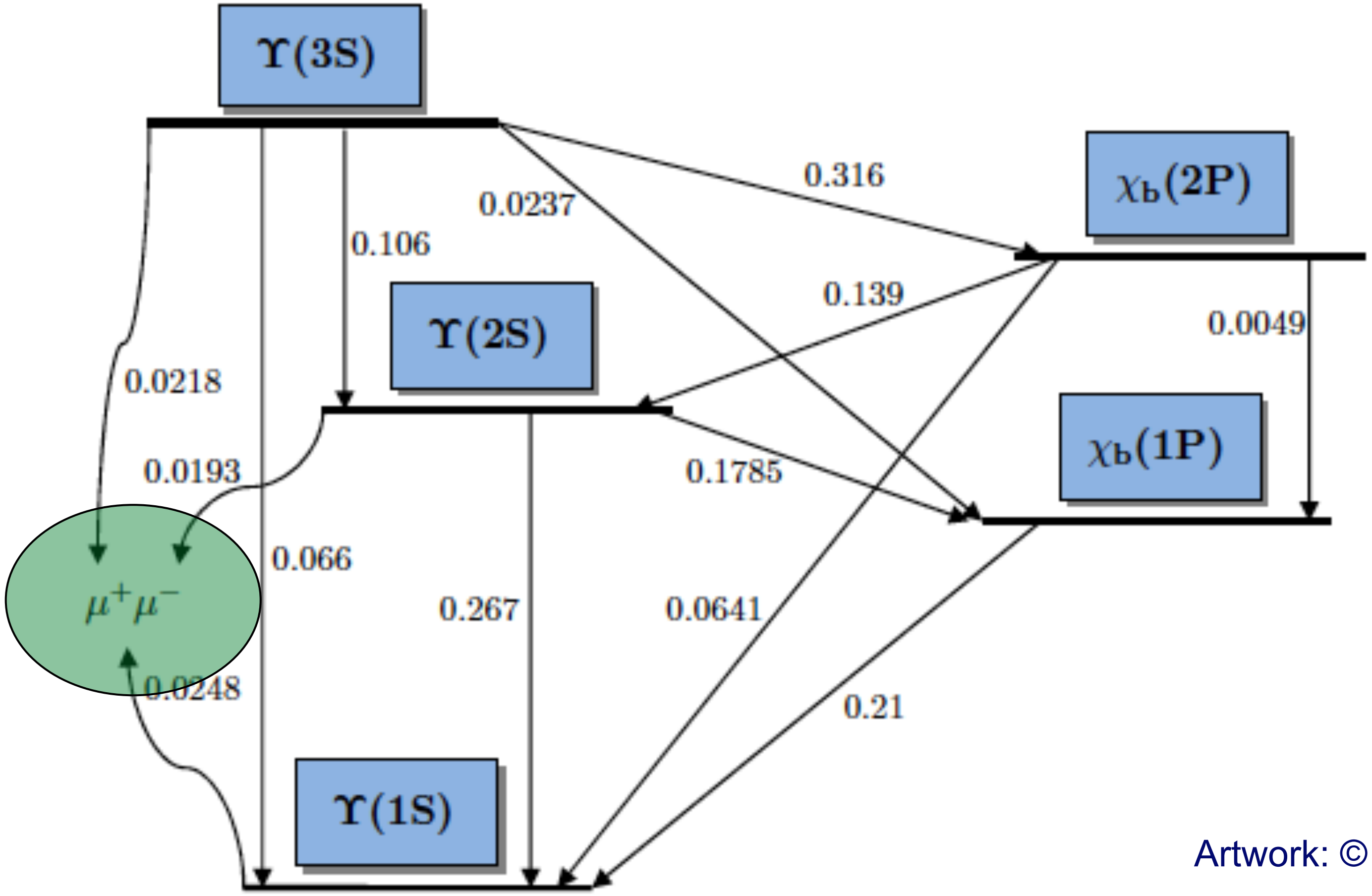
$p_T = 0$

$p_T = 12$ GeV/c

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

Feed-down cascade

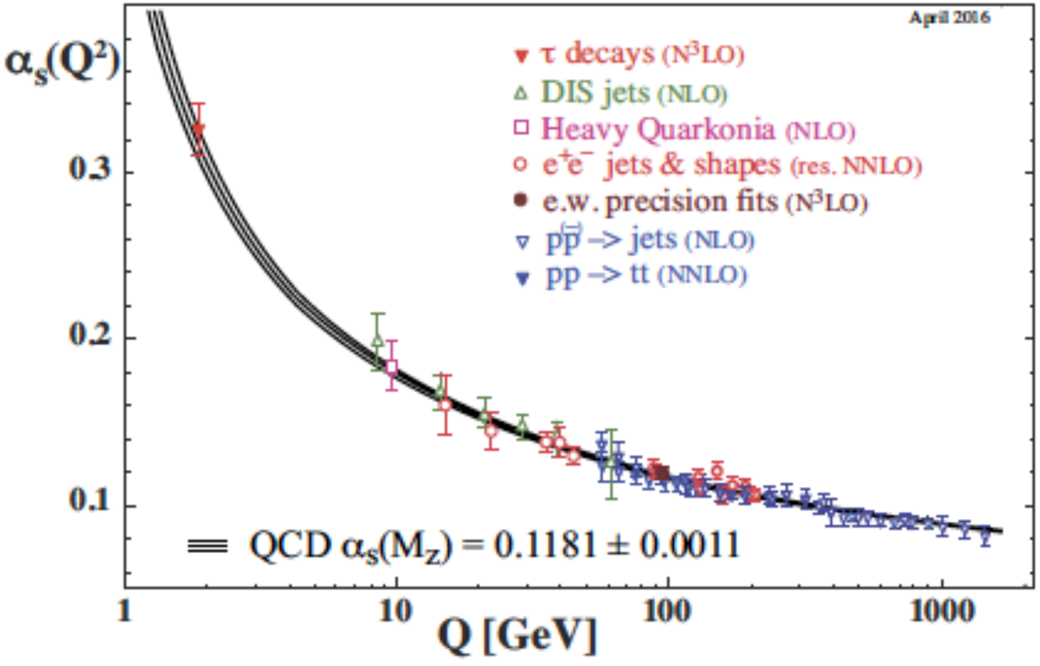
Feed-down is reduced if excited states are screened or depopulated



Artwork: © Simone Nendzig

FIG. 6. (Color online) Branching ratios for decays within the bottomium family $\Upsilon(nS)$ and $\chi_b(nP)$ and into $\mu^{\pm}$-pairs according to [28].

