Lecture 3

Quarkonia

in Deconfined Matter

Contents

1. Quarkonia are very **unusual** hadrons

2. Quarkonia **melt** in a hot QGP

3. Quarkonium production is **suppressed** in nuclear collisions

4. Quarkonia can be **created** at QGP hadronization

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

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

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

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

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

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
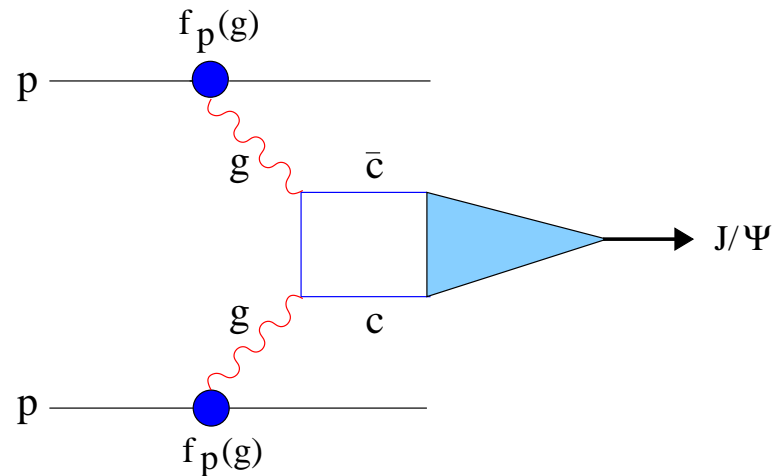
$\Rightarrow$ quarkonia are **unusual**

− very small:

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

− very tightly bound:

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

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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 <u>elementary collisions</u>:

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

- $(dN_{\text{ch}}/dy) \sim \ln s$

- $N_{c\bar{c}}/N_{\text{ch}}$ grows with collision energy   **compare** $[N_{s\bar{s}}/N_{\text{ch}}]$

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

- $(dN_{J/\psi}/dy)/(dN_{c\bar{c}}/dy) \simeq 0.02,$ **compare** $[N_\rho/N_{\text{ch}}]$
  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

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Quarkonium production in elementary collisions: no medium

What happens to quarkonia in hot strongly interacting media?

2. Quarkonia melt 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 $r_D(T_i) = r_i$,
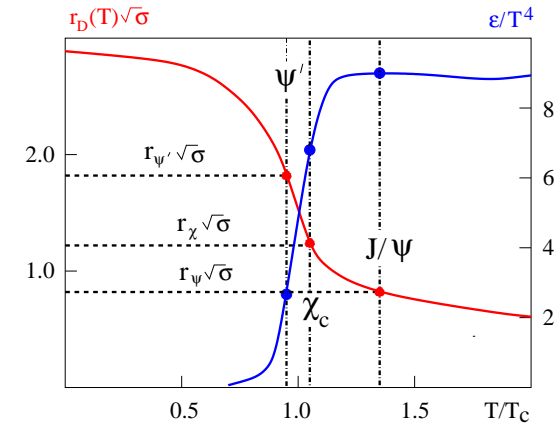specify temperature of QGP

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
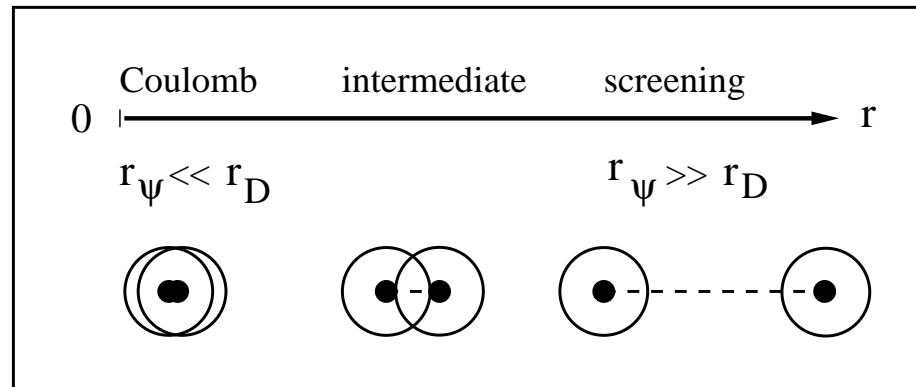
- $r_{J/\psi} \ll r_D(T)$: quarkonium does not see medium

