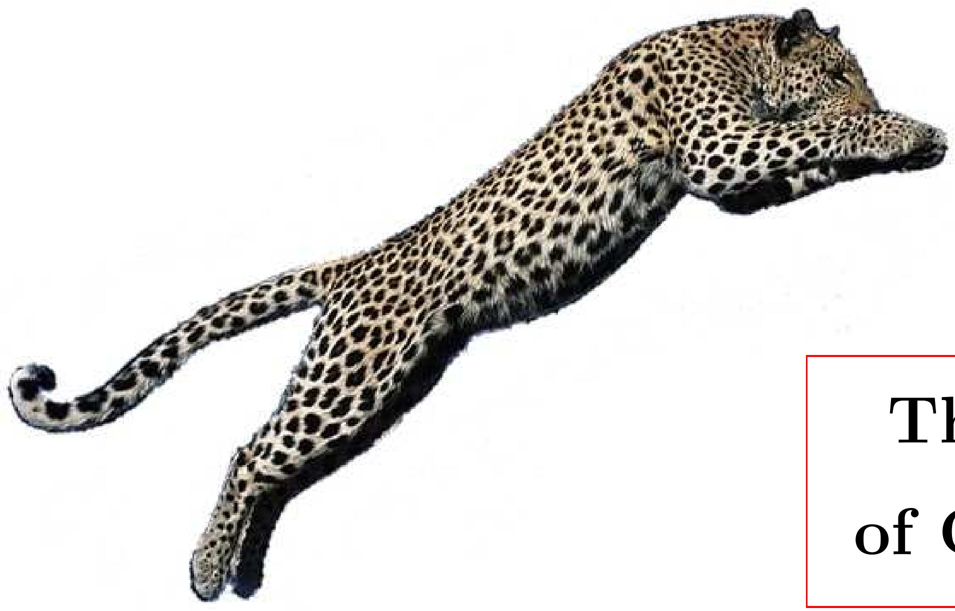

# The Deconfinement of Charm and Beauty

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International Workshop on Discovery Physics at the LHC: KRUGER 2012

Protea Hotel, Kruger Gate, South Africa

**Statistical QCD shows**

**∃ color deconfinement,**

**∃ 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.**

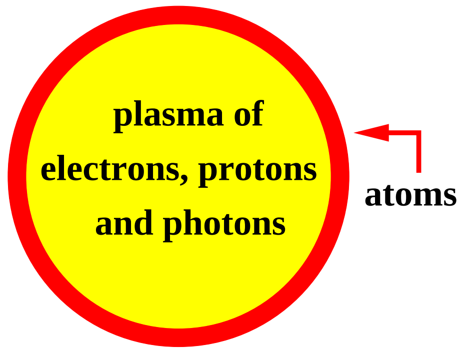
# What can we use as QGP Thermometer?

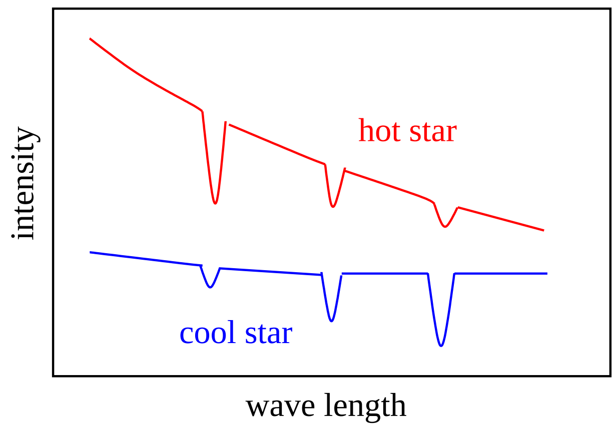
hadron abundances $\Rightarrow$ hadronization stage of QGP

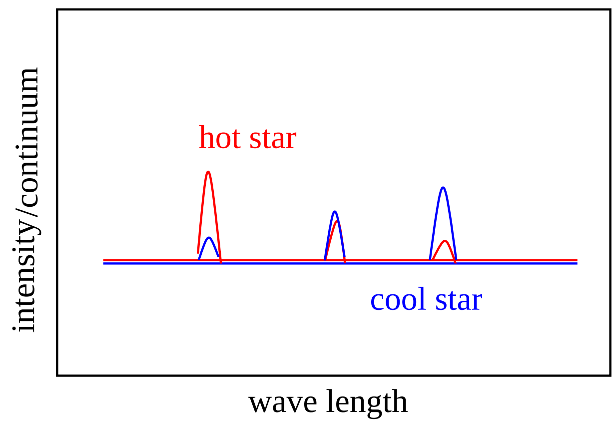
$\exists$ probe of earlier hot QGP,
not accessible to direct measurements?

