The In-Medium Behaviour of Finite Width Charmonia

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Statistical QCD

For $T \geq T_c \simeq 150 - 200$ MeV, strongly interacting matter becomes plasma of deconfined quarks and gluons (QGP)

How to probe QGP in strong interaction thermodynamics?

- **e-m signals (real or virtual photons)**
- **quarkonia ($Q\bar{Q}$ pairs)**
- **jets (fast partons)**

Ultimate aim:

ab initio **calculation of in-medium behaviour of probes**

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Survival of Charmonium States in Hot QGP

⇒ Spectral Analysis of QGP ⇐

NB: Thermodynamics, not nuclear collisions

Conceptual basis

- QGP consists of deconfined colour charges, hence

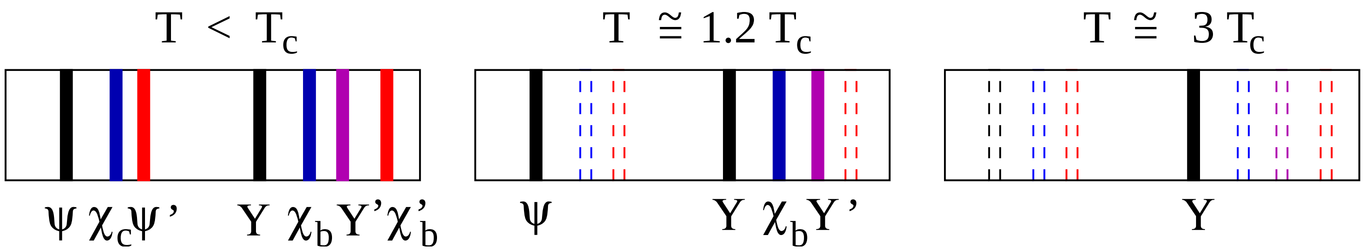
  $\exists$ colour charge screening for $Q\bar{Q}$ probe

- screening radius $r_D(T)$ decreases with temperature T

- when $r_D(T)$ 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 specify temperature of QGP



How can one calculate quarkonium dissociation points?

Two possibilities:

- **solve Schrödinger equation using a temperature-dependent heavy quark potential** $\boldsymbol{V(r,T)}$
- **calculate quarkonium spectrum directly in finite** T **lattice QCD**

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1. Potential Models for Quarkonium Dissociation

- heavy quark potential $\sim$ Schwinger model

Karsch et al. 1988

Digal et al. 2001

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

with screening mass $\mu(T) = 1/r_D(T)$

solve Schrödinger equation: with increasing T, bound state i disappears at some $\mu_i(T) = \mu(T_i)$

use screening mass from lattice estimates $\mu(T) \simeq 4\,T$ for $T > 0$ to determine dissociation temperature T_i

charmonia:

$$\boxed{\begin{array}{c} \psi' \text{ and } \chi_c \text{ dissociated at } T \simeq T_c \\ J/\psi \text{ at } T \simeq 1.2\ T_c \end{array}}$$

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- determine potential $V(r,T)$ from lattice studies of heavy quark free energy; various different forms

  Shuryak & Zahed 04; Wong 04,...; Alberico et al. 05,...; Digal et al. 05; Mocsy & Petreczky 05,...

  Lattice studies provide free energy difference $F(r,T)$ between medium with and without heavy quark pair; one possibility:

  $F = U - TS,\ S = (\partial F/\partial T)$ specifies internal energy $U(r,T)$

$$V(r,T) = U(r,T) = F(r,T) - T(\partial F/\partial T)$$

  with $N_f = 2$ lattice results for $F(r,T)$.

  no need of any separate screening mass

solve Schrödinger equation: with increasing T, bound state i disappears at some T_i

charmonia:

ψ' dissociated at $T \simeq 1.1\ T_c$

χ_c dissociated at $T \simeq 1.2\ T_c$

J/ψ survives up to $T \simeq 2\ T_c$

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- reason for later dissociation: $U(r,T)$ provides stronger binding than Schwinger model potential

  ambiguity in specifying "lattice" potential: $U(r,T)$ or $F(r,T)$

  $F(r,T)$ results $\sim$ Schwinger model

  various alternatives: $V(r,T) = a\ F(r,T) + b\ U(r,T)$ reduce binding, lower dissociation temperatures

- dissociation defined mathematically, by $r \to \infty,\ \Delta E \to 0$

  hence $\exists$ a bound state region in which $r > 1/T,\ \Delta E < T$

what does that mean?

resolution: determine dissociation points <u>directly</u> in finite $\boldsymbol{T}$ lattice QCD

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2. Lattice Studies of In-Medium Charmonium Survival

quenched: Umeda et al. 01,...; Asakawa & Hatsuda 04; Datta et al. 04,...; Iida et al. 05; Jakovac et al. 05; unquenched: Aarts et al. 05,...