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

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

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

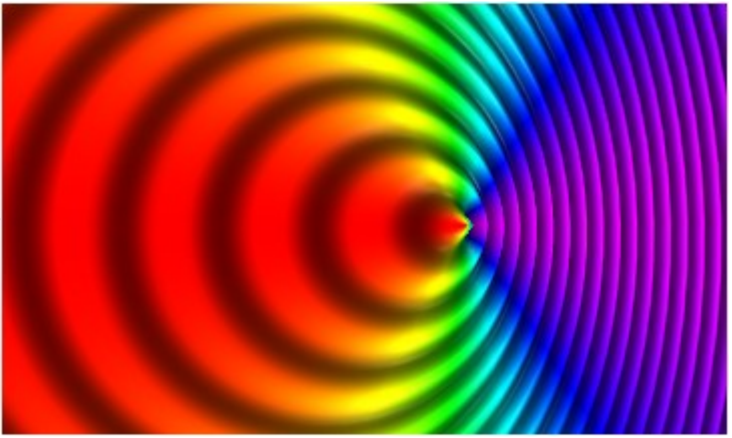
$\alpha_{nl}(T)=\alpha_s[\langle 1/r\rangle_{nl}(T)]$ depends on the solution $g_{nl}(r,T)$ of the Schrödinger eq.: Iterative solution