- $r_{J/\psi} \gg r_D(T)$: 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 <u>free energy difference</u> $F(r, T) = F_Q(r, T) - F_0(T)$

<u>internal energy difference</u> $U(r, T)$ & <u>entropy difference</u> $S(r, T)$

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

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

- **weakly interacting plasma** (QED, perturbative QCD)

Laine et al. 2007, Beraudo et al. 2008, 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)

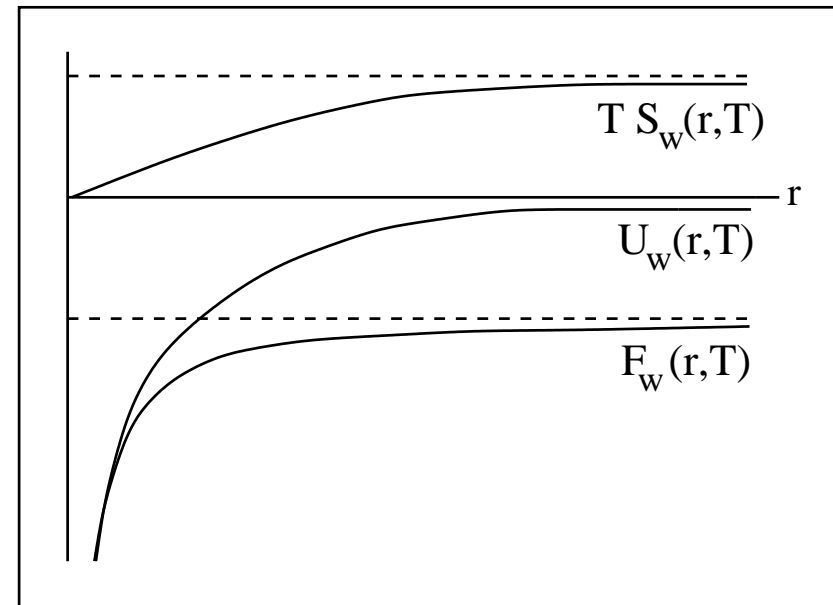**short distance limit (Coulomb regime)**

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

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

melting process:

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

overall energy balance $= 0$

T S_w(r,T)

r

U_w(r,T)

F_w(r,T)

so far: perturbative limit $\sim$ weakly interacting plasma

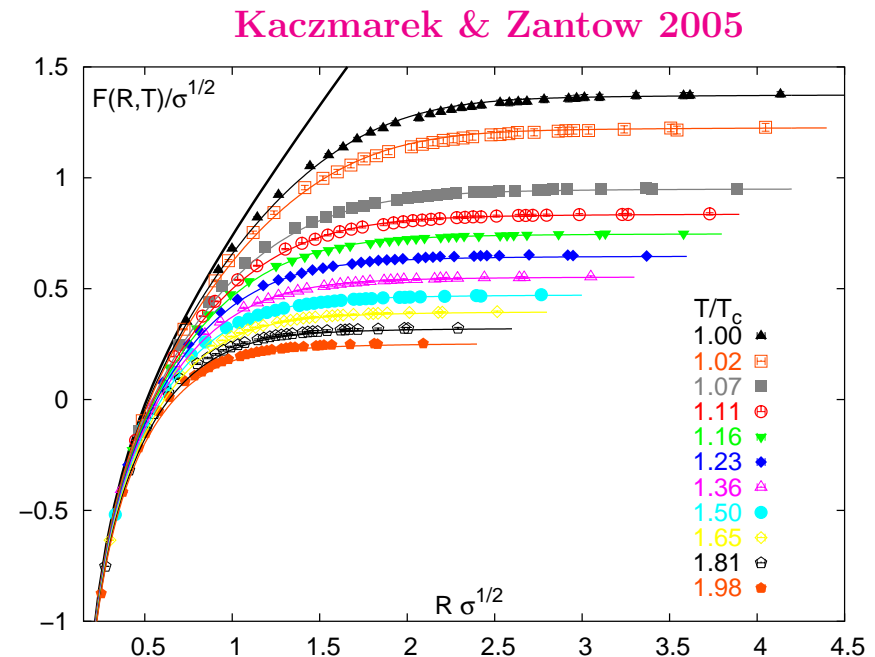(Debye-Hückel theory, slightly non-ideal gas)