Calculate correlation function $G_i(\tau, T)$ for specific mesonic quantum number channel i, specified by spectral distribution $\sigma_i(\omega, T)$

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

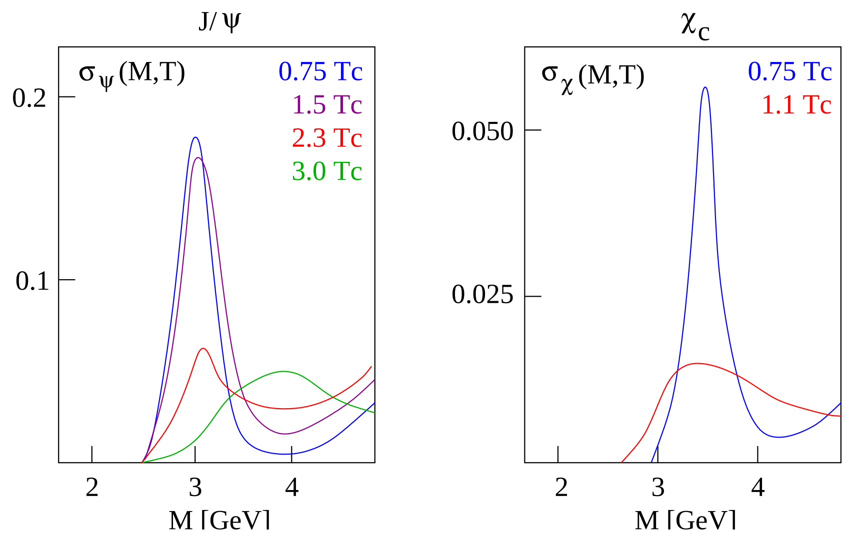
with kernel

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

relating imaginary time τ and $c\bar{c}$ energy ω; invert $G(\tau, T)$ by MEM to get $\sigma(\omega, T)$:

- results for quenched and unquenched ($N_f = 2$) QCD agree schematic pattern

lattice resolution limits precision; reliable only for resonance peak strength & position, not for widths & continuum ($\omega > 4 - 5$ GeV)



charmonia

χ_c is dissociated for $T \geq 1.1\ T_c$

J/ψ persists up to $1.5\ T_c < T < 2.3\ T_c$

preliminary conclusion: – higher excited states melt near T_c

– J/ψ melts around $2\,T_c$

(in accord with U-based potential model studies)

- caveat: finite T widths

report here on an attempt to address this problem:
H.-T. Ding, O. Kaczmarek, F. Karsch, HS (in preparation)

3. Construction Kit for Spectral Distributions

recall correlator $G(\tau, T) = \int d\omega\ \sigma_i(\omega, T)\ K(\omega, \tau, T)$

with kernel $K(\omega, \tau, T) = \cosh[\omega(\tau - (1/2T))]/\sinh(\omega/2T)$

and spectral distribution $\sigma_i(\omega, T)$ in $c\bar{c}$ channel i

present standard lattice study of charmonia in hot QGP:

compare correlator $G(\tau, T)$ for $T > T_c$
to a reference correlator $G_0(\tau, T)$
using spectral function at $T = 0$

$$G_0(\tau, T) = \int d\omega\ \sigma_i(\omega, T = 0)\ K(\omega, \tau, T)$$

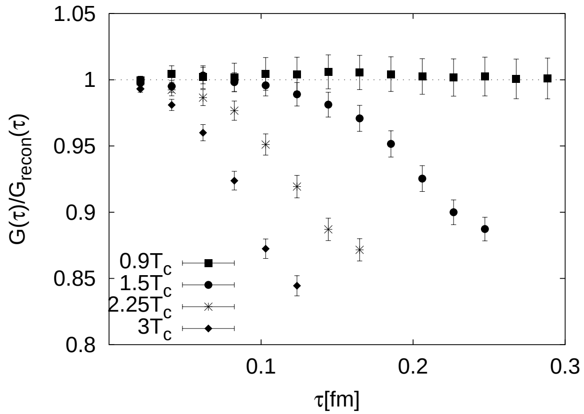
shows what correlator would look like if spectrum at $T > T_c$ were same as at $T = 0$

ratio $R(\tau, T) = G(\tau, T)/G_0(\tau, T)$

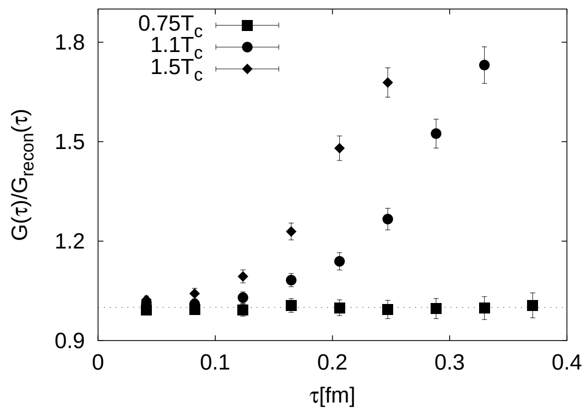
indicates finite temperature modifications of spectrum

use for $\sigma_i(\omega, T=0)$ spectrum obtained for $0 < T \ll T_c$ from lattice QCD via MEM (some lattice artifacts cancel); get

Datta et al. 04



J/ψ (vector channel)

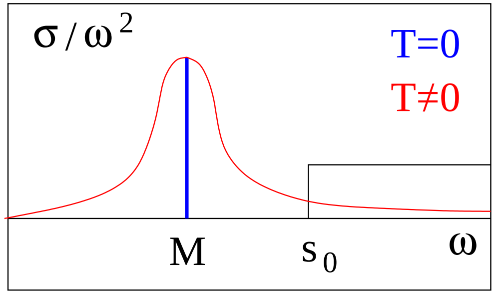


χ_{c0} (scalar channel)

what does this tell us about spectrum, about compatibility of potential theory and lattice results?

