Quarkonia in Deconfined Matter

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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/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
ΔM [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

⇒ quarkonia are unusual

– very small:

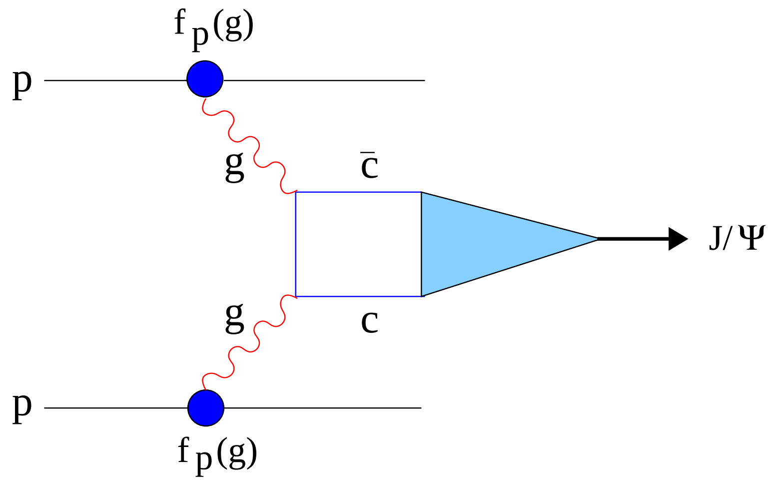
$$r_{J/\psi} \simeq 0.25 \text{ fm}, \ r_\Upsilon \simeq 0.14 \text{ fm} \quad \ll \Lambda_{\text{QCD}}^{-1} \simeq 1 \text{ fm}$$

– very tightly bound:

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

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/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:

- $(dN_{c\bar{c}}/dy) \sim s^a$
- $(dN_{\rm ch}/dy) \sim \ln s$
- $N_{c\bar{c}}/N_{\rm ch}$ 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

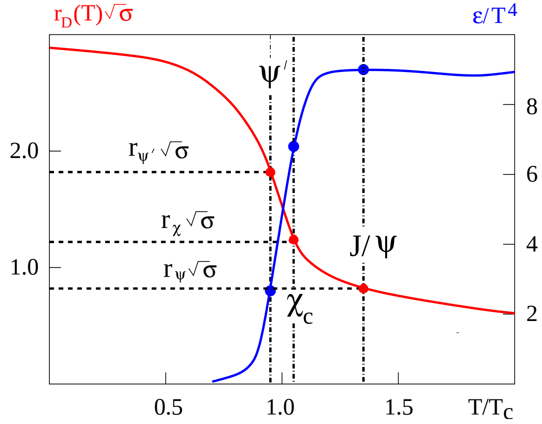
Matsui & HS 1986, Karsch et al. 1988

- **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 $\Rightarrow$ 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



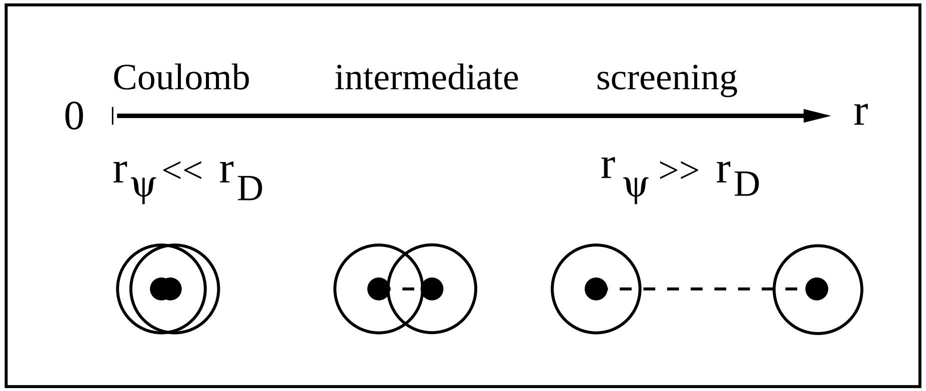
determine temperature $\Rightarrow$ energy density of medium

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

Consider static $Q\bar{Q}$ pair in QGP above T_c, at separation r

$\exists$ three interaction ranges, depending on $Q\bar{Q}$ separation distance



- **$r_{J/\psi} \ll r_D(T)$: quarkonium does not see medium**
- **$r_{J/\psi} \gg r_D(T)$: Q does not see $\bar{Q}$**
- **$r_{J/\psi} \sim r_D(T)$: complex interactions**

How to calculate $Q\bar{Q}$ potential?

