The Temperature of the Quark-Gluon Plasma

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Statistical QCD shows for strongly interacting matter

$\exists$ color deconfinement,

$\exists$ a transition to a hot quark-gluon plasma,

for $T > T_c$;

but it does not specify

what thermometer can measure the temperature

of a deconfined medium.

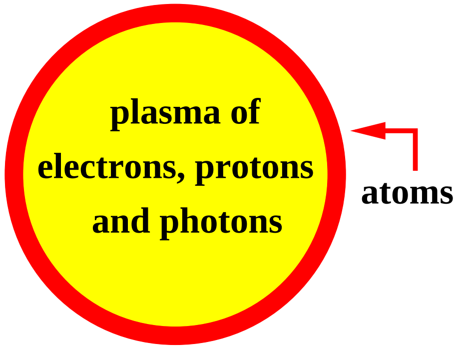
What can we use as QGP Thermometer?

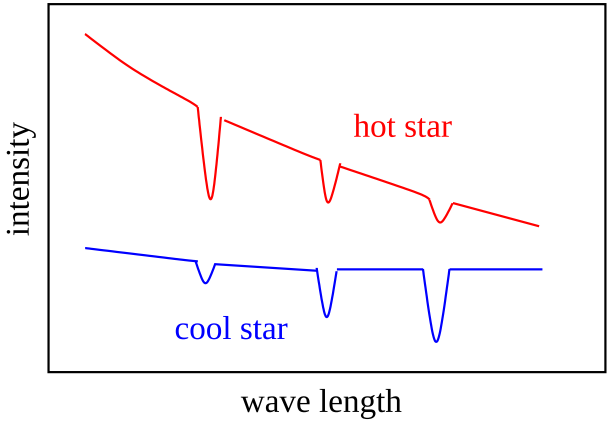
hadron abundances ⇒ hadronization stage of QGP

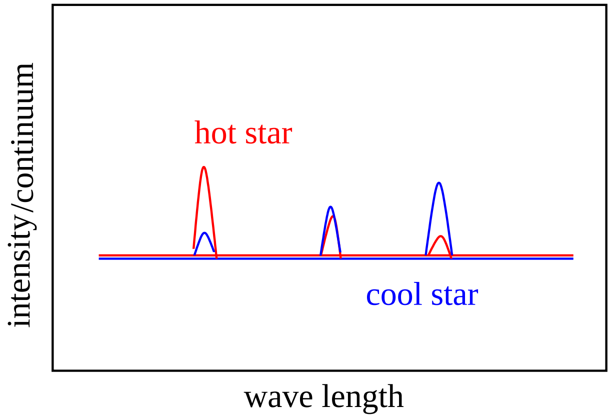
∃ probe of earlier hot QGP,
not accessible to direct measurements?

∃ 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.

Contents

1. Quarkonia are very unusual hadrons

heavy quark ($Q\bar{Q}$) bound states stable under strong decay

- heavy: $m_c \simeq 1.2 - 1.4$ GeV, $m_b \simeq 4.6 - 4.9$ GeV
- stable: $M_{c\bar{c}} \leq 2M_D$ and $M_{b\bar{b}} \leq 2M_B$

What is "usual"?

- light quark ($q\bar{q}$) constituents
- hadronic size $\Lambda_{\rm QCD}^{-1} \simeq 1$ fm, independent of mass
- loosely bound, $M_\rho - 2M_\pi \gg 0,\ M_\phi - 2M_K \simeq 0$
- relative production abundances $\sim$ energy independent, statistical: at large $\sqrt{s}$, rate $R_{i/j} \sim$ phase space at T_c
- $(dN_{q\bar{q}}/dy) \sim \ln s$

Quarkonia: heavy quarks $\Rightarrow$ non-relativistic potential theory

Jacobs et al. 1986

Schrödinger equation $\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\Phi_i(r)$

with confining ("Cornell") potential $V(r) = \sigma\, r - \frac{\alpha}{r}$

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

($m_c = 1.25$ GeV, $m_b = 4.65$ GeV, $\sqrt{\sigma} = 0.445$ GeV, $\alpha = \pi/12$)

excellent account of full quarkonium spectroscopy:

spin-averaged masses , binding energies, radii.

