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The Quarkonium Analysis of the QGP

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Statistical QCD shows

$\exists$ color deconfinement,

$\exists$ hot quark-gluon plasma,

for $T > T_c$;

but it does not tell us

what thermometer can measure temperature

to identify a hot, deconfined medium.

Only measurable observables are observables.

What can we use as QGP Thermometer?

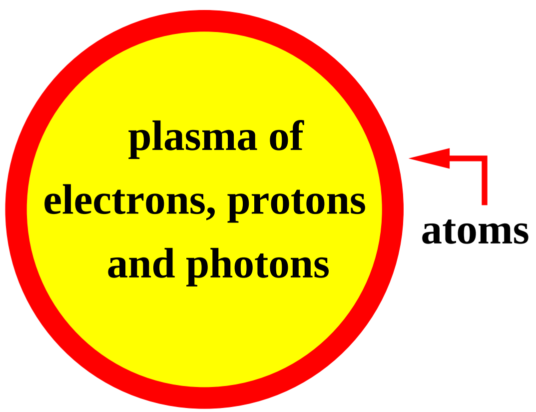
hadron abundances $\Rightarrow$ hadronization stage of QGP

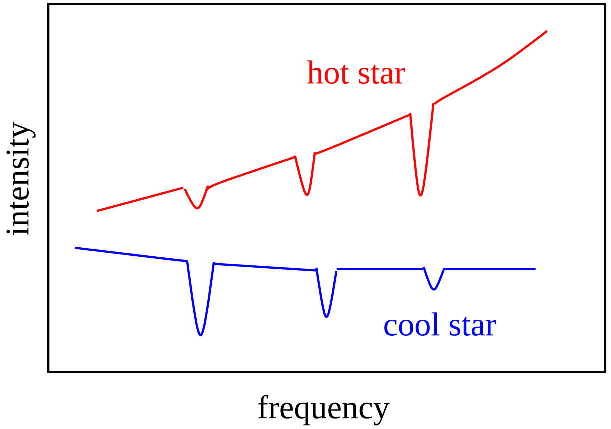
$\exists$ probe of earlier hot QGP,
not accessible to direct measurements?

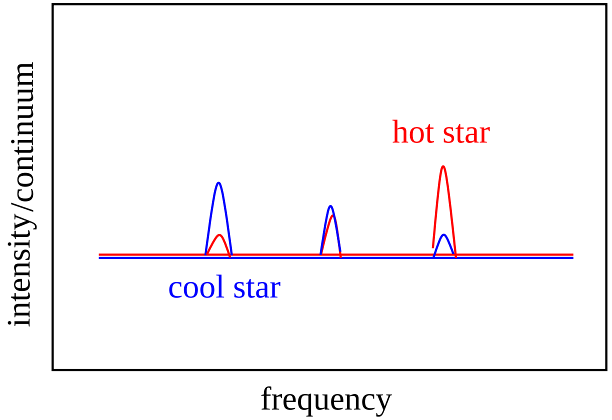
$\exists$ a similar problem in astrophysics:

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

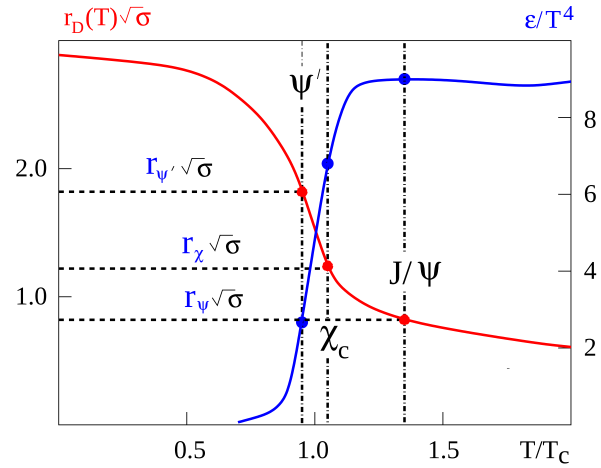
∃ no crust of QGP, but ∃ early hard production of quarkonia

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

- quarkonia are very unusual hadrons
  - very small:

    $r_{J/\psi} \simeq 0.25$ fm, $r_\Upsilon \simeq 0.14$ fm $\ll \Lambda_{QCD}^{-1} \simeq 1$ fm
  - very tightly bound:

    $2M_D - M_{J/\psi} \simeq 0.64$ GeV $2M_B - M_\Upsilon \simeq 1.10$ GeV
  - survive deconfinement, exist in QGP up to some T
- quarkonia melt in hot QGP through color screening, gluon dissociation
  - when screening radius $r_D(T)$ becomes smaller than binding radius r_i, quarkonium state i melts; melting points determine temperature, energy density of QGP



Challenge to theory: quarkonium dissociation temperatures?

- potential theory: large $m_Q \longrightarrow$ NR Schrödinger eq'n

$$\left\{2m_Q - \frac{1}{m_Q}\nabla^2 + V(r,T)\right\}\Phi_i(r,T) = M_i\Phi_i(r,T)$$

heavy quark lattice studies $\longrightarrow$ heavy quark binding free or internal energy to specify potential?

- direct lattice studies: measure correlator

$$G_i(\tau,T) = \int d\omega\ \sigma_i(\omega,T)\ K(\omega,\tau,T)$$

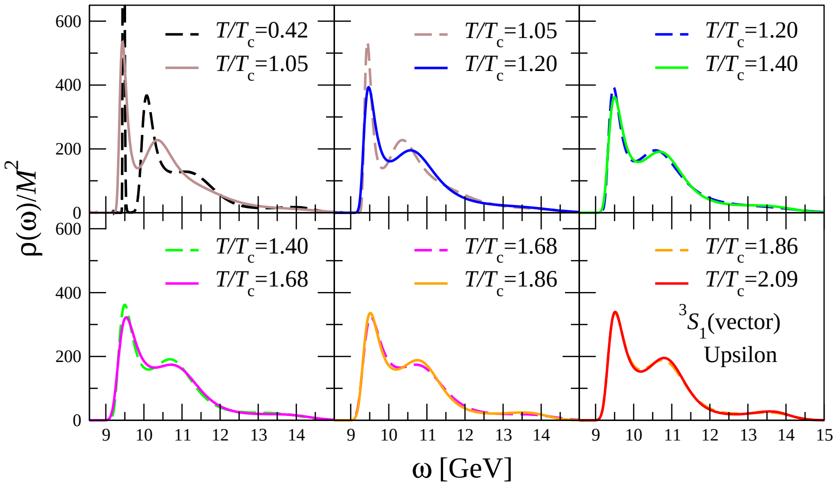
invert integral transform to get spectrum $\sigma_i(\omega,T)$;
$G_i(\tau,T)$ not known for enough values of τ;
maximum entropy method (MEM) $\longrightarrow$ most likely result.

tentative result:

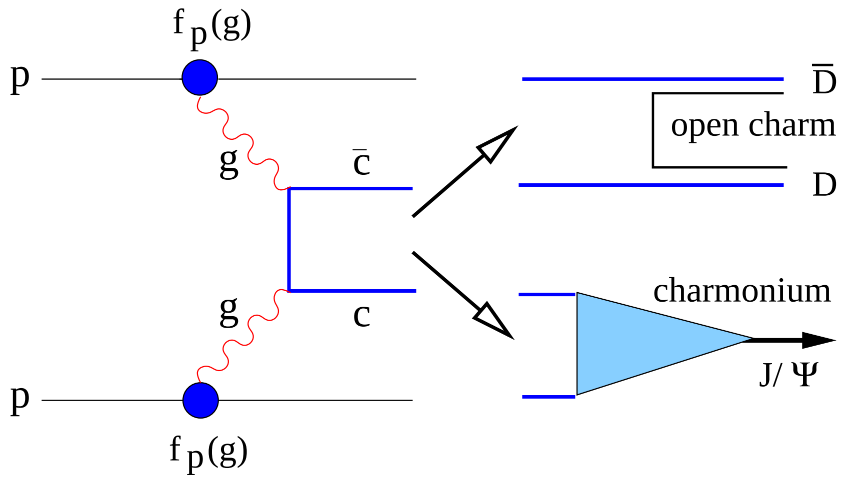
[Ding et al., 2012]