- 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?

- <u>weakly interacting plasma</u> (QED, perturbative QCD)

Laine et al. 2007, Beraudo 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 (modulo $2m_c$)

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

large distance limit (screening regime)

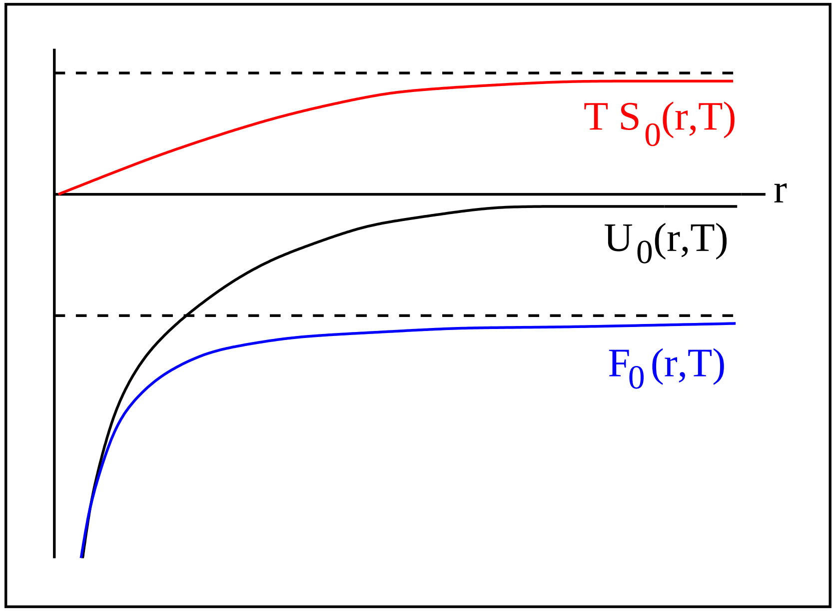
$$F_w(\infty, T) = -TS_w(\infty, T) = -\alpha\mu; \quad U_w(\infty, T) = 0$$