⇒ quarkonia are **unusual**

– very small, mass-dependent size:

$$r_{J/\psi} \simeq 0.25 \text{ fm}, \; r_{\Upsilon} \simeq 0.14 \text{ fm} \quad \ll \Lambda_{\rm QCD}^{-1} \simeq 1 \text{ fm}$$

– very tightly bound:

$$\left.\begin{array}{l} 2M_D - M_{J/\psi} \simeq 0.64 \text{ GeV} \\ 2M_B - M_{\Upsilon} \quad \simeq 1.10 \text{ GeV} \end{array}\right. \gg \Lambda_{\rm QCD} \simeq 0.2 \text{ GeV}$$

- Potential model study of quarkonia: conceptually simple

more recent and more basic approaches:

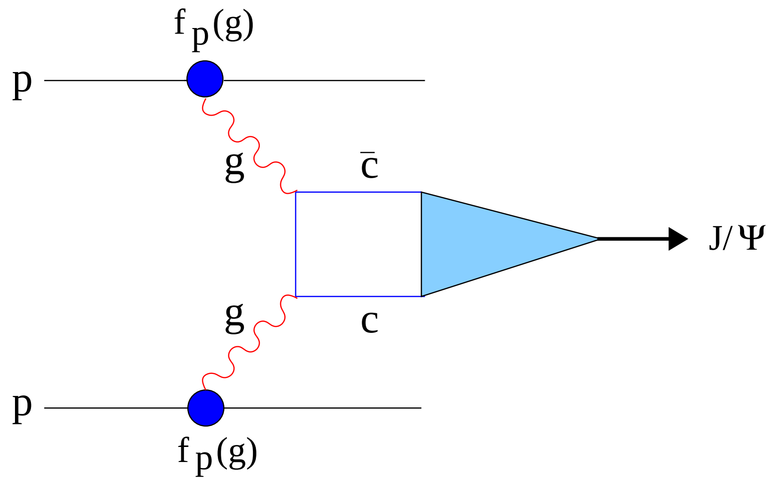
– finite temperature lattice QCD
– effective field theories, weak coupling expansion
– AdS/CFT, and more...

see e.g. N. Brambilla et al, arXiv:1010.5827

M. Laine, arXiv:0810.1112

primary production via partonic interaction dynamics

Einhorn & Ellis 1975, Baier & Rückl 1983, Lansberg 2006



given parton distribution functions from DIS,
$c\bar{c}$ production is perturbatively calculable (cum grano salis)

J/ψ binding is not, but it is independent of collision energy:

$$R[(J/\psi)/c\bar{c}] \sim |\phi_{J/\psi}(0)|^2 \neq f(s)$$

results for/from elementary collisions:

- heavy flavor & quarkonium production are dynamical, not statistical statistical hadronization as light hadrons

Quarkonium production in elementary collisions: no medium

What happens to quarkonia in hot strongly interacting media?

2. Quarkonia melt in a hot QGP

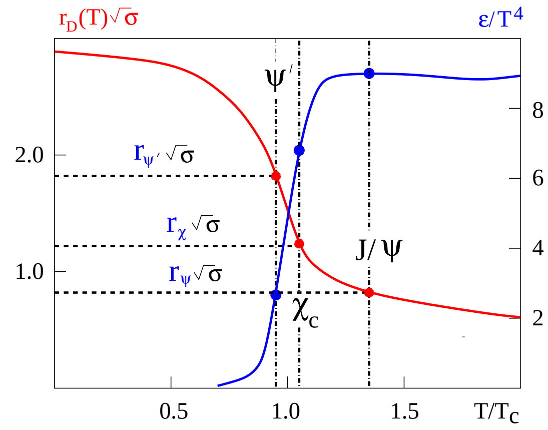
Matsui & HS 1986, Karsch et al. 1988

- 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

Color screening $\Rightarrow$ binding weaker and of shorter range

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

How to 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

Heavy Quark Studies in Finite Temperature QCD

Hamiltonian $\mathcal{H}_Q$ for QGP with/without color singlet $Q\bar{Q}$ pair:

$$F_Q(r,T) = -T \ln \int d\Gamma \exp\{-\mathcal{H}_Q/T\}$$

$$F_0(T) = -T \ln \int d\Gamma \exp\{-\mathcal{H}_0/T\}$$

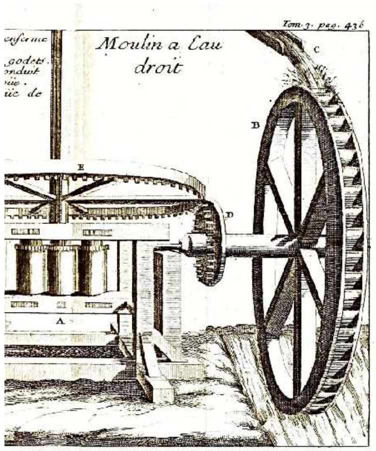
study free energy difference $F(r,T) = F_Q(r,T) - F_0(T)$,

internal energy difference $U(r,T)$ & entropy difference $S(r,T)$

$$F(r,T) = U(r,T) - TS(r,T)$$

what is the relevant potential? $V = U$ or $V = F$ or mixture?

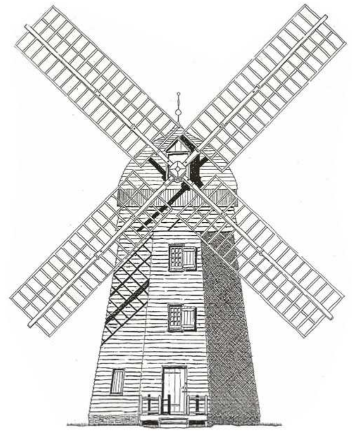
Digal et al. 2001; Shuryak & Zahed 2004; Wong 2004/5; Alberico et al. 2005; Digal et al. 2005; Mocsy & Petreczky 2005/6



Solution:

HS 2015

Energetic vs. Entropic Force



Pressure P specifies the force acting on the $Q\bar{Q}$ pair

$$P(T,r) = -\left(\frac{\partial F}{\partial r}\right)_T = -\left(\frac{\partial U}{\partial r}\right)_T + T\left(\frac{\partial S}{\partial r}\right)_T = K_u(T,r) + K_s(T,r).$$

$K_u(T,r)$: energetic force $\sim$ watermill

$K_s(T,r)$: entropic force $\sim$ windmill

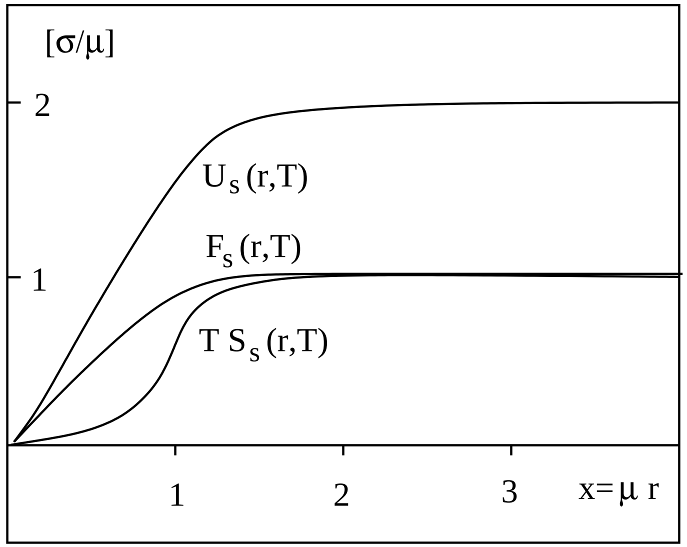
- Model for $Q\bar{Q}$ in strongly coupled QGP; free energy