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

• <u>strongly interacting QGP</u> $(T_c \leq T \leq 3\,T_c)$

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

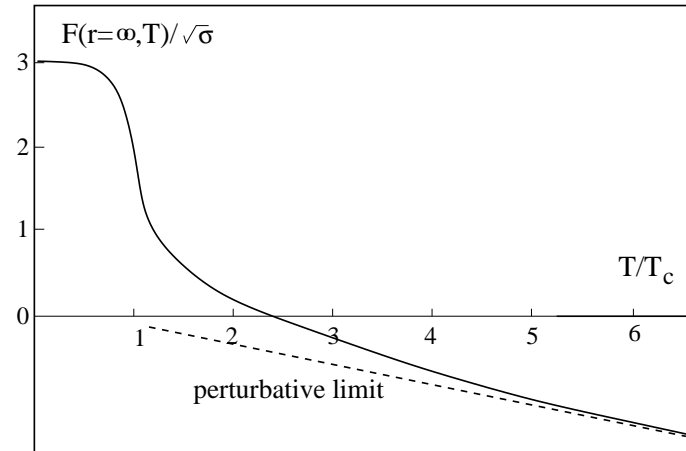   separate strong part

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

Kaczmarek & Zantow 2005

$F(R,T)/\sigma^{1/2}$

T/T_c
1.00
1.02
1.07
1.11
1.16
1.23
1.36
1.50
1.65
1.81
1.98

$R\,\sigma^{1/2}$

$T_c \leq T \lesssim 3\,T_c$: 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 $F_s(\infty, T) = \sigma/\mu(T)$
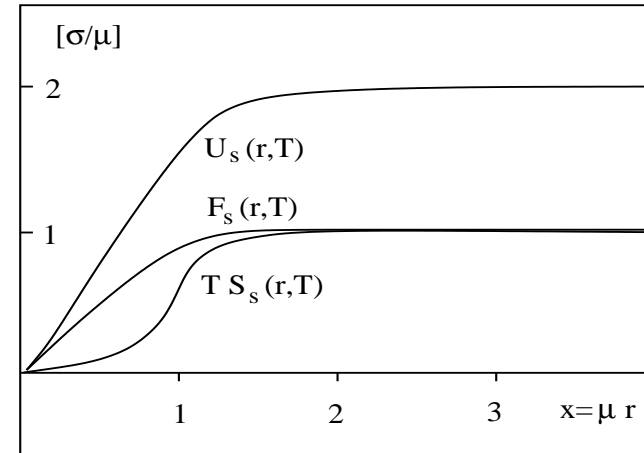
in contrast to $\qquad F_w(\infty, T) = -\alpha\mu(T)$

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

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the more the pair pays, the tighter is its binding....with obvious consequences on dissociation temperatures

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

  potential model calculations must use parametrization of lattice data
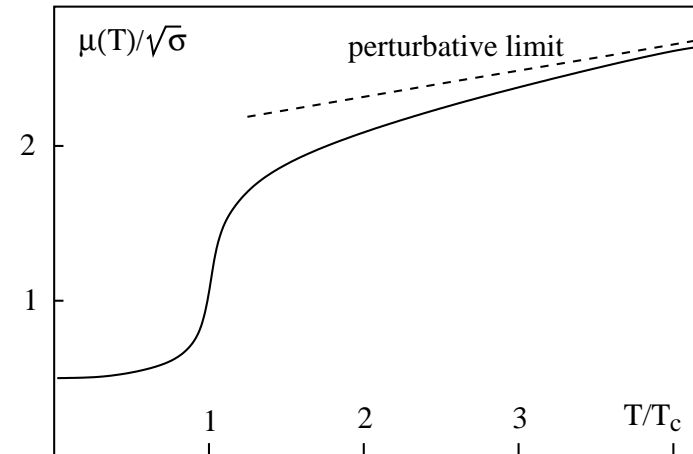
indicative results
for T_{diss}/T_c

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

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• <u>Lattice Studies of Quarkonium Spectrum</u>

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 (small) discrete number of lattice points with limited precision ("mosaic fragments")

general solution: Maximum Entropy Method (MEM)

here: Asakawa and Hatsuda 2004

technical aspects:

– MEM requires input reference ("default") function for σ;
dependence on default function?