($\alpha\mu/2$ 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

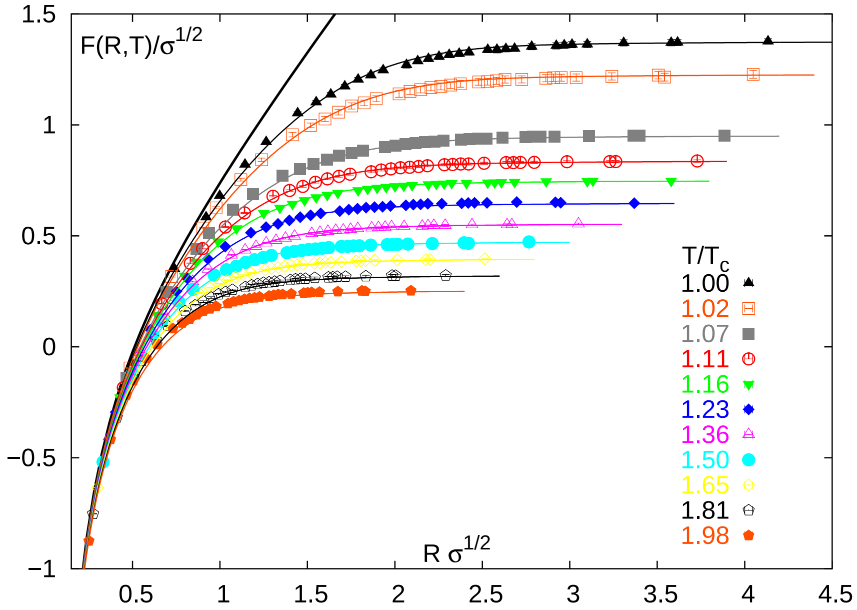
overall energy balance = 0

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

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

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

Kaczmarek & Zantow 2005



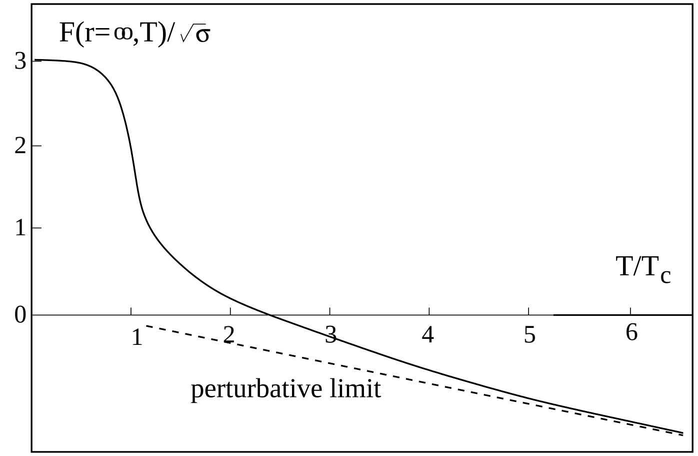
$\Rightarrow$ very different behavior
(lattice results, $N_f = 2$)

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

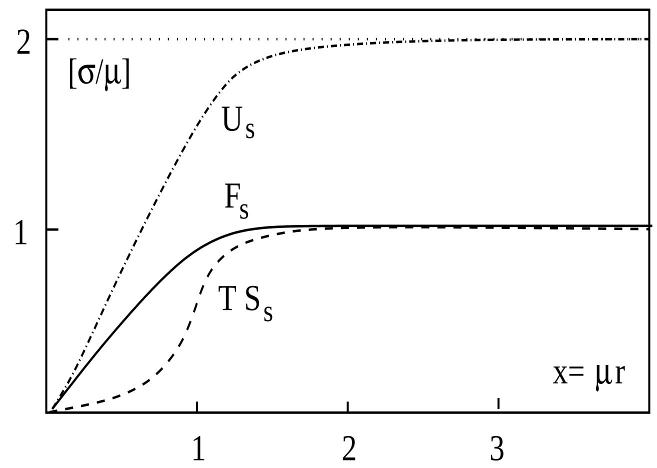
near T_c, $F_s \gg F_w$: $Q\bar{Q}$ in strongly interacting QGP?

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 σ/μ to separate Q and $\bar{Q}$, and another σ/μ 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

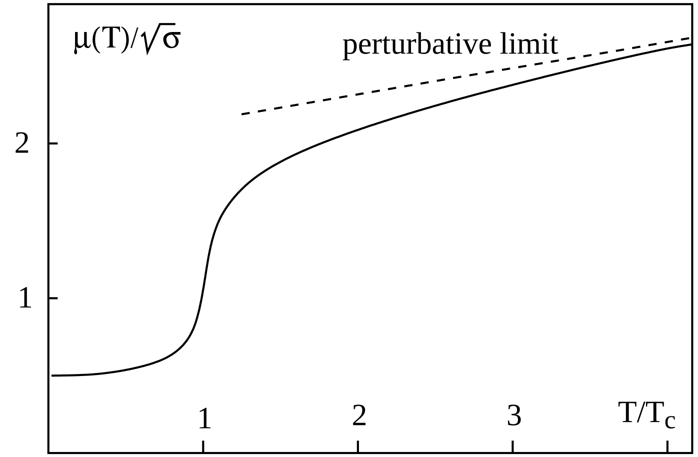
$V(r,T) = xF(r,T) + (1-x)U(r,T)$ — medium and pair split the entropy cost the more the pair pays, the tighter is its binding....with obvious consequences on dissociation temperatures

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

  potential model calculations

  must use

  parametrization of lattice data



indicative results

for $T_{\rm diss}/T_c$

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 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?