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
T_d/T_c	1.5 - 2.0	1.1	1.1	> 4.0	1.8	1.6	1.2	1.2

- recent NRQCD studies with temperature scan for Υ [Aarts et al., 2012]



- apply to nuclear collisions; production scheme in *pp*



Find:

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

– 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

previous analysis procedure:

- **measure production in pp and pA**

  determine pdf modification (shadowing, antishadowing)

  determine parton energy loss

  determine cold nuclear matter effect

- construct model for AA

  scale pp by number of collisions

  incorporate initial & cnm final state modifications

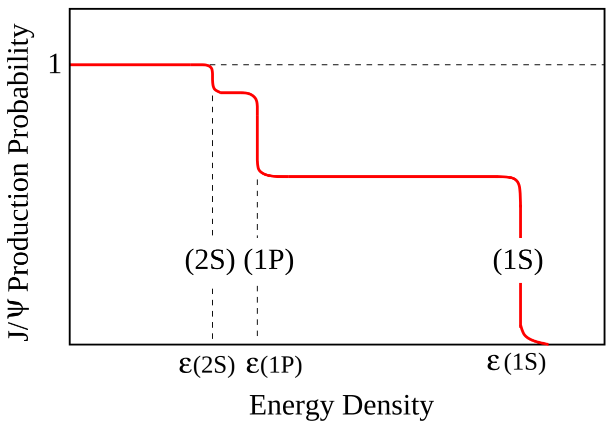
- compare to AA data: is there *anomalous behavior?*

  $\exists$ something not accounted for by model? $\longrightarrow$ **inconclusive**

Theoretical Scenarios

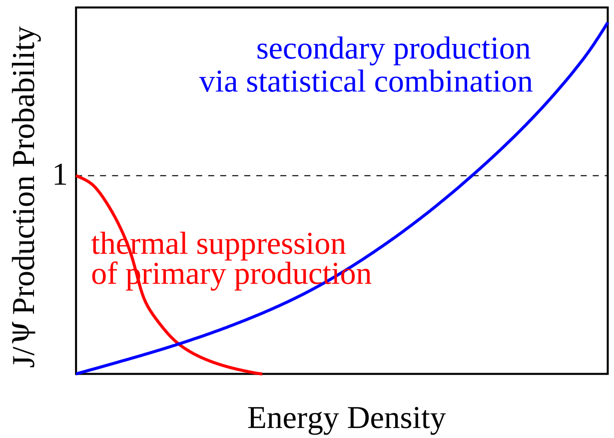
- sequential suppression

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



- statistical enhancement

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



What is J/ψ production probability?

– 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”

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

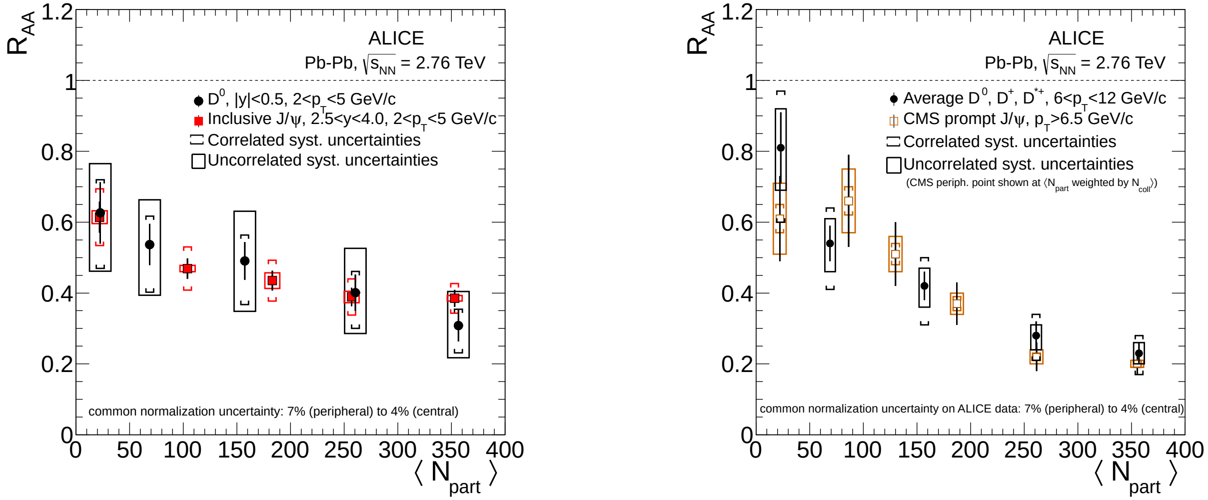
$$R_{AA}(c\bar{c}) = N_{AA}(c\bar{c})/n_c N_{pp}(c\bar{c})$$