$\exists$ 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

$\exists$ no crust of QGP, but $\exists$ 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 $T_c$
- $(dN_{\rm ch}/dy) \sim \ln s$

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 | $J/\psi$ | $\chi_c$ | $\psi'$ | $\Upsilon$ | $\chi_b$ | $\Upsilon'$ | $\chi_b'$ | $\Upsilon''$ |
|---|---|---|---|---|---|---|---|---|
| mass [GeV] | 3.10 | 3.53 | 3.68 | 9.46 | 9.99 | 10.02 | 10.26 | 10.36 |
| $\Delta E$ [GeV] | 0.64 | 0.20 | 0.05 | 1.10 | 0.67 | 0.54 | 0.31 | 0.20 |
| $\Delta M$ [GeV] | 0.02 | -0.03 | 0.03 | 0.06 | -0.06 | -0.06 | -0.08 | -0.07 |
| 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.

masses to better than 1 %...

NB:

recent work on field theoretical quarkonium studies,

NRQCD Brambilla & Vairo 1999, Brambilla et al. 2000

$\Rightarrow$ quarkonia are unusual

– very small, mass-dependent size:

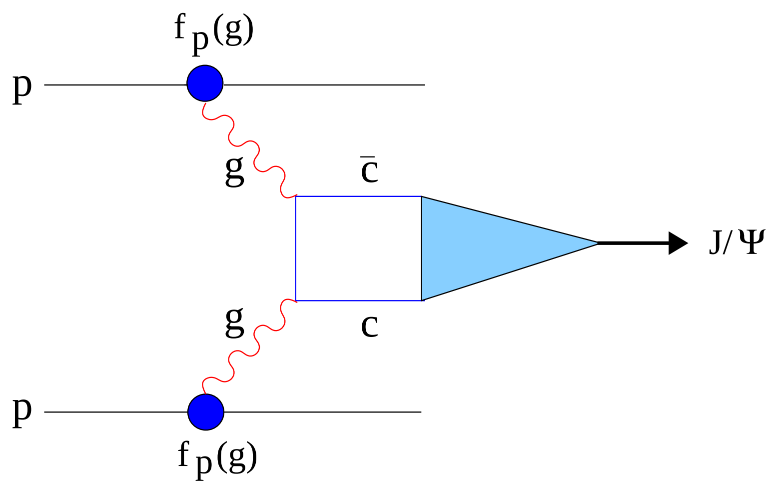
$$r_{J/\psi} \simeq 0.25 \text{ fm}, \; r_{\Upsilon} \simeq 0.14 \text{ fm} \quad \ll \Lambda_{\rm QCD}^{-1} \simeq 1 \text{ fm}$$

– very tightly bound:

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

**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)

**$J/\psi$ 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:**

- $(dN_{c\bar{c}}/dy) \sim s^a$
- $(dN_{\rm ch}/dy) \sim \ln s$
- $N_{c\bar{c}}/N_{\rm ch}$ grows with collision energy  compare $[N_{s\bar{s}}/N_{\rm ch}]$

$\Rightarrow$ heavy flavor production is dynamical and not statistical

- $(dN_{J/\psi}/dy)/(dN_{c\bar{c}}/dy) \simeq 0.02$,  compare $[N_{\rho}/N_{\rm ch}]$
  factor 10 bigger than ratio of statistical weights at $T_c$
  much more hidden charm than statistically predicted
- $(dN_{\psi'}/dy)/dN_{J/\psi}/dy) \simeq 0.2$,  compare $[N_{\rho}/N_{\omega}]$
  factor five bigger than ratio of statistical weights at $T_c$
  ratios of states $\sim$ wave functions, not Boltzmann factors

$\Rightarrow$ quarkonium binding is dynamical and not statistical

**Quarkonium production in elementary collisions: no medium**

**What happens to quarkonia in hot strongly interacting media?**

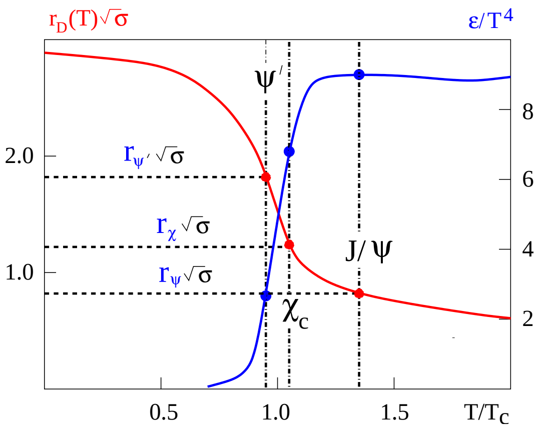
## 2. Quarkonia melt in a hot QGP

**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 ⇒ binding weaker and of shorter range

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




⇒ quarkonium dissociation points

determine temperature ⇒ 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 color singlet $Q\bar{Q}$ pair:

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

Hamiltonian $\mathcal{H}_0$ for QGP without $Q\bar{Q}$ pair:

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

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

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

$$U(r,T) = -T^2 \left( \frac{\partial [F(r,t)/T]}{\partial T} \right) = F(r,T) + TS(r,T)$$

relation to potential? $V = U$ or $V = F$ or mixture?