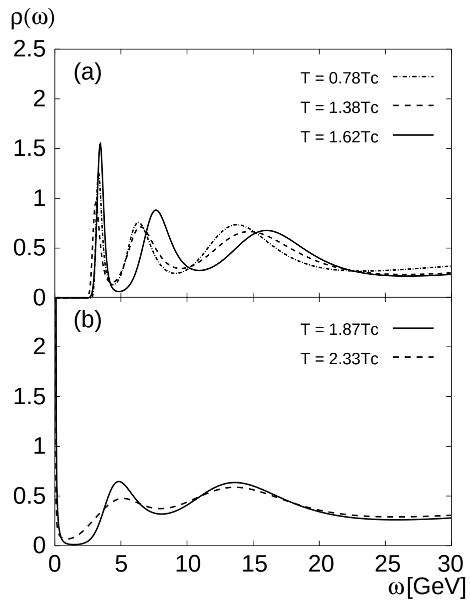
charmonia quenched:

- 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?

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

choose two extreme cases as DF

– DF1: $\sigma(\omega, T = 0)$, quarkonium spectrum in vacuum
– DF2: $\sigma_{\text{free}}(\omega, T)$, spectrum for free $Q\bar{Q}$ pair at T

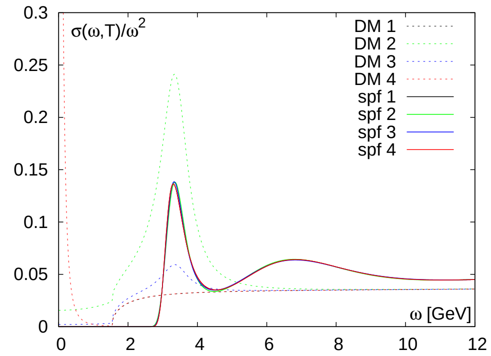
- what does MEM specify for $\sigma(\omega, T)$ from correlators at T?

- consider calculations in quenched QCD for PS channel

– at $T = 0.75\ T_c$ for $N_x = 128$, $N_\tau = 96$, 132 configs.
– at $T = 1.50\ T_c$ for $N_x = 128$, $N_\tau = 48$, 471 configs.
– at $T = 2.25\ T_c$ for $N_x = 128$, $N_\tau = 36$, xxx configs.
– at $T = 3.00\ T_c$ for $N_x = 128$, $N_\tau = 24$, xxx configs.

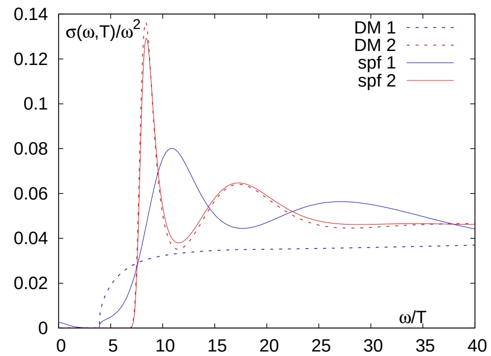
information sufficient for unique MEM results; spatial lattice size insufficient for resonance width