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

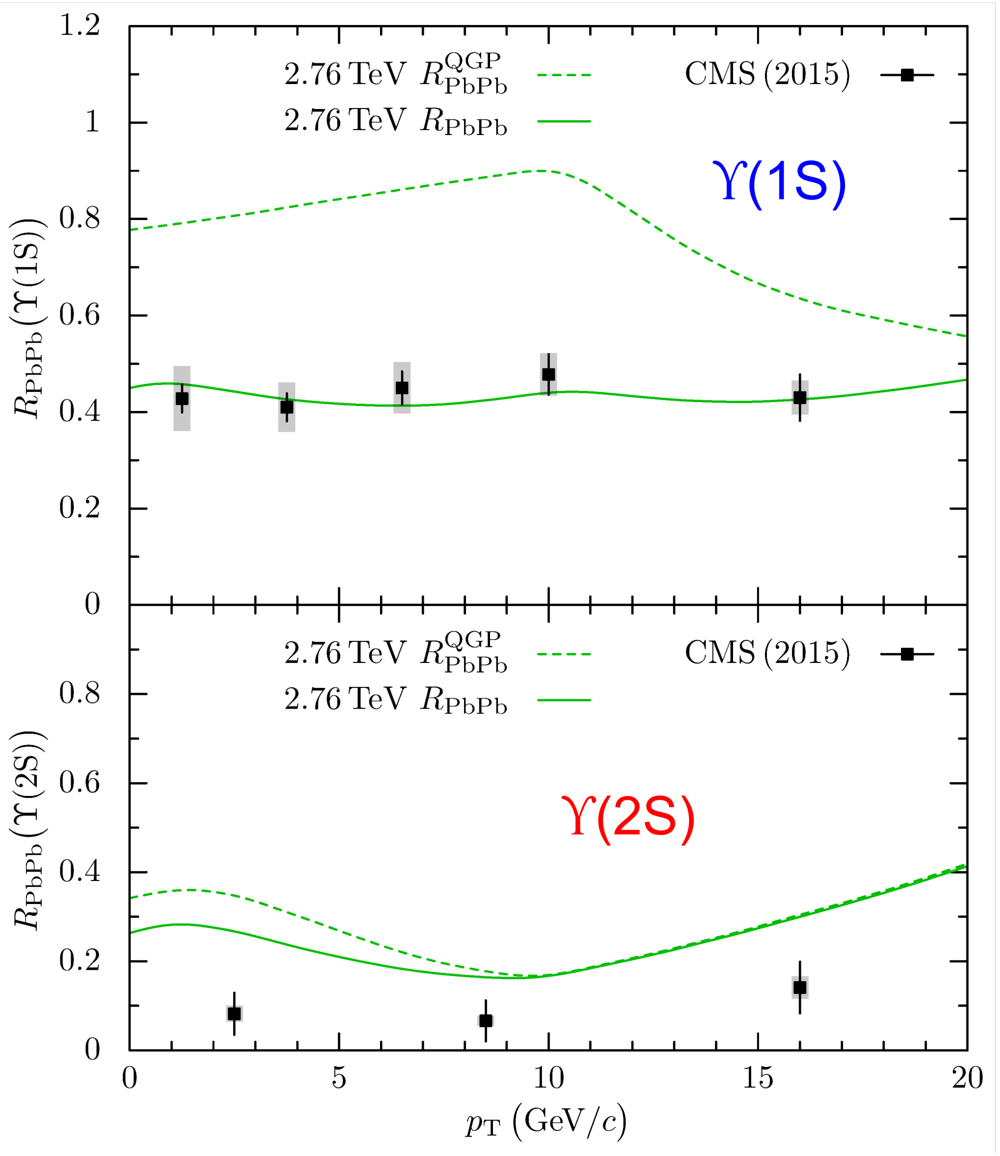
θ = 0°, blueshift

u = 0.7 c

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

Selected results