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

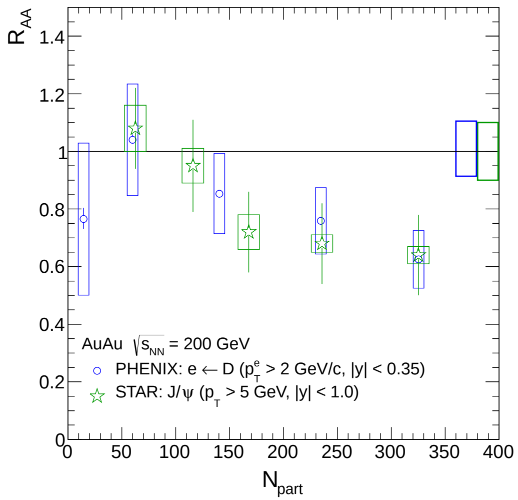


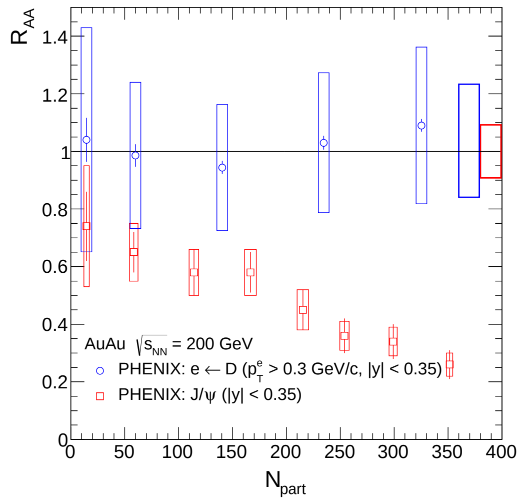
Data from ALICE & CMS: J/ψ vs. open charm production at intermediate & high transverse momenta
(thanks to Zaida Conesa del Valle)

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



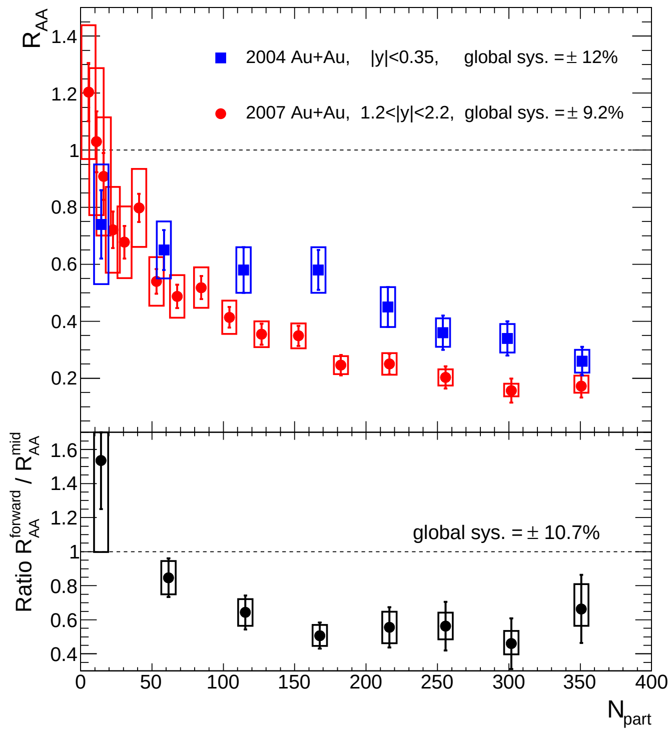


Data from PHENIX & STAR: J/ψ vs. open charm production at high & low transverse momenta (thanks to Torsten Dahms)

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.