$$T = 0.75\ T_c$$



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

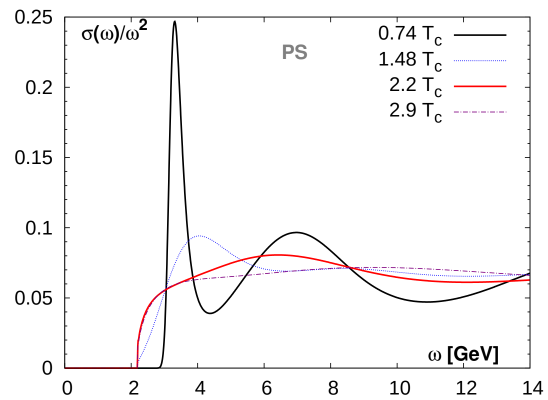
$$T = 1.50\ T_c$$



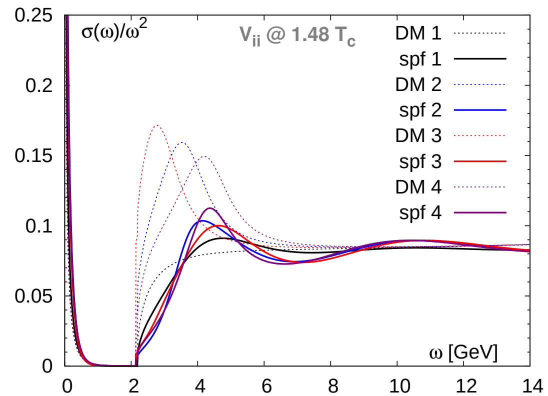
- **better statistics, larger N_τ should resolve MEM results**
- **larger N_x should (eventually) resolve resonance width**

Some further results:

increasing T shifts "peak"
to higher mass:
$\Rightarrow$ thermal peak of
unbound heavy quarks



change of default peak
not accepted by MEM



Tentative summary so far:

- J/ψ survives up to $T \simeq 1.5 - 2.0\ T_c$
- χ and ψ' dissociated at or slightly above T_c

But there are further questions:

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

– Lattice calculations provide quarkonium spectrum with given resonance width, position;
  how wide can it get, how far can it shift and still be J/ψ?

Possible way out: melting region is quite narrow in T?

$\exists$ observable consequences for nuclear collision experiments?

3. Quarkonium production is suppressed in nuclear collisions

...but for a variety of reasons

- **nuclear modification ("shadowing") of parton distribution functions**
- **parton energy loss in cold nuclear matter**
- **pre-resonance dissociation ("absorption") in cold nuclear matter**
- **dissociation by screening ("melting") and/or collisions in hot QGP**

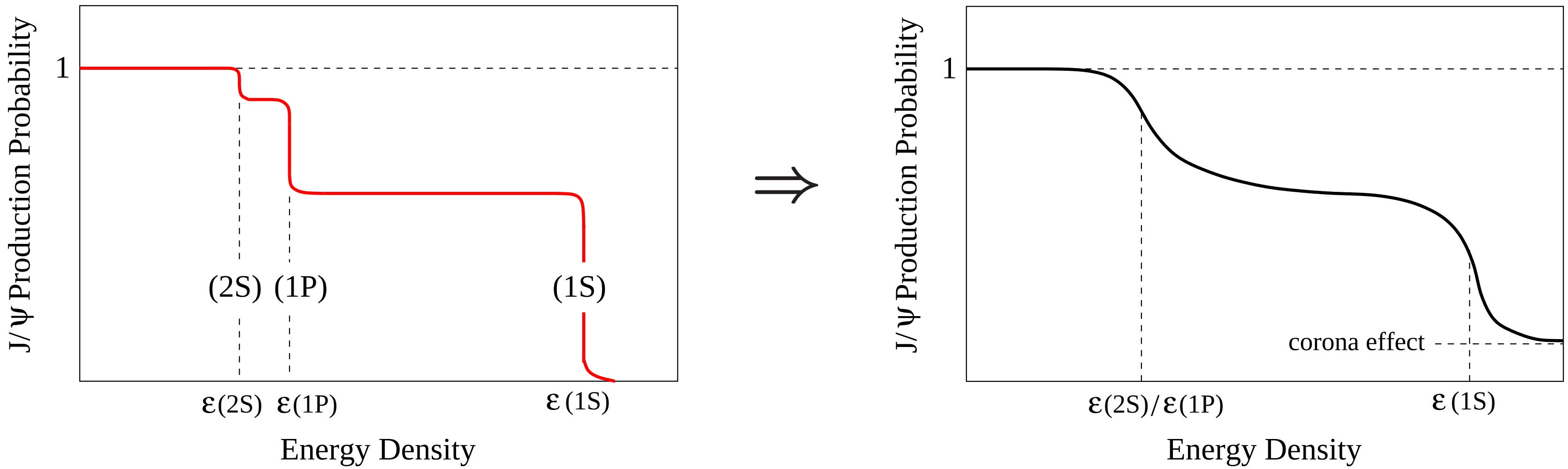
assume both initial & final state cold nuclear matter effects are taken into account correctly;

SPS & RHIC: $\exists$ remaining 50 % $\pm$? "anomalous" suppression

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

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

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



IF charmonium/bottomonium thresholds are measurable:

- experimental test of quantitative statistical QCD results

$\Rightarrow$ no charmonium production at the LHC?