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

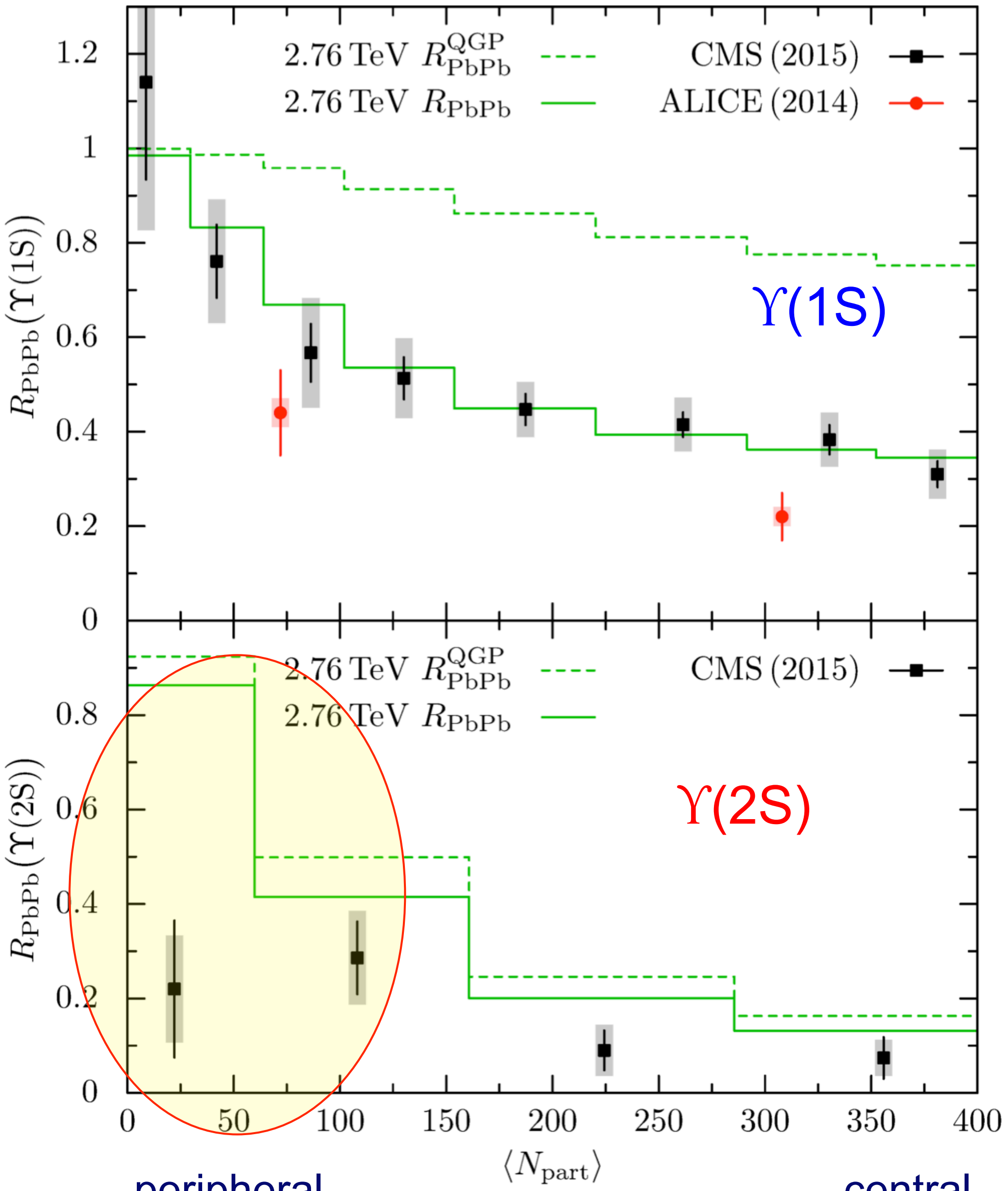
🡐 Including reduced feed-down

(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 data: CMS and ALICE



peripheral central

