1.12.13

The Quarkonium Analysis of the QGP

Helmut Satz

Universität Bielefeld, Germany

SaporeGravis, Nantes **December 2013**

What can we use as QGP Thermometer?

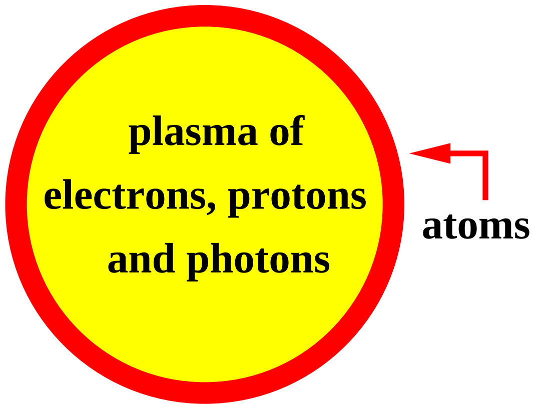
hadron abundances $\Rightarrow$ hadronization stage of QGP

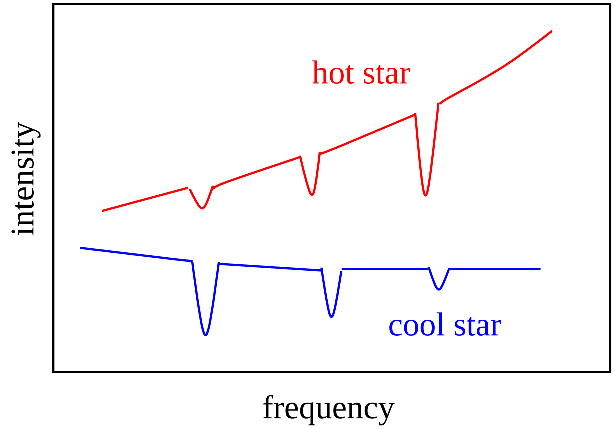
$\exists$ probe of earlier hot QGP,
not accessible to direct measurements?

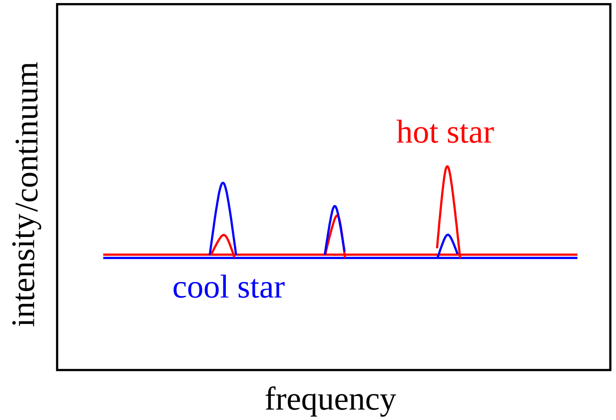
$\exists$ a similar problem in astrophysics:

How does one measure temperatures of stellar interiors?

photons from plasma core are emitted, absorbed by atoms in crust, lead to absorption lines in stellar spectra







- absorption lines indicate presence of atomic species
- absorption strength gives temperature of stellar interior

Conjecture: Quarkonia are the spectral lines of the QGP

Matsui & HS, 1986

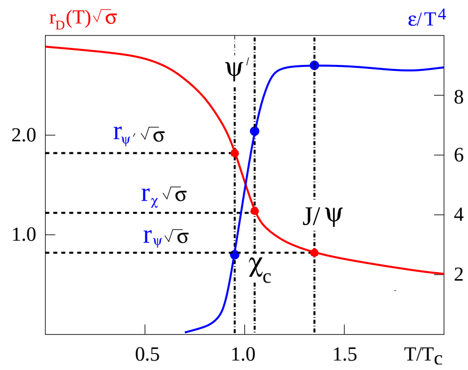
∃ no crust of QGP, but ∃ early hard production of quarkonia

they're there when QGP appears, and its effect on different quarkonium states tells how hot the QGP is.