- 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

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

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

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

large distance limit (screening regime)

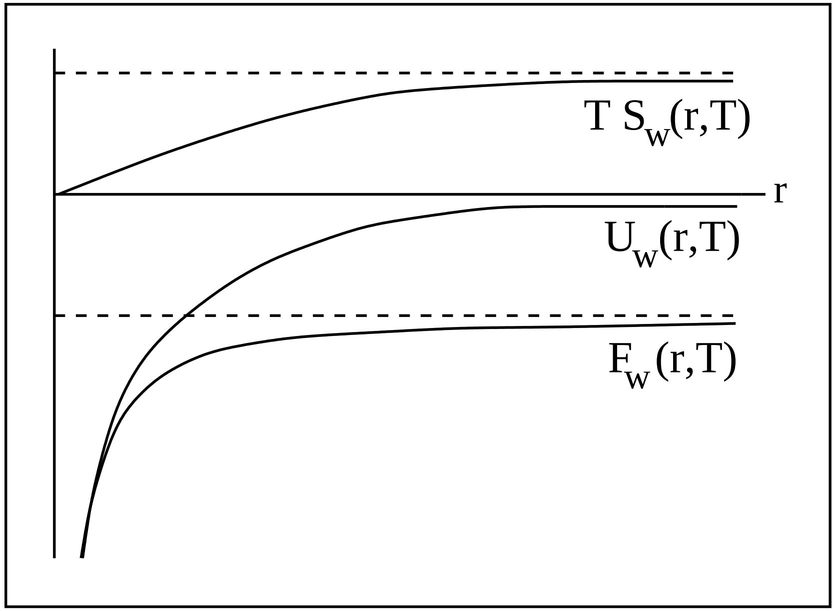
$$F_w(\infty, T) = -TS_w(\infty, T) = -\alpha\mu; \quad U_w(\infty, T) = 0$$

($\alpha\mu/2$ is "mass" of polarization cloud)

short distance limit (Coulomb regime)

$$F_w(r, T) = U_w(r, T) = -\frac{\alpha}{r}$$

$$TS_w(r, T) \to 0$$




melting process:

work done to separate $Q\bar{Q}$ is converted into entropy

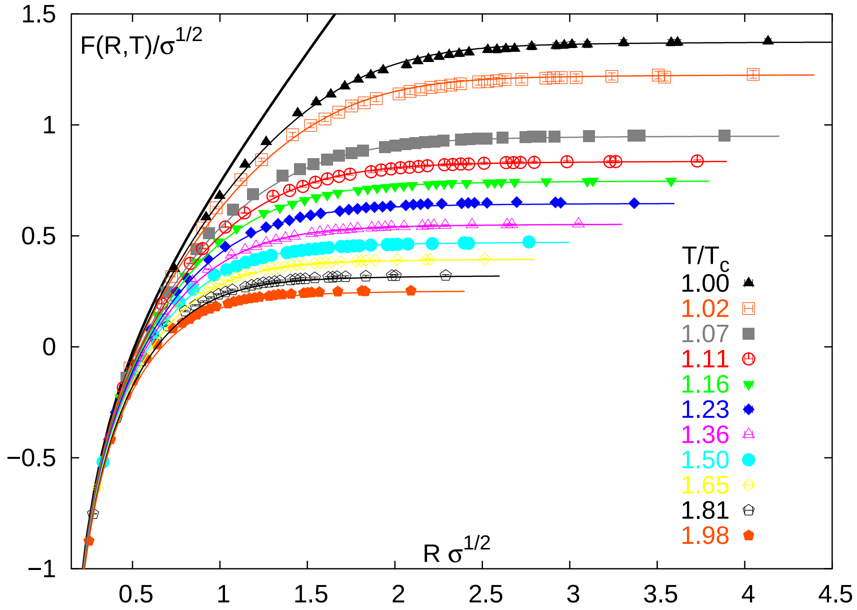
overall energy balance = 0

so far: perturbative limit $\sim$ weakly interacting plasma
(Debye-Hückel theory, slightly non-ideal gas)

QCD: very high $T \gg \Lambda_{\mathrm{QCD}}$ and/or very small $r \ll \Lambda_{\mathrm{QCD}}^{-1}$

- strongly interacting QGP ($T_c \leq T \leq 3\ T_c$)