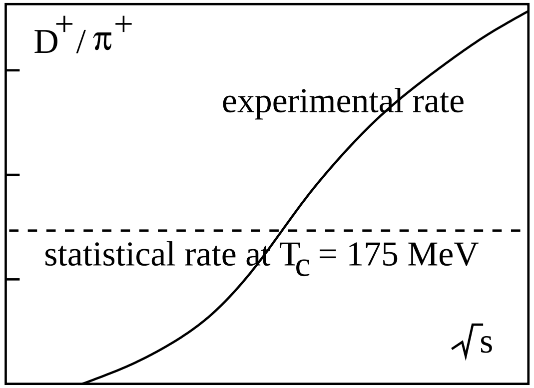
– corona effect

– 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 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**

- **simplified illustration...assume at "LHC" per event**

100 $c\bar{c}$ pairs   1000 $q\bar{q}$ pairs

non-statistical fraction; statistical $\sim 10^{-3}$ for $T_c = 175$ MeV

primary rates:

1 J/ψ, 99 D, 99 $\bar{D}$, 901 light hadrons $\Rightarrow$ $R_{AA} \simeq 1$

rates for statistical combination of given quark abundances:

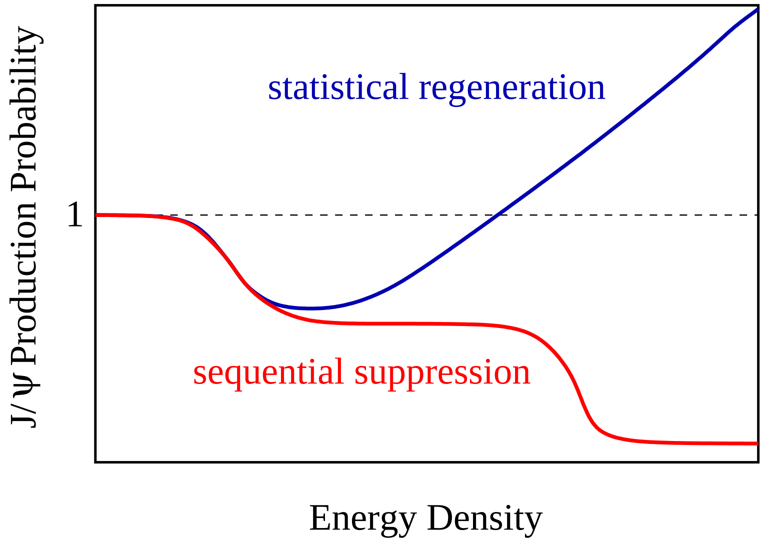
10 J/ψ, 90 D, 90 $\bar{D}$, 910 light hadrons $\Rightarrow$ $R_{AA} \simeq 10$

$\Rightarrow$ J/ψ production strongly <u>enhanced</u> re scaled pp rate

$$\Rightarrow \frac{J/\psi}{D} \simeq 0.1 \text{ instead of } 0.01 \text{ in } pp$$