Mocsy & Petreczky 05,...; Wong 06,...; Alberico et al. 06;...

idealized spectrum at $T = 0$



$$\sigma(\omega, T = 0) = f\ \delta(\omega - M) + c\ \omega^2\theta(\omega - s_0)$$

$f \sim$ strength of resonance
$c \sim$ strength of continuum

assume that at $T > 0$ resonance broadens (relativistic B-W),
but retains same strength

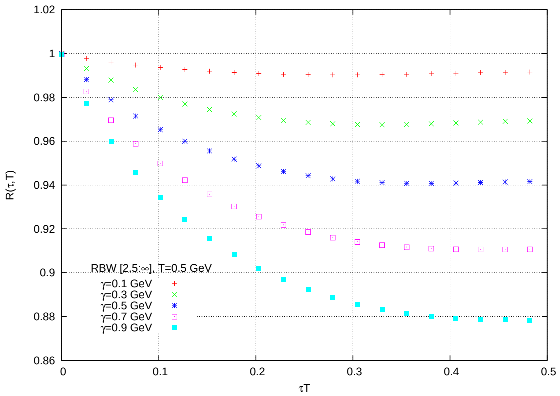
$$\sigma_r(\omega, T) = N(\gamma)\ f\ \frac{M}{\pi}\left\{\frac{2\omega\gamma}{\omega^2\gamma^2 + (\omega^2 - M^2)^2}\right\}$$

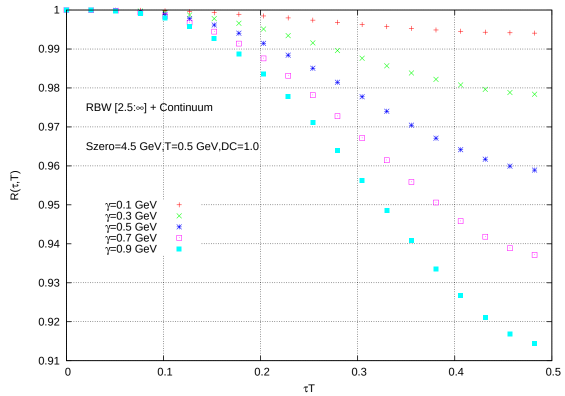
$N(\gamma)$ assures normalization for width $\gamma = \gamma(T)$

calculate correlator ratio $R(\tau, T) = G(\tau, T)/G_0(\tau, T)$

– using resonance contribution only, with $2\ m_c \leq \omega$
– using resonance, with $2\ m_c \leq \omega$, plus $T = 0$ continuum

[NB: no zero mode]

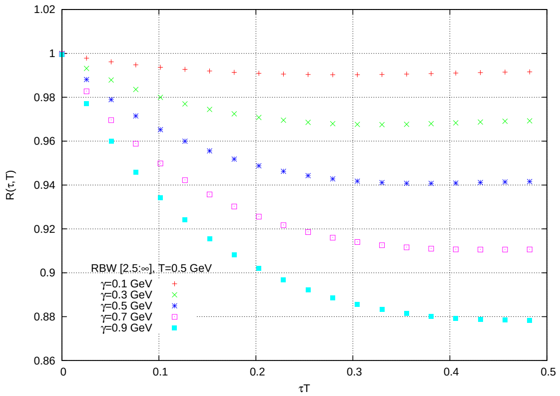


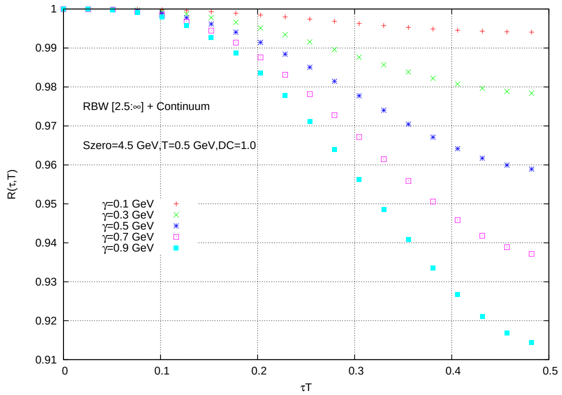


resonance only **resonance + continuum**

for $\gamma \leq 0.5 - 0.8$ GeV correlator ratio decreases with τ,
but varies less than 10 %

conclusion: $R(\tau, T) \simeq 1$ compatible with resonance broadening over wide range of widths





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