Kaczmarek & Zantow 2005



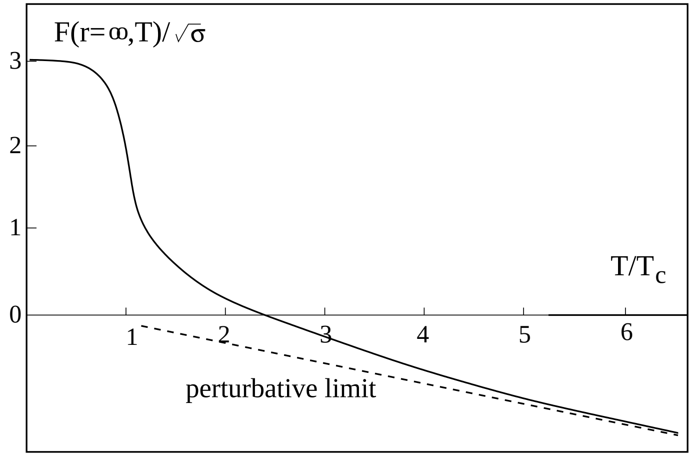

$\Rightarrow$ very different behavior
(lattice results, $N_f = 2$)

separate strong part

$$F(r,T) = F_w(r,T) + F_s(r,T)$$

$T_c \leq T \lesssim 3\,T_c$: strong deviations from perturbative limit

large distance limit




to parametrize lattice results

use 1-d Schwinger string form:

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

large distance limit $F_s(\infty, T) = \sigma/\mu(T)$

in contrast to $F_w(\infty, T) = -\alpha\mu(T)$

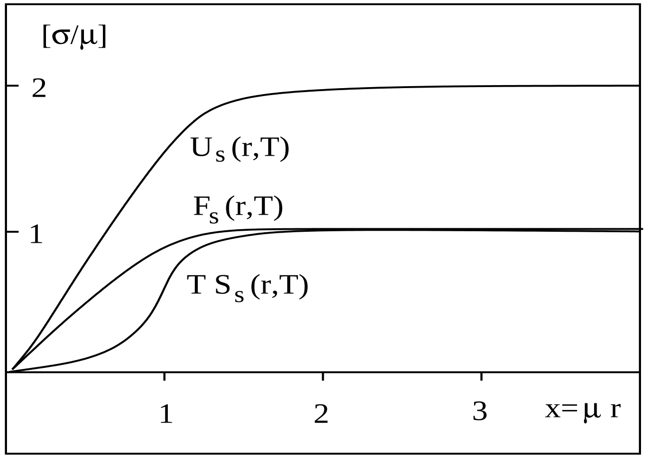
near $T_c$, $F_s \gg F_w$: $Q\bar{Q}$ in strongly interacting QGP?

two modifications:

- with $\mu(T) \sim T$, now obtain

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

$$U_s(r,T) = \frac{\sigma}{\mu}\left[2 - (2 + \mu r)e^{-\mu r}\right]$$




need one $\sigma/\mu$ to separate $Q$ and $\bar{Q}$, and another $\sigma/\mu$ to form polarization clouds (entropy change)

Who pays for what?

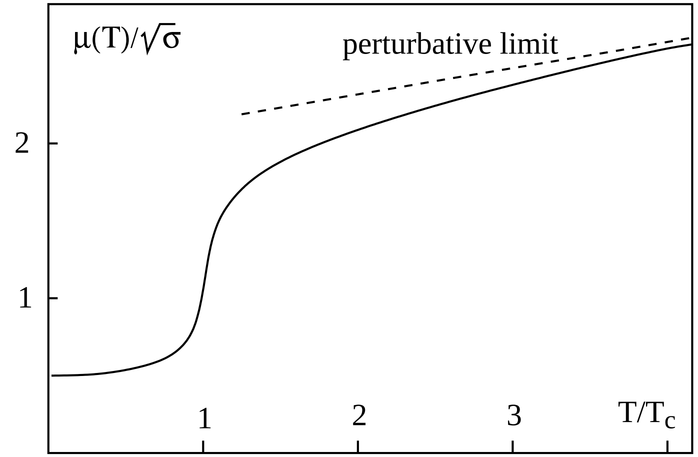
$V(r,T) = U(r,T)$ — the heavy quark pair pays all

$V(r,T) = F(r,T)$ — the medium pays the entropy change

$V(r,T) = xF(r,T) + (1-x)U(r,T)$ — medium and pair split the entropy cost the more the pair pays, the tighter is its binding....with obvious consequences on dissociation temperatures

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

  potential model calculations must use parametrization of lattice data




indicative results for $T_{\text{diss}}/T_c$

| state | $J/\psi(1S)$ | $\chi_c(1P)$ | $\psi'(2S)$ |
|---|---|---|---|
| $V(r,T) = U(r,T)$ | 2.1 | 1.2 | 1.1 |
| $V(r,T) = F(r,T)$ | 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 $\tau$ and $c\bar{c}$ energy $\omega$ 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 $\sim 1000$ points in $\omega$**

• 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?