Quarkonia in a hot QGP

- QGP consists of deconfined color charges, hence
  $\exists$ color screening for $Q\bar{Q}$ state
- screening radius $r_D(T)$ decreases with temperature T
- if $r_D(T)$ falls below binding radius r_i of $Q\bar{Q}$ state i,
  Q and $\bar{Q}$ cannot bind, quarkonium i cannot exist
- quarkonium dissociation points T_i, from $r_D(T_i) = r_i$,
  specify temperature of QGP

when force range/screening radius become less than binding radius, Q and $\bar{Q}$ cannot "see" each other



$\Rightarrow$ quarkonium dissociation points
determine temperature $\Rightarrow$ energy density of medium

calculate quarkonium dissociation temperatures:

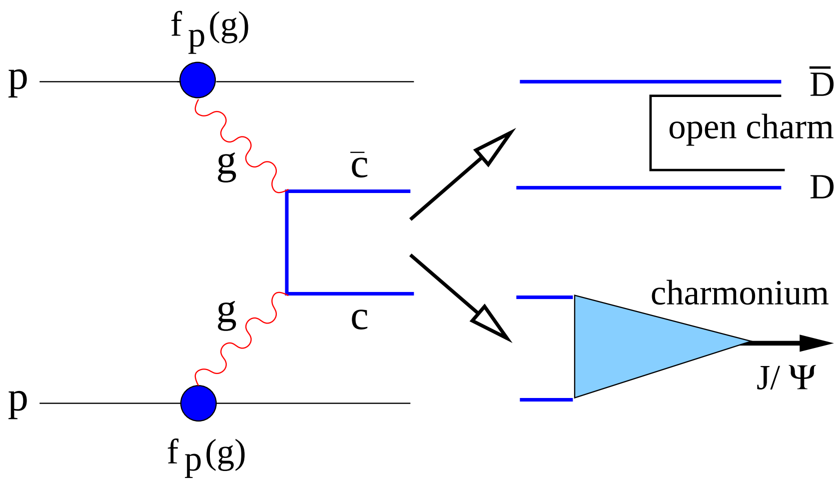
- determine heavy quark potential $V(r, T)$ in finite temperature QCD, solve Schrödinger equation
- calculate in-medium quarkonium spectrum $\sigma(\omega, T)$ directly in finite temperature lattice QCD

Tentative present summary:

- Υ survives up to $T \geq 4\ T_c$
- $J/\psi, \Upsilon', \chi_b$ survive up to $T \simeq 1.5\ T_c$
- $\chi_c, \psi', \Upsilon''$ dissociated at or slightly above T_c

apply to quarkonium production in nuclear collisions

Schematic: charm production in hadron-hadron collisions:



Find:

– **fixed partitioning of total $c\bar{c}$ into open and hidden charm:**

$$\sim 90\% \text{ open}, \sim 10\% \text{ hidden}$$

– **fixed partitioning of hidden charm into different charmonia**

$$\sigma_{hh\to J/\psi}(s) = g_{c\bar{c}\to J/\psi}\,\sigma_{hh\to c\bar{c}}(s) \quad \text{(color evaporation)}$$

– fixed partitioning of open charm into different D etc.

$$\sigma_{hh\to D^+}(s) = g_{D^+}\,\sigma_{hh\to c\bar{c}}(s) \quad \text{(statistical hadronisation)}$$

– observed J/ψ receives feed-down from higher excitations

60 % direct (1S), 30 % from χ_c(1P), 10 % from ψ'(2S)

similar pattern for bottomonia; basic question:

how are these pp features modified in AA collisions?

NB: the production dynamics in AA collisions is different from that in pp collisions !

- initial state effects

  pdf modification (shadowing, antishadowing)

  energy loss of incident parton (gluon)

- final state effects

  energy loss of primary $c\bar{c}$

  cold nuclear matter effect on (nascent) charmonium

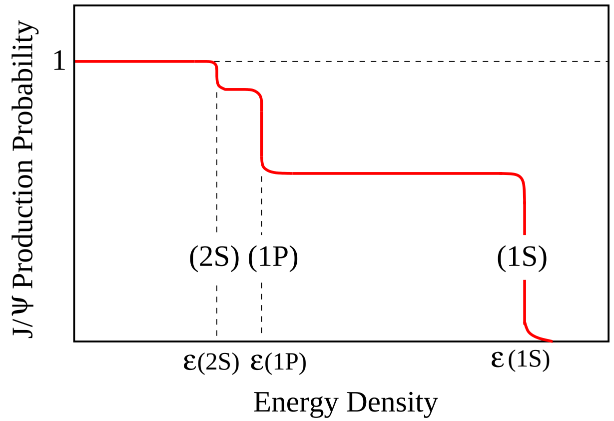
  secondary matter effect on (nascent) charmonium

  what do we expect?