– constant contribution at $\omega = 0$
must be removed

charmonia quenched:

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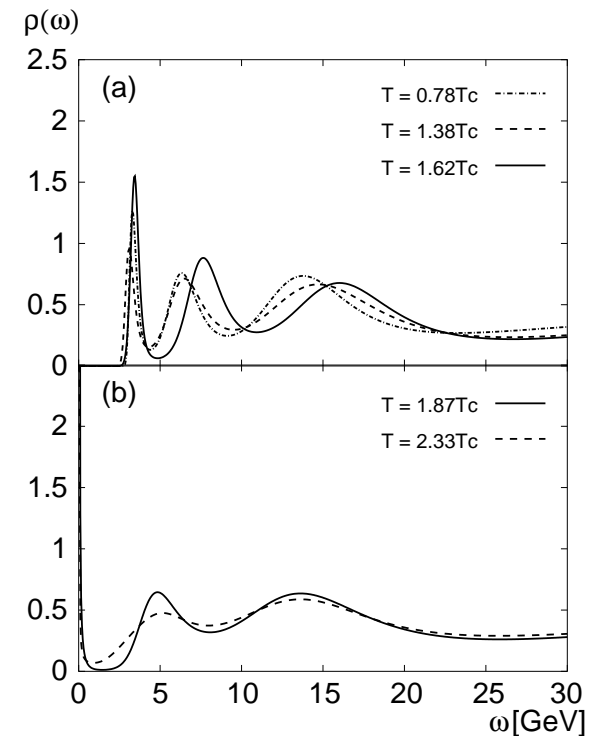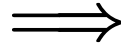Asakawa & Hatsuda 2004
Datta et al. 2004
Iida et al. 2005
Jakovac et al. 2005

charmonia unquenched:

Aarts et al. 2005, 2007

$\Longrightarrow$

Tentative summary of present results

- J/ψ survives up to $T \simeq 1.5 - 2.0\ T_c$

- χ and ψ' dissociated at or slightly above T_c

- in accord with U-based potential studies

preliminary, extensive work in progress Ding et al. 2009

NB: correlator ratio studies $\Rightarrow$ so far inconclusive...

if <u>statistical QCD</u> determines T_{diss} for all quarkonium states, $\exists$ observable consequences for nuclear collision <u>experiments</u>?

<u>3. Quarkonium production is suppressed</u>

<u>in nuclear collisions</u>

...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 $\rightarrow$ 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
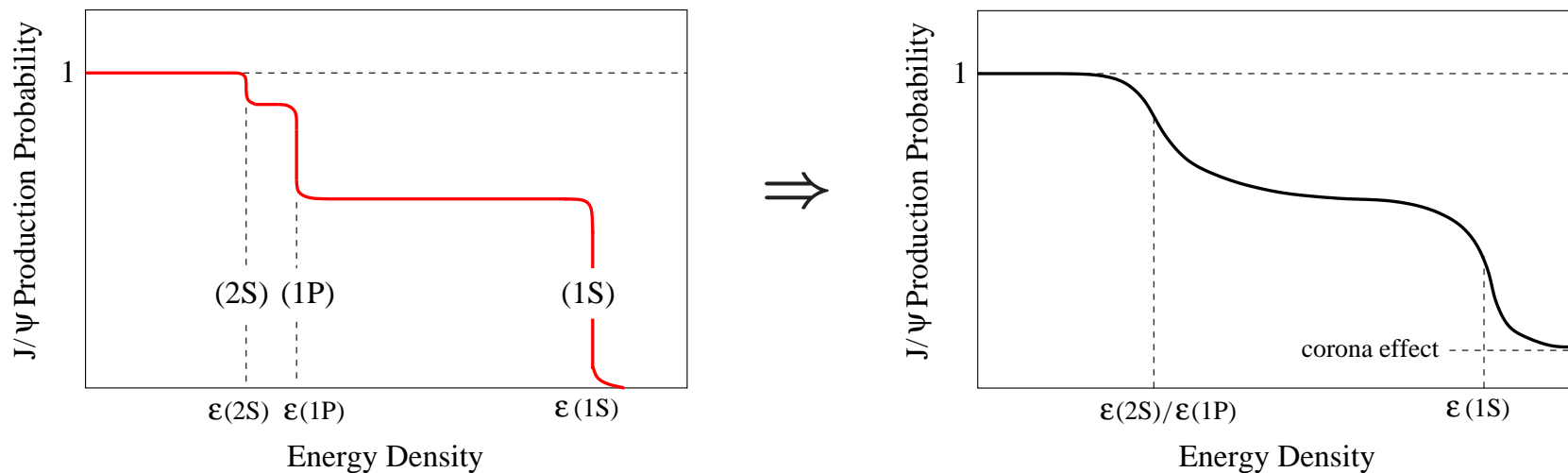
IF charmonium/bottomonium thresholds are measurable:

 • (the only?) experimental test of <u>quantitative</u> statistical
                                                        QCD results
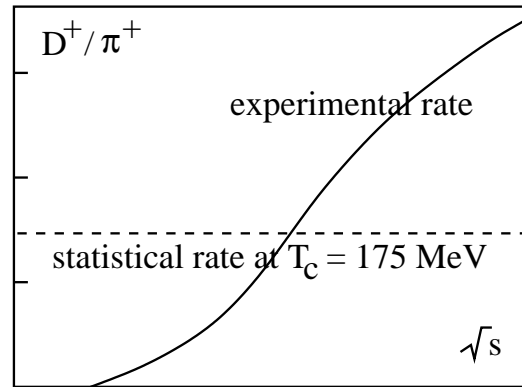
$\Rightarrow$ no charmonium production at the LHC?

– corona effect

– significant B production $\rightarrow$ charmonium production via feed-
   down from B decay; check through pp studies

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

The figure shows a plot with axis labels D^+/π^+ (vertical) and $\sqrt{s}$ (horizontal). A curve labeled "experimental rate" rises with $\sqrt{s}$, and a horizontal dashed line is labeled "statistical rate at $T_C = 175$ MeV".

- 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

$$100 \; c\bar{c} \text{ pairs} \qquad 1000 \; q\bar{q} \text{ pairs}$$

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

primary rates:

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

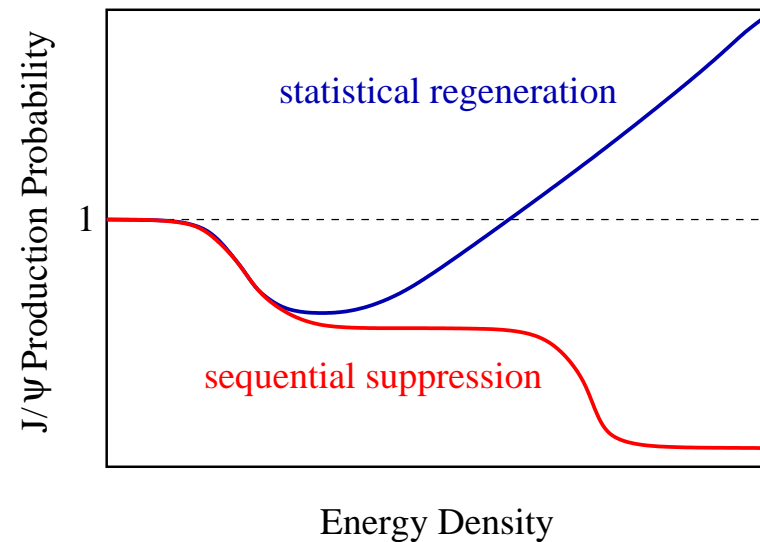rates for statistical combination of given quark abundances:

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

$\Rightarrow J/\psi$ 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...

Crucial Questions

- what is the correct potential in strongly interacting QGP?

- quantitative predictions for dissociation from NRQCD(T)?

- direct lattice QCD calculation of quarkonium spectra?

- control of all cold nuclear matter effects?

- sequential suppression or statistical regeneration?

Crucial Questions

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Can the LHC lead to the Answers?