$$F(r,T) = \sigma r \left[\frac{1-e^{-\mu r}}{\mu r}\right] = \frac{\sigma}{\mu}[1-e^{-x}],\ x = \mu r$$

leads to entropy and internal energy

$$TS(T,r) = (\sigma/\mu)\,[1-(1+x)e^{-x}]$$

$$U(T,r) = (\sigma/\mu)\,[2-(2+x)e^{-x}]$$



large distance limit of internal energy:

one σ/μ work against string,
one σ/μ polarization clouds
for Q and $\bar{Q}$ (entropy increase)

Consider force on $Q\bar{Q} \sim$ pressure

$$P(T,r) = -\left(\frac{\partial F}{\partial r}\right)_T = -\left(\frac{\partial U}{\partial r}\right)_T + T\left(\frac{\partial S}{\partial r}\right)_T = K_u(T,r) + K_s(T,r)$$

two components:

- attractive energetic force $K_u(T,r) = [-\sigma(1+x)e^{-x}]$
- repulsive entropic force $K_s(T,r) = [\sigma x e^{-x}]$
- effective $Q\bar{Q}$ force: $K(T,r) = K_u(T,r) + K_s(T,r) = -\sigma e^{-x}$

internal energy U increases
by work against string ($\sim$ attractive force) and
by formation of polarization clouds ($\sim$ repulsive force)

only overall force component is relevant for binding: $F(T,r)$

- weakly interacting plasma (QED, perturbative QCD)

Laine et al. 2007, Beraudo et al. 2008, Brambilla et al. 2008, Escobedo & Soto 2008, Burnier et al. 2009, 2014

real-time propagator of $Q\bar{Q}$ pair in medium

$$V_w(r,T) = -\alpha\left[\mu(T) - \frac{1}{r}e^{-\mu(T)r}\right]$$

with $\mu(T) = 1/r_D(T) \sim \alpha T$,

imaginary-time propagator of $Q\bar{Q}$ pair in medium

$$F_w(r,T) = -\alpha\left[\mu(T) - \frac{1}{r}e^{-\mu(T)r}\right]$$

in perturbative limit, potential (real part) is free energy

Combine strong and weak coupling components

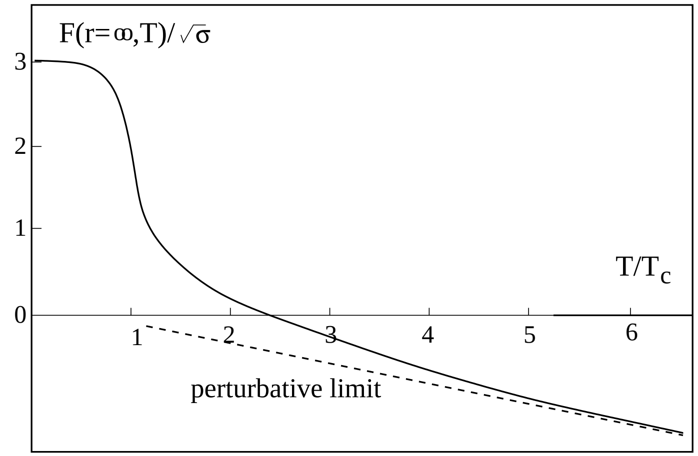
$$F(r,T) = \frac{\sigma}{\mu(T)}\left[1 - e^{-\mu(T)r}\right] - \alpha\left[\mu(T) - \frac{1}{r}e^{-\mu(T)r}\right]$$