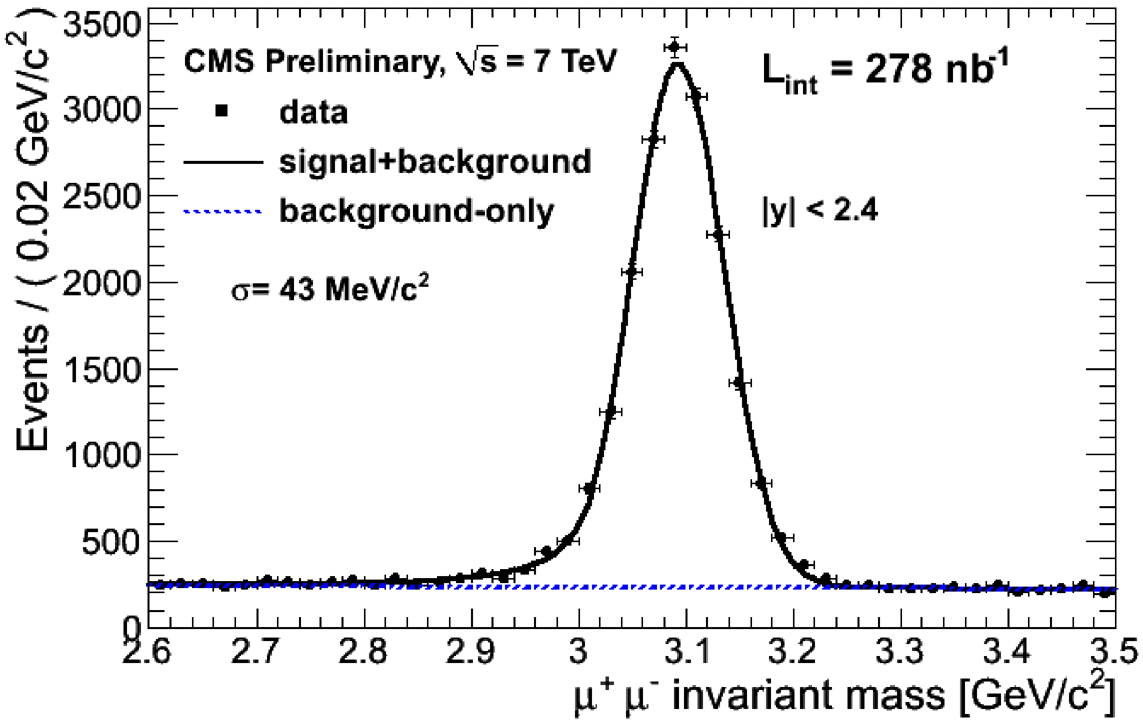
ratio of hidden/open charm strongly enhanced re pp ratio