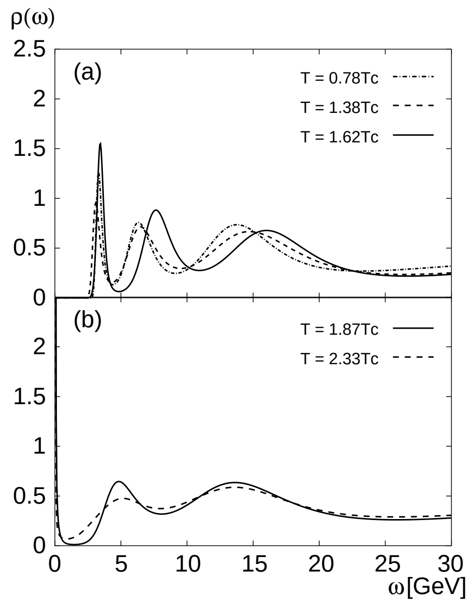
charmonia quenched:

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 $\Longrightarrow$

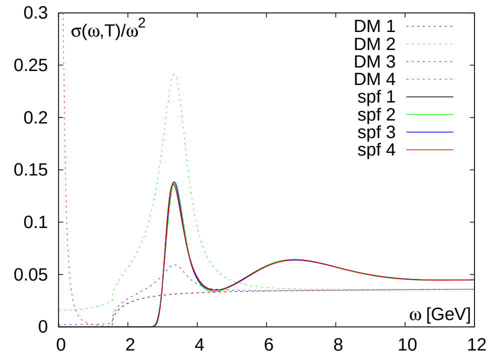


• MEM requires input reference ("default") function for $\sigma$;
form of and dependence on default function?

Preliminary work: Heng-Tong Ding, O. Kaczmarek, F. Karsch, HS

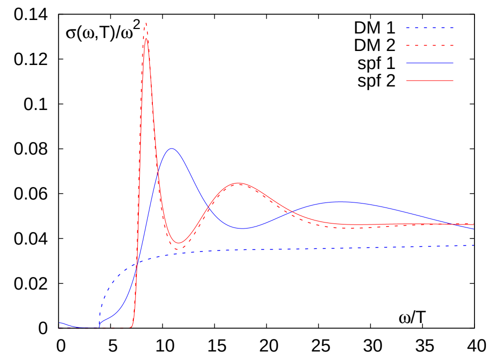
information sufficient
for unique MEM results;
spatial lattice size
insufficient for resonance width

$T = 0.75\ T_c$




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

$T = 1.50\ T_c$



- **better statistics, larger $N_\tau$ should resolve MEM results**
- **larger $N_x$ should (eventually) resolve resonance width**

**Tentative summary so far:**

- **$J/\psi$ survives up to $T \simeq 1.5\ T_c$**
- **$\chi$ and $\psi'$ dissociated at or slightly above $T_c$**

**But some further questions remain:**

**– Schrödinger equation provides dissociation temperature as point where $J/\psi$ radius diverges, binding energy vanishes; $R \simeq 5$ fm, $\Delta E \simeq 10$ MeV in medium of $T \simeq 250$ MeV?**

**– if lattice calculations eventually provide $J/\psi$ spectrum with given position, width;**
**how wide can it get, how far can it shift and still be $J/\psi$?**

**and, of course, the question**

**∃ observable consequences for nuclear collision experiments?**

## 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**
- **pre-resonance dissociation in cold nuclear matter**
- **dissociation by color screening ("melting") in hot QGP**

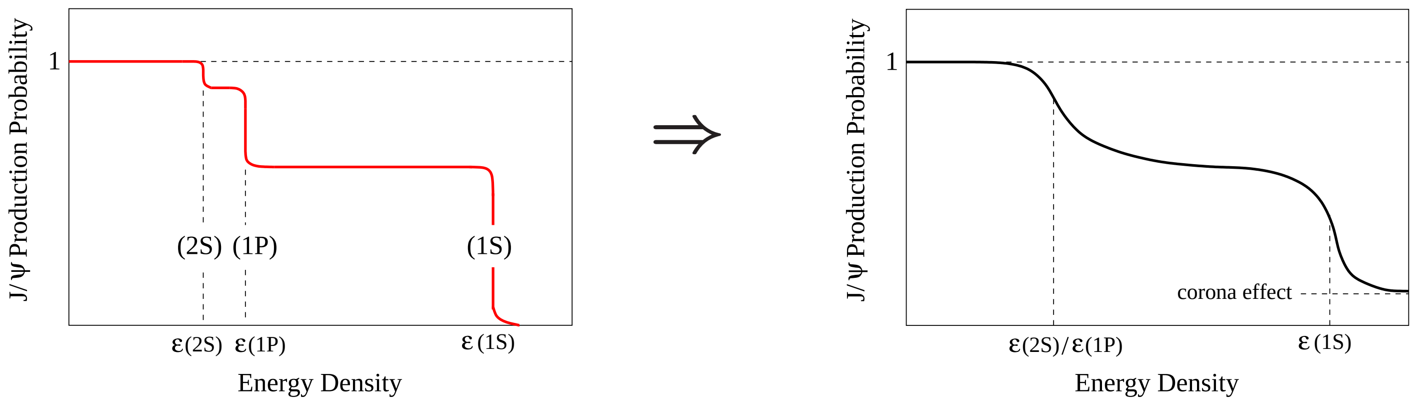
**if initial & final state cold nuclear matter effects are taken into account, SPS & RHIC find some 50 %** *anomalous suppression* **.**