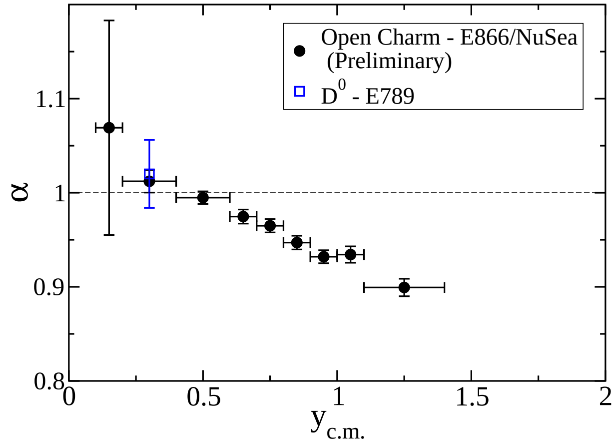
Complementary aspect: so-called "RHIC puzzle"

"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



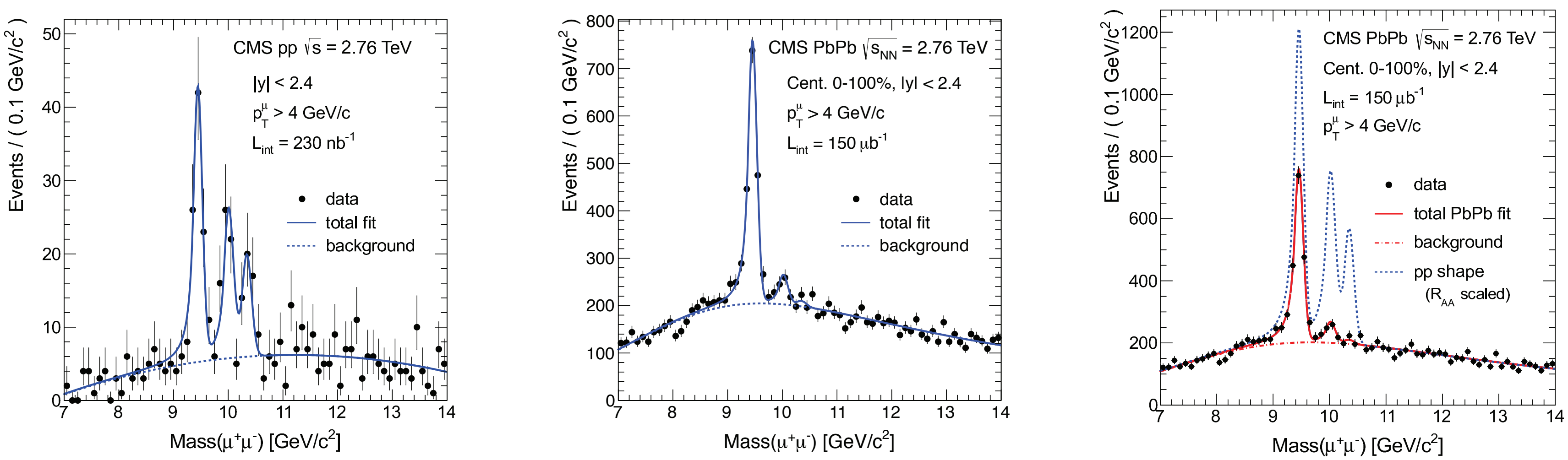
Rapidity dependence of open charm production in $\boldsymbol{pA}$ at 800 GeV, with parametriztion $\boldsymbol{\sigma_{pA} = A^{\alpha}\sigma_{pp}}$.
(thanks to Mike Leitch)

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



Clear evidence of sequential suppression...see CMS paper.

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.