For $T_c \leq T \lesssim 3\,T_c$: strong component dominates

now large distance limit of $F(r,T)$

becomes $F_s(\infty,T) = \sigma/\mu(T)$

instead of $F_w(\infty,T) = -\alpha\mu(T)$



moreover, effects of critical behavior on $\mu(T)$

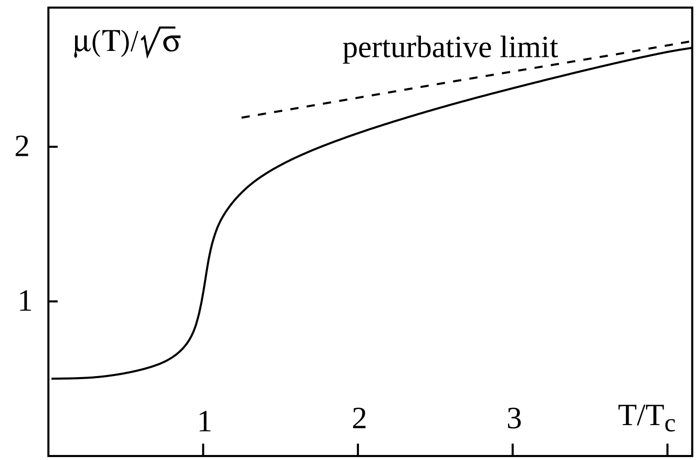
- in the critical region $\mu(T) \not\sim T$,

  much stronger variation;

  potential model calculations

  must use

  parametrization of lattice data



using $V(T,r) = F_{\text{lattice}}(T,r)$ in Schrödinger equation,
indicative results for T_{diss}/T_c

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	1.2	1.0	1.0	> 3.0	1.2	1.2	1.0	1.0

Digal et al. 2001; Shuryak & Zahed 2004; Wong 2004/5; Alberico et al. 2005;
Digal et al. 2005; Mocsy & Petreczky 2005/6

- **Lattice Studies of Quarkonium Spectrum**

Calculate correlation function $G_i(\tau, T)$ for mesonic channel i determined by quarkonium spectrum $\sigma_i(\omega, T)$

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

relates imaginary time τ and $c\bar{c}$ energy ω through kernel

$$K(\omega, \tau, T) = \frac{\cosh[\omega(\tau - (1/2T))]}{\sinh(\omega/2T)}$$

invert $G_i(\tau, T)$ to get quarkonium spectra $\sigma_i(\omega, T)$

Basic Problem

correlator given at discrete number $N_\tau/2$ of lattice points with limited precision; presently best $N_\tau = 96$ $(0.75\ T_c)$, 48 $(1.5\ T_c)$

want spectra $\sigma_i(\omega, T)$ at ~ 1000 points in ω

• brute force solution: calculate correlators for $N_\tau = 2000$ then inversion is well-defined – project for FAR distant future

• in the meantime: invert $G(\tau, T)$ by MEM to get $\sigma(\omega, T)$

Maximum Entropy Method (MEM)   here: Asakawa and Hatsuda 2004

what is the most likely solution for given data, given errors and some basic information?

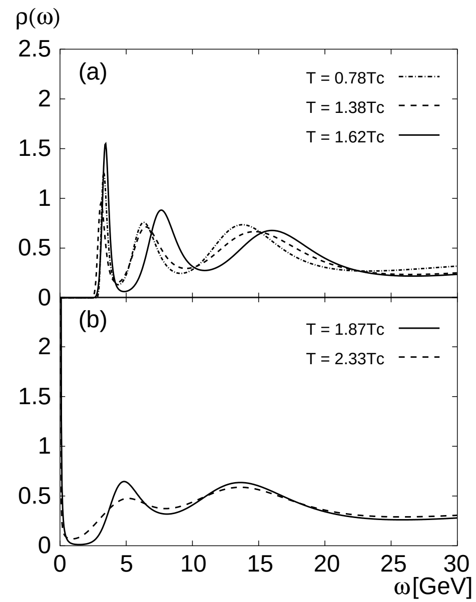
charmonia quenched:

Umeda et al. 2001
Asakawa & Hatsuda 2004
Datta et al. 2004
Iida et al. 2005
Jakovac et al. 2005

charmonia unquenched:

Aarts et al. 2005, 2007

first results $\Longrightarrow$

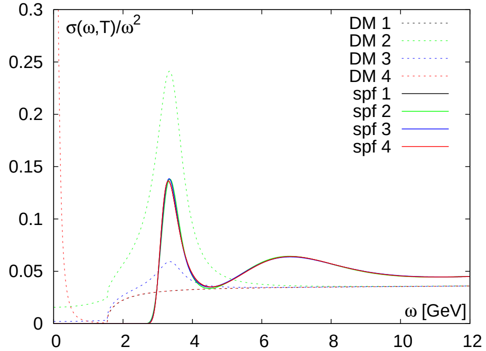


- MEM requires input reference (“default”) function for σ; form of and dependence on default function?

Recent work: Heng-Tong Ding et al., 2012

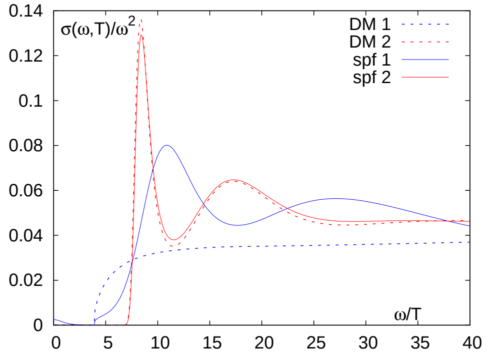
information sufficient
for unique MEM results;
spatial lattice size
insufficient for resonance width

$T = 0.75\ T_c$



information insufficient
for unique MEM results;
spatial lattice size
insufficient for resonance width

$T = 1.50\ T_c$



- better statistics, larger N_τ should resolve MEM results
- larger N_x should (eventually) resolve resonance width

Tentative summary so far:

- J/ψ is dissociated at or around $T \simeq 1.5\ T_c$
- χ and ψ' dissociated at or slightly above T_c

3. Quarkonium production is suppressed in nuclear collisions

...but for a variety of reasons

- nuclear modifications of parton distribution functions
- parton energy loss in cold nuclear matter
- dissociation in cold nuclear matter, by hadronic comovers
- dissociation by color screening ("melting") in hot QGP

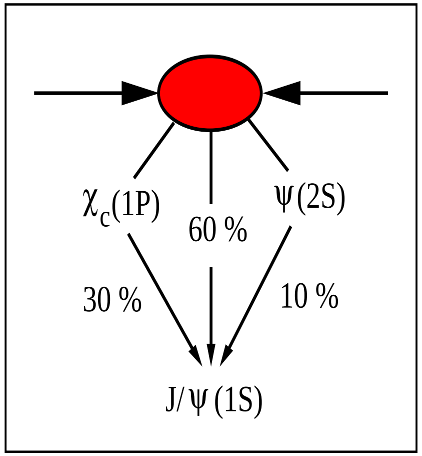
once initial & final state cold nuclear matter effects are taken into account, SPS & RHIC find some 50 % anomalous suppression.

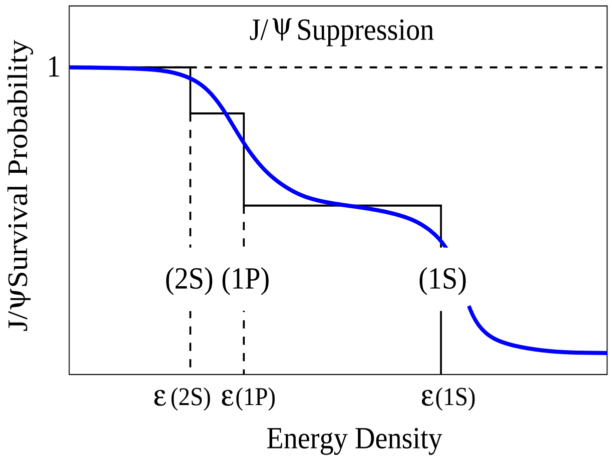
NB: suppression with respect to what? Elementary rates for hidden to open charm/beauty, excited to ground state.