Theoretical Scenarios

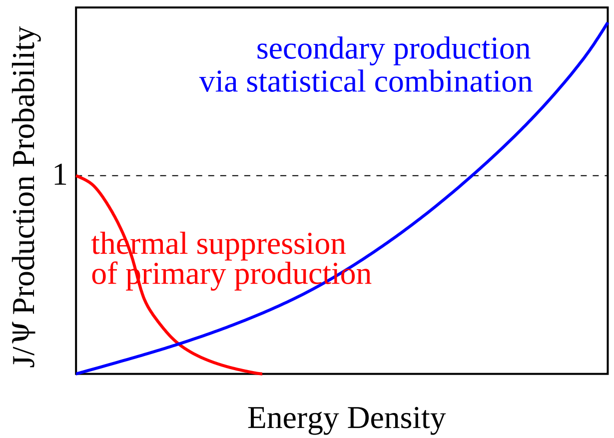
- sequential suppression

  color screening dissociates charmonium states in QGP first higher excited states (2S), (1P), then ground state (1S)



- <u>statistical enhancement</u>

  all primary charmonia dissociated at high collision energy, overabundance of charm quarks equilibration, $c\bar{c}$ excess survives hadronisation by statistical combination



What is <u>J/ψ production probability?</u>

– both scenarios claim that presence of medium modifies the relative fraction of $c\bar{c}$ going into charmonia, vs. open charm;

– neither says anything about how many $c\bar{c}$ pairs are produced in AA relative to scaled pp.

more explicitly:

- if the total number of $c\bar{c}$ pairs produced in AA collisions is reduced by a factor two relative to scaled pp rates, but as before, 90 % go into open charm, 10 % into charmonia, then there is neither suppression nor enhancement of J/ψ production;
- the crucial question is what happens to the produced $c\bar{c}$ pairs, not how many there are to begin with; the medium can only affect those that are there.

Conclude:

the correct calibration is hidden to open charm, so that the relevant observable is

$$S_{J/\psi} = \left(\frac{N_{AA}(J/\psi)}{N_{AA}(c\bar{c})}\right) \Big/ \left(\frac{N_{pp}(J/\psi)}{N_{pp}(c\bar{c})}\right)$$

If measured over all phase space, in

$$N_{AA}(J/\psi)/N_{AA}(c\bar{c}),$$

initial state effects cancel out, can check if different from

$$N_{pp}(J/\psi)/N_{pp}(c\bar{c})$$

i.e., if the medium has had an effect on charmonium binding.

Using "nuclear modification factors"

$$R_{AA}(J/\psi) = N_{AA}(J/\psi)/n_c N_{pp}(J/\psi)$$

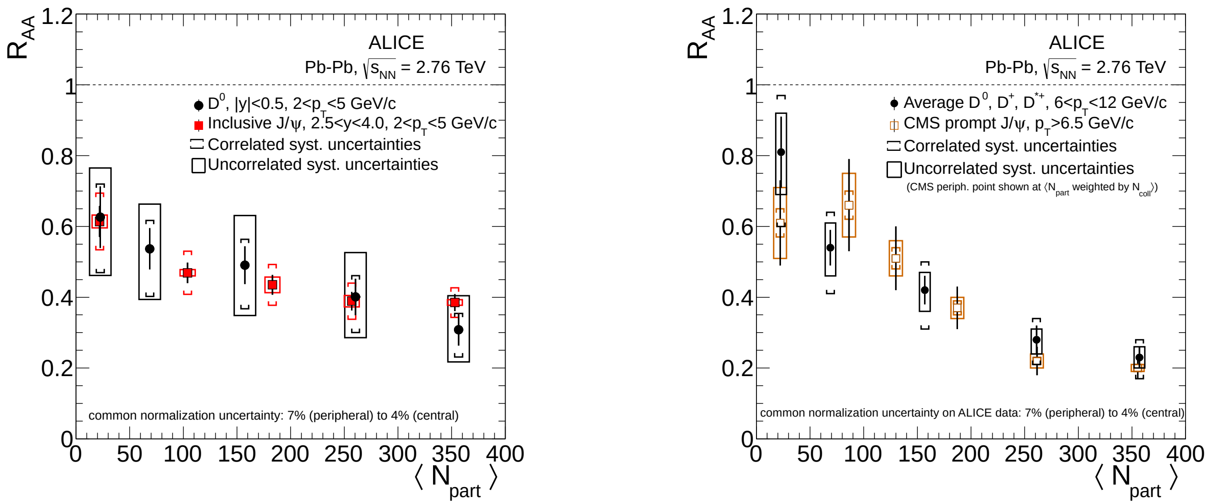
$$R_{AA}(c\bar{c}) = N_{AA}(c\bar{c})/n_c N_{pp}(c\bar{c})$$

correct J/ψ production probability thus is $S_{J/\psi} = \dfrac{R_{AA}(J/\psi)}{R_{AA}(c\bar{c})}$

NB: the often used observable $R_{AA}(J/\psi)$ alone is at best inconclusive, at worst misleading: have to compare open to hidden charm!