**NB: suppression with respect to what? Return to this shortly.**

If due to melting in hot QGP $\Rightarrow$ sequential $J/\psi$ suppression

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

- measured $J/\psi$'s are about 60% direct 1S, 30% $\chi_c$ decay, 10% $\psi'$ decay
- narrow excited states decay outside medium;
- $J/\psi$ survival rate shows sequential reduction: first due to $\psi'$ and $\chi_c$ melting, then later direct $J/\psi$ dissociation
- experimental smearing of steps; corona effect



**WHEN quarkonium thresholds are calculable, and**

**IF quarkonium thresholds are measurable,**

**THEN they provide a quantitative test of statistical QCD.**

**Does a sufficiently hot QGP $\Rightarrow$**
**no charmonium production at the LHC?**

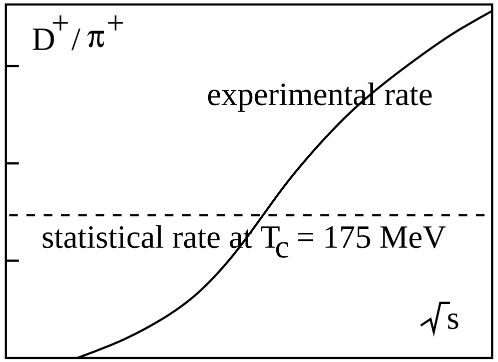
**– corona effect**

**– significant $B$ production $\longrightarrow$ charmonium production via feed-down from $B$ decay; check through $pp$ studies. And:**

## 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**

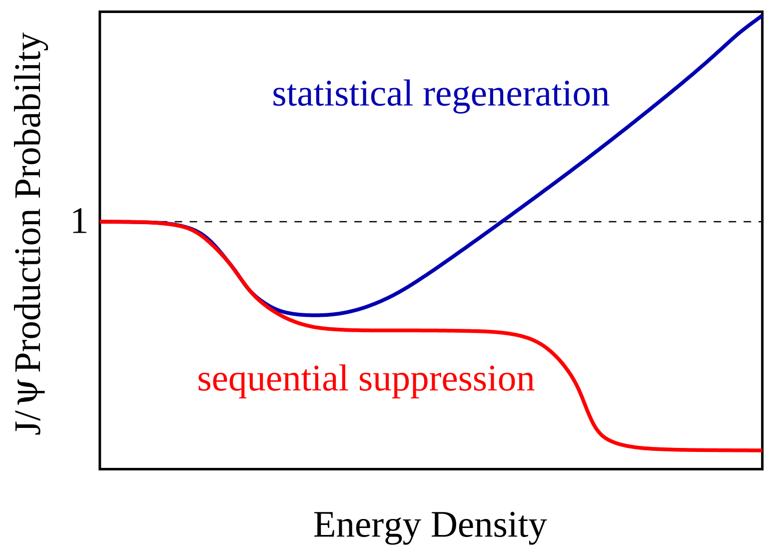
- **"secondary" charmonium production by fusion of** $c$ **and** $\bar{c}$ **produced in different primary collisions**

- **insignificant at "low" energy, since very few charm quarks; could be dominant production mechanism at high energy**

Secondary statistical $J/\psi$ production implies that in sufficiently high energy nuclear collisions

- $J/\psi$ production is strongly enhanced re scaled $pp$ rate
- ratio of hidden/open charm strongly enhanced re $pp$ ratio

two readily distinguishable predictions for anomalous $J/\psi$ production




dynamical vs. statistical momentum spectra Mangano & Thews 2003

NB: assumption of statistical quarkonium binding...

If ∃ statistical regeneration of charmonium,

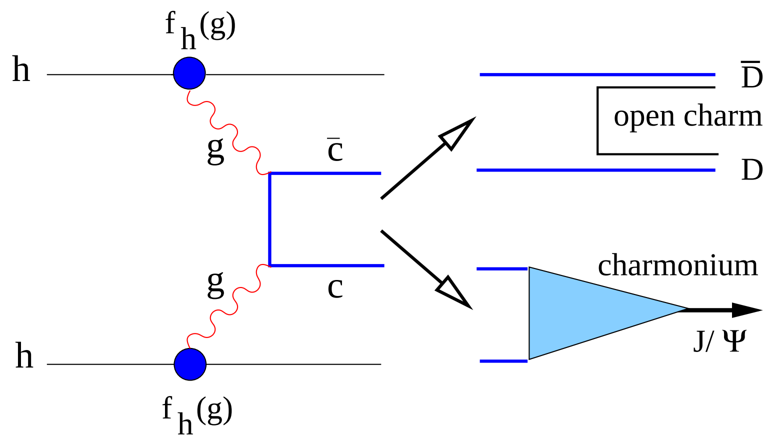
– evidence for thermalization of even charm quarks;