2.76 TeV PbPb LHC

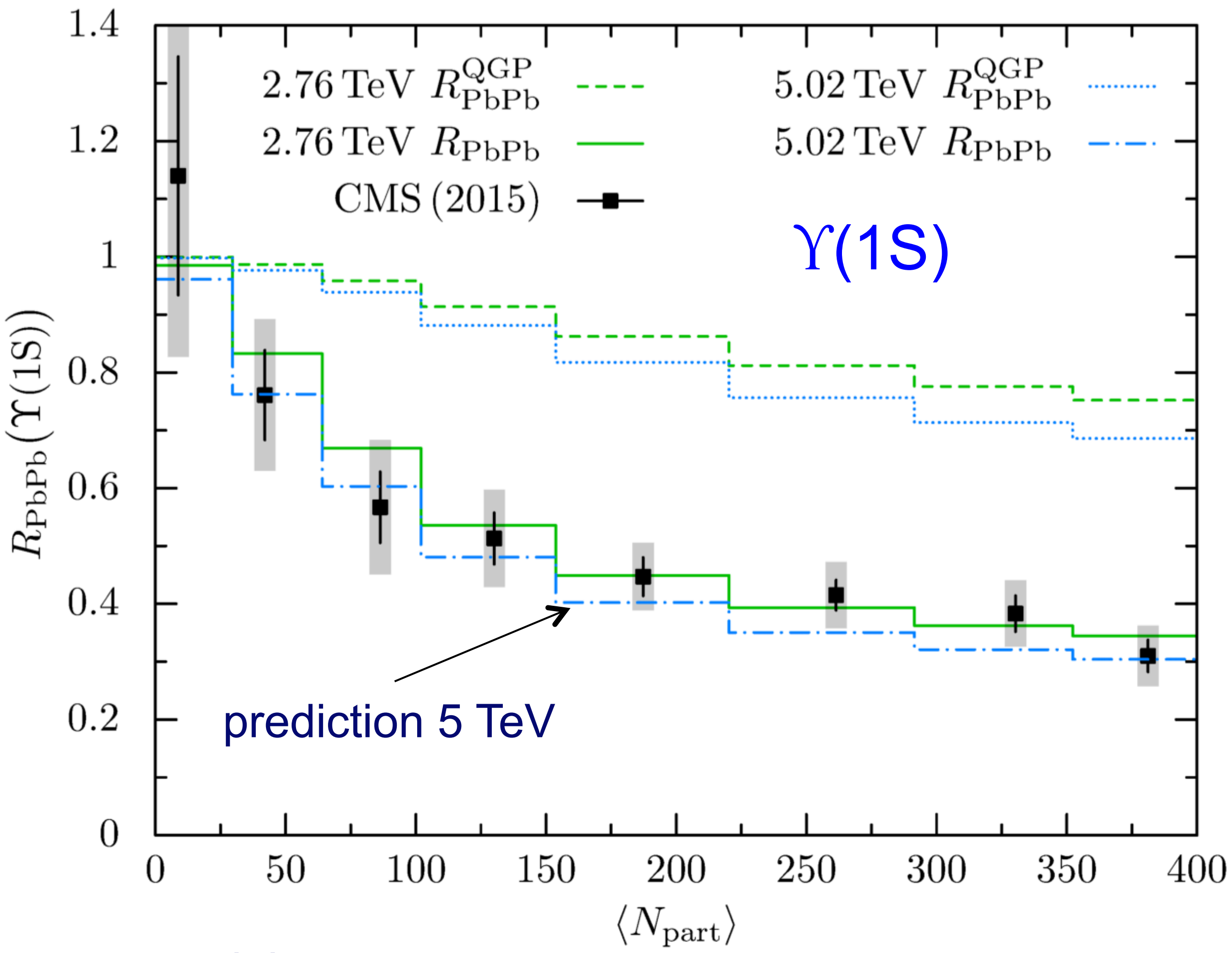
t_F= 0.4 fm/c: Υ formation time

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 insufficient; direct pions may contribute, and magnetic dissociation.