Look at data – illustration only so far, kinematics...

LHC Data

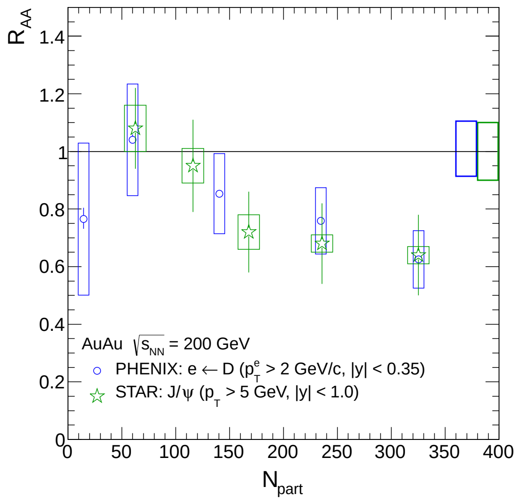


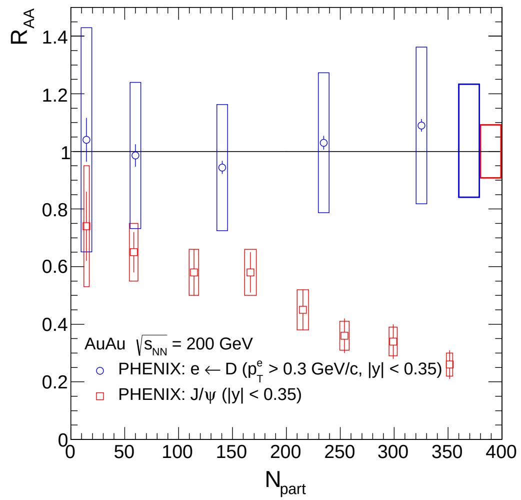
Data from ALICE & CMS: J/ψ vs. open charm production at intermediate & high transverse momenta (thanks to Zaida Conesa del Valle)

in AA, as many $c\bar{c}$ pairs make J/ψ as in scaled pp, but there just are fewer now to begin with

here neither J/ψ suppression nor enhancement; low P_T?

RHIC Data



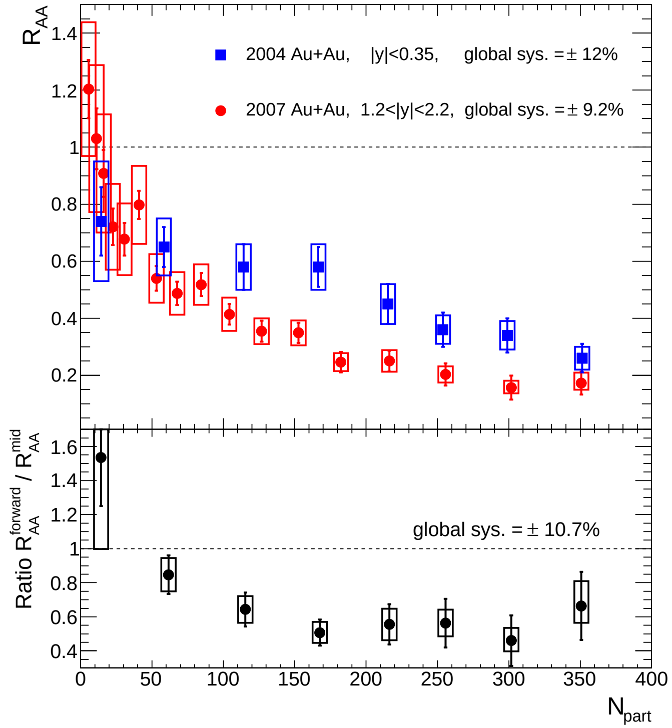


Data from PHENIX & STAR: J/ψ vs. open charm production at high & low transverse momenta (thanks to Torsten Dahms)

at high p_T, as at LHC;
at low p_T, up to 80 % J/ψ suppression:
here ∃ no medium effect on $c\bar{c}$ production,
only on charmonium binding.