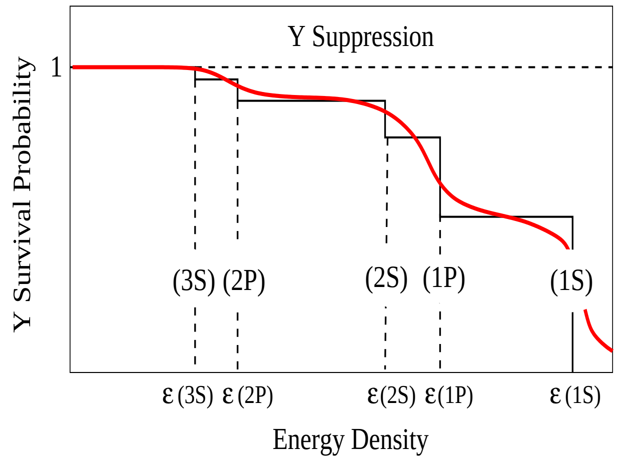
Melting in hot QGP ⇒ sequential quarkonium suppression

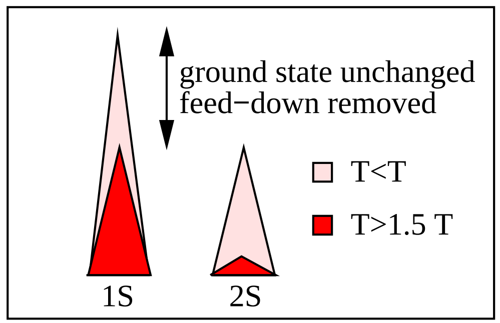
Karsch & HS 1991; Gupta & HS 1992; Karsch, Kharzeev & HS 2006

- measured quarkonia x% direct,
  y% from feed-down decay,
- plasma affects different states differently,
  loosely bound are easier to dissociate
- excited states decay outside medium;
- sequential quarkonium reduction:
  first excited states, later direct states









When quarkonium thresholds are calculable and measurable,

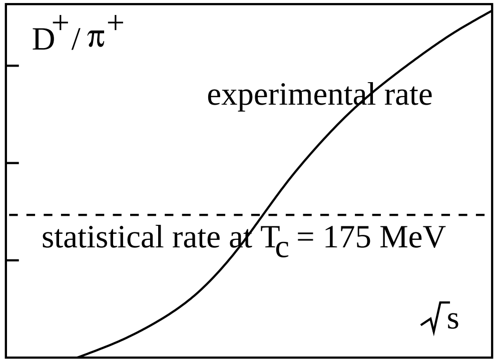
then they can provide a <u>quantitative</u> test of statistical QCD.

4. Quarkonia can be created at QGP hadronization

Braun-Munzinger & Stachel 2001, Thews et al. 2001, Grandchamp & Rapp 2002
Andronic et al. 2003, Zhuang et al. 2006

- $c\bar{c}$ production is a dynamical hard process:

  at high energy, produced medium contains more than the *statistical* number of charm quarks



- assume
  - charm quark abundance constant in evolution to T_c
  - charm quarks form part of equilibrium QGP at T_c
  - equilibrium QGP at T_c hadronizes statistically
  - charmonium production via statistical $c\bar{c}$ fusion

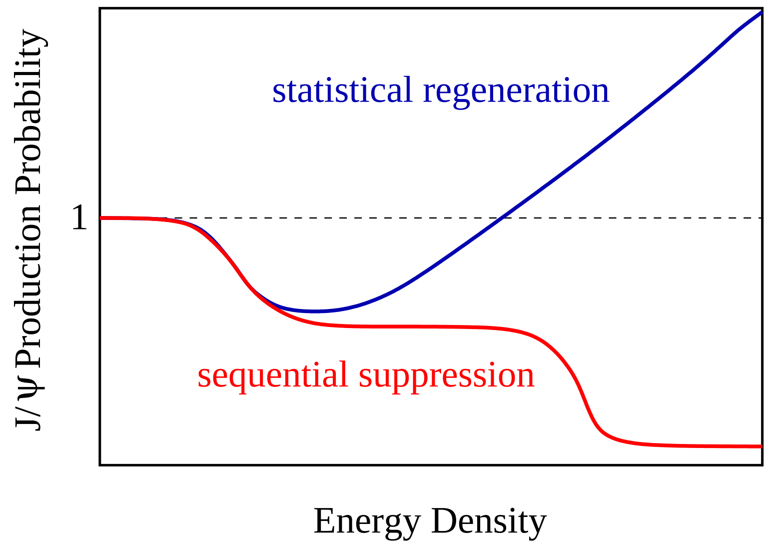
- “secondary” charmonium production: fusion of c and $\bar{c}$ from different primary collisions: “statistical regeneration”