two readily distinguishable predictions for anomalous J/ψ production

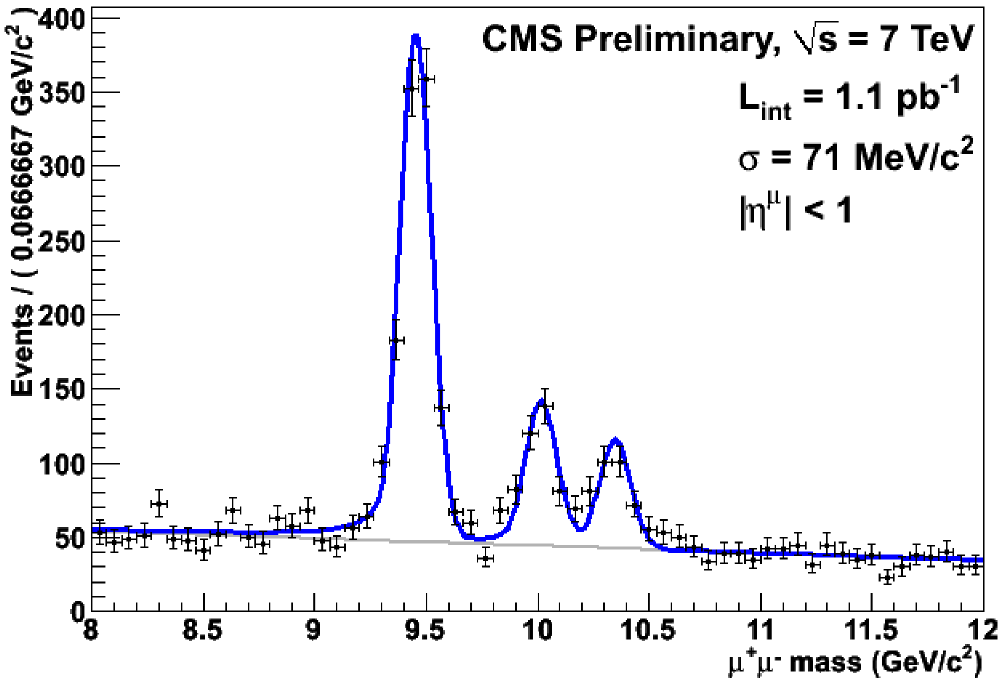


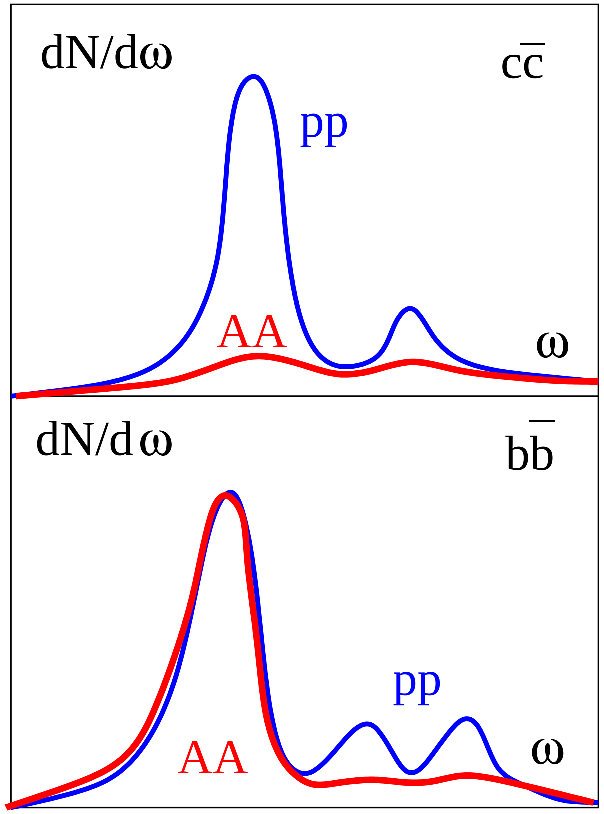
dynamical vs. statistical momentum spectra Mangano & Thews 2003

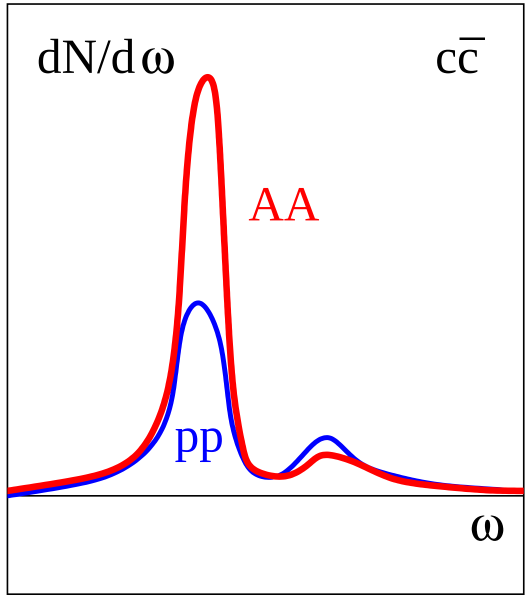
NB: assumption of statistical quarkonium binding...



CMS Preliminary, √s = 7 TeV
data
signal+background
background-only
σ= 43 MeV/c²
L_int = 278 nb⁻¹
|y| < 2.4
Events / (0.02 GeV/c²)
μ⁺ μ⁻ invariant mass [GeV/c²]


CMS Preliminary, √s = 7 TeV
L_int = 1.1 pb^-1
σ = 71 MeV/c^2
|η^μ| < 1
Events / (0.0666667 GeV/c^2)
μ^+μ^- mass (GeV/c^2)
0
50
100
150
200
250
300
350
400
8
8.5
9
9.5
10
10.5
11
11.5
12





sequential suppression by color screening: only (possible) survivor is Υ

statistical regeneration: more J/ψ than in scaled pp

Conclusions

Given reference measurements of open charm/bottom production,

experimental quarkonium studies at the LHC can ask

conceptual [model-independent] questions and provide

conceptual [model-independent] answers to these.

Quantitative details require specific theory/model input.