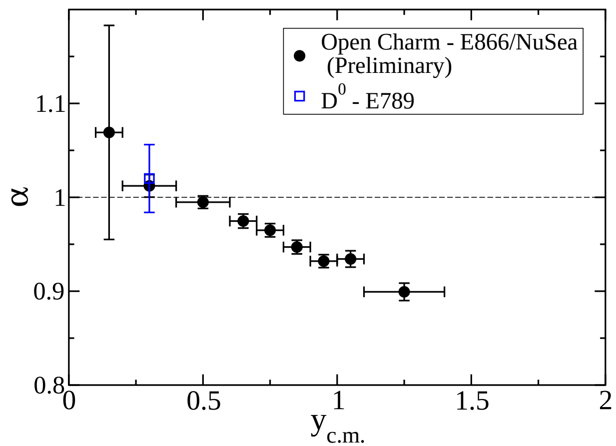
Complementary aspect: so-called “RHIC puzzle”

“more J/ψ suppression” in forward than in central production, based on R_{AA}



Could it be that there are just fewer $c\bar{c}$ pairs produced at forward than at mid rapidity?

Check by looking at open charm production in pA collisions



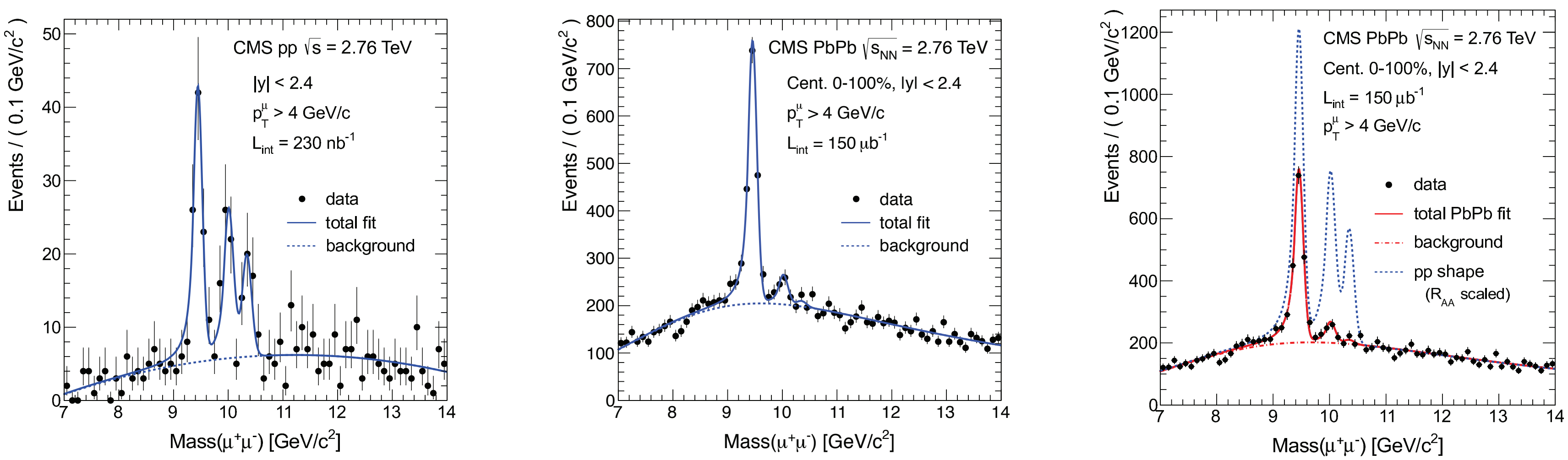
Rapidity dependence of open charm production in $\boldsymbol{pA}$ at 800 GeV, with parametriztion $\boldsymbol{\sigma_{pA} = A^{\alpha}\sigma_{pp}}$.
(thanks to Mike Leitch)

The puzzle seems not so puzzling with correct calibration; but need to check quantitatively

Additional Probe: excited vs. ground state

ratio of excited to ground state in AA: $\Upsilon(1S) : \Upsilon(2S) : \Upsilon(3S)$

does the presence of a medium change this from pp?
initial state effects cancel here as well; example



Evidence of sequential suppression?...pA results?

Conclusions

Measurements of hidden/open heavy flavor production,

measurements of excited/ground state quarkonium production

in pp, pA, AA

can provide model-independent answers

to model-independent questions.