Secondary statistical J/ψ production implies that in sufficiently high energy nuclear collisions

– J/ψ production is strongly enhanced re scaled pp rate

– ratio of hidden/open charm strongly enhanced re pp ratio

two readily distinguishable predictions for anomalous J/ψ production



NB: assumption of statistical quarkonium binding...

Conclusions

Measurements of hidden/open heavy flavor production,

measurements of excited/ground state quarkonium production

can provide conceptual answers to

conceptual questions.

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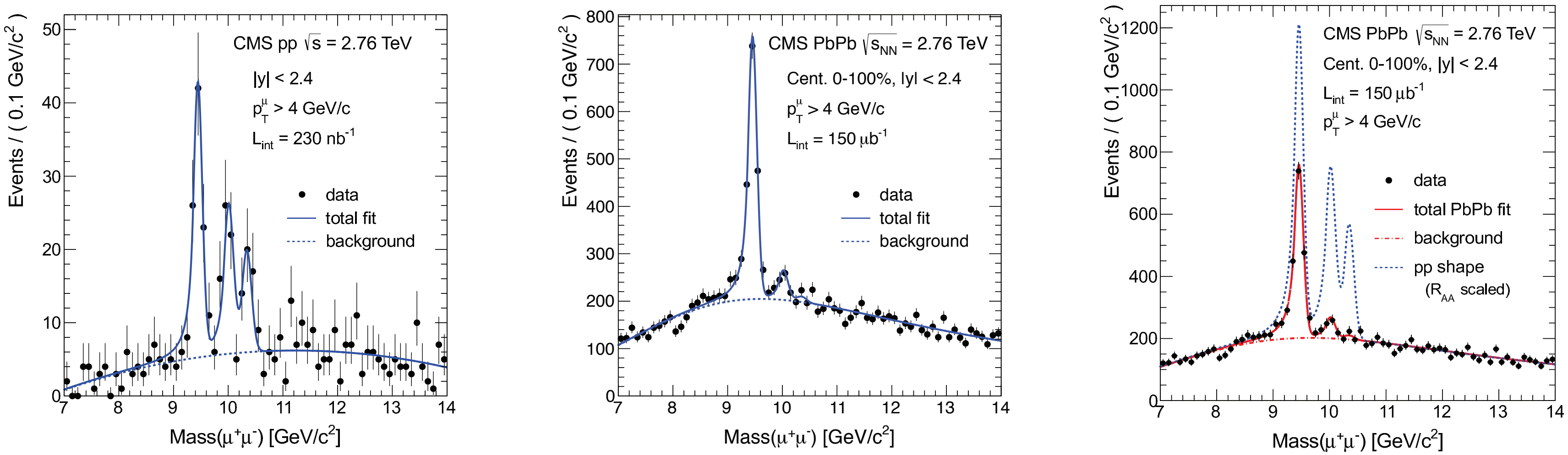
So is there a conclusion?

Ratio excited/ground state in AA: $\Upsilon(1S):\Upsilon(2S):\Upsilon(3S)$

does the presence of a medium change this from pp behavior?

initial state effects largely cancel. CMS expt. at CERN-LHC:



Excited states suppressed, feed-down to ground state gone:

sequential suppression.