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

Prediction for Υ(1S) suppression at 5.02 TeV PbPb



prediction 5 TeV

peripheral

central

T_{max} @ t_F: 513 MeV

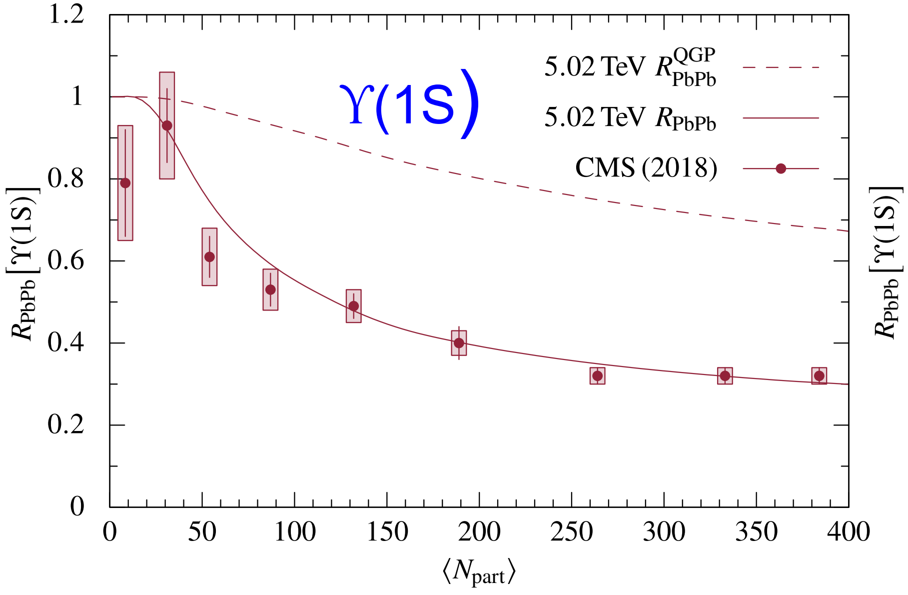
t_F= 0.4 fm/c

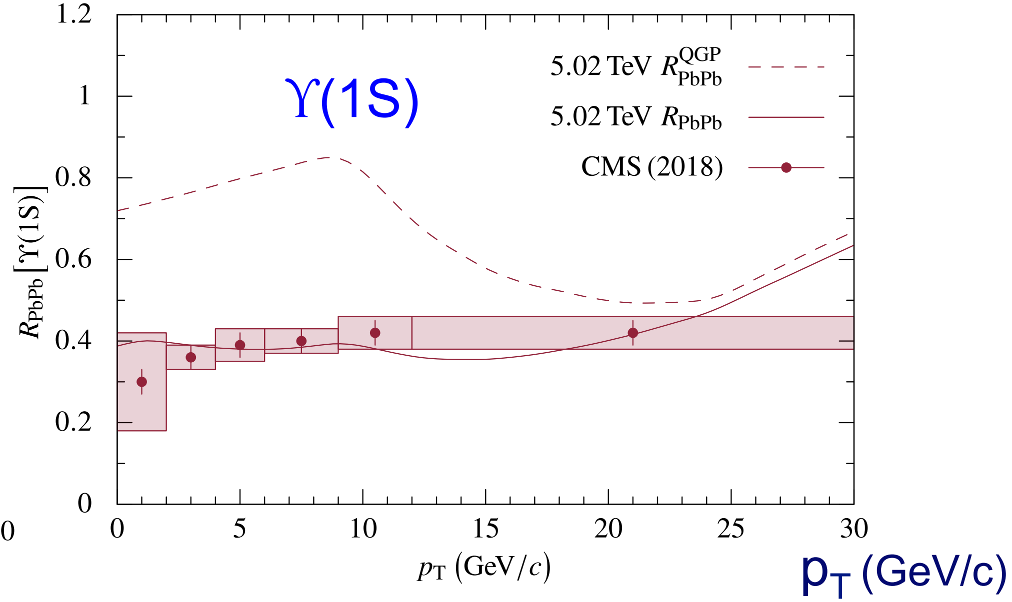
$$s_0 \propto dN_{ch}/d\eta \propto T_0^3$$

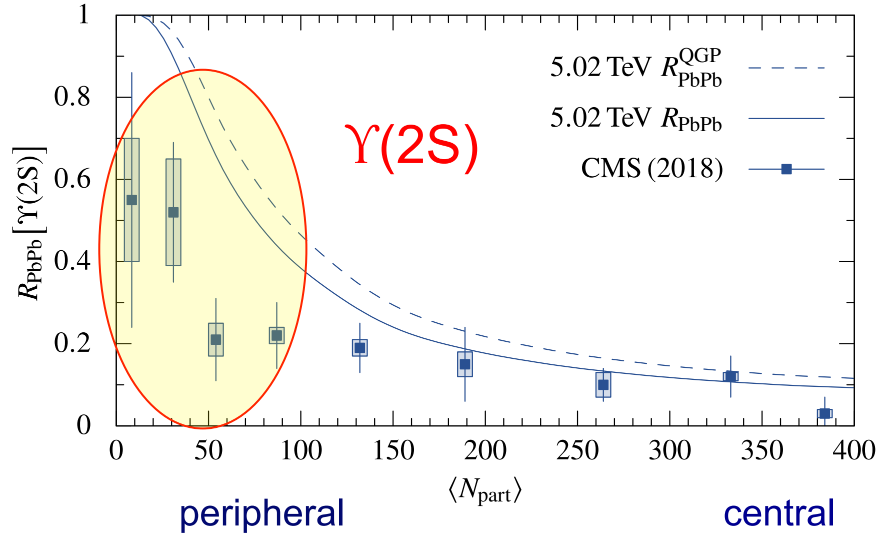
with reduced feed-down
<10% higher suppression at
5.02 TeV vs 2.76 TeV, within
experimental error bars

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

Prediction for ϒ suppression at 5.02 TeV 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 QM2018, Venice

Conclusion

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

Thank you for your attention !