– use sequential suppression in bottomonium production as tool to compare heavy ion data to QCD calculations

## 5. What is the reference for quarkonium production?

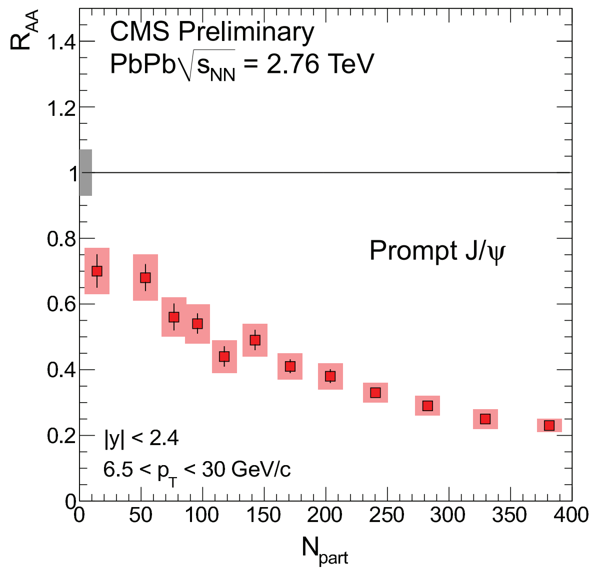
recall heavy flavor production:

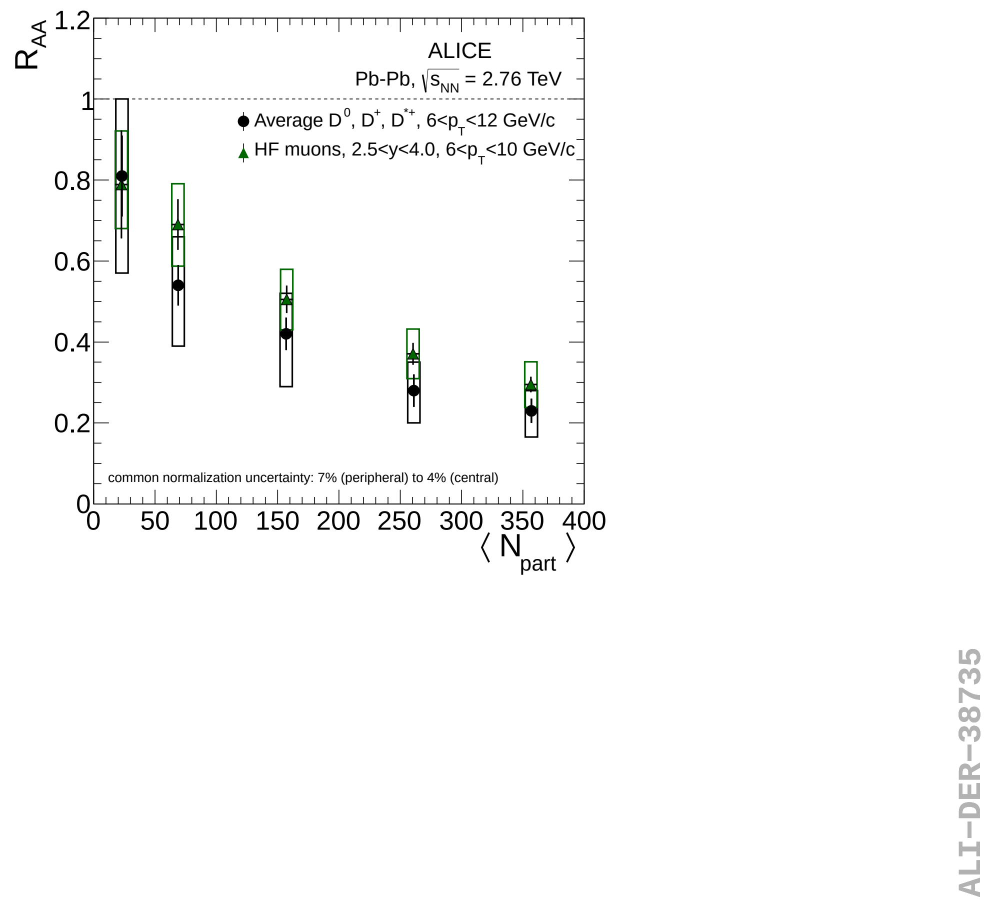
in elementary collisions (no medium)
90% open charm,
10 % charmonium.




- Does presence of a medium change the relative fraction of $c\bar{c}$ or $b\bar{b}$ production going into hidden vs. open heavy flavor?

- **Quarkonium suppression/enhancement means reduction/increase of hidden to open heavy flavor production; all initial state effects are eliminated, only medium effects on quarkonia (in all evolution stages) remain.**
- **Determining suppression re *pp* production rate ($\boldsymbol{R_{AA}}$)** *can* **be very misleading:**



- Quarkonium suppression/enhancement means reduction/increase of hidden to open heavy flavor production; all initial state effects are eliminated, only medium effects on quarkonia (in all evolution stages) remain.
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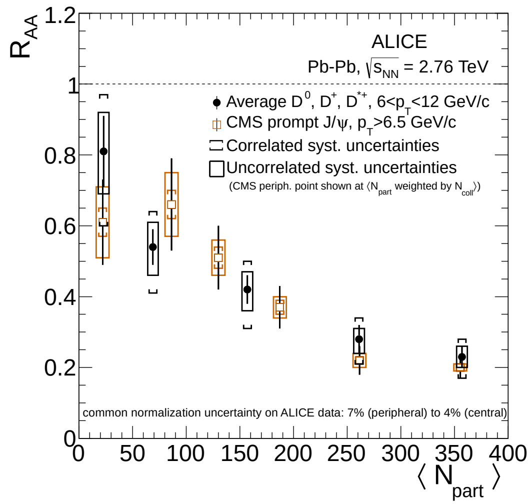
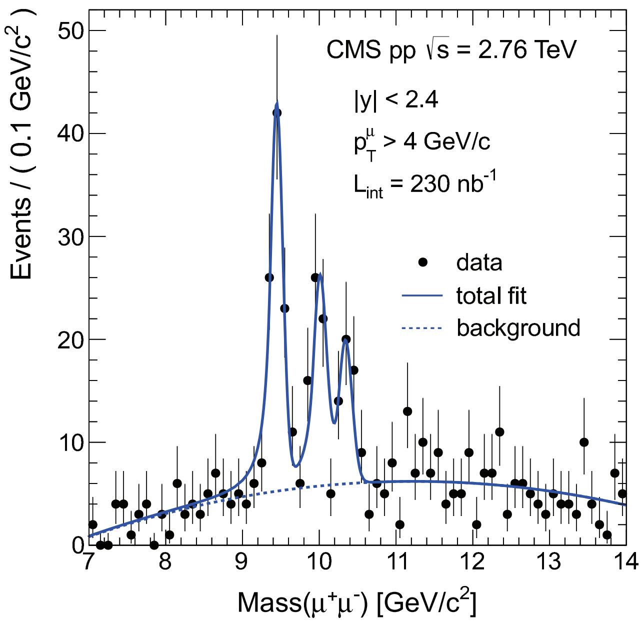
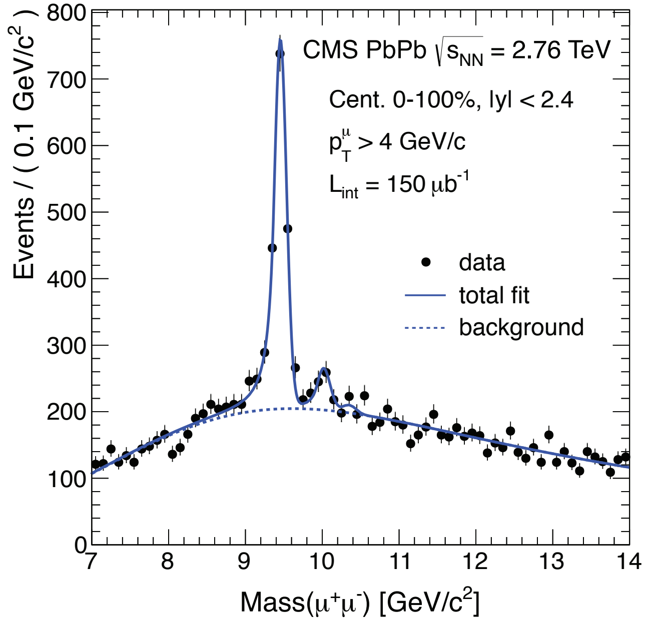



Z. Conesa del Valle, QM2012

$\boldsymbol{J/\psi}$ **is reduced with centrality because** $\boldsymbol{c\bar{c}}$ **is; the ratio hidden/open is approximately the same as for no medium.**

- **But it is not always misleading: sequential suppression means reduction of ($nS$) states relative to ($1S$) state going from $AA$ to $pp$, and the ratio open $AA$ to open $pp$ is not expected to vary much between ($1S$) and ($nS$).**




**Seems evidence of sequential suppression...see CMS paper.**

## Conclusions

**Only measurements of hidden/open heavy flavor production,**

**measurements of excited/ground state quarkonium production**

**can provide conceptual [model-independent] answers to**

**conceptual [model-independent] questions.**

**Quantitative details require specific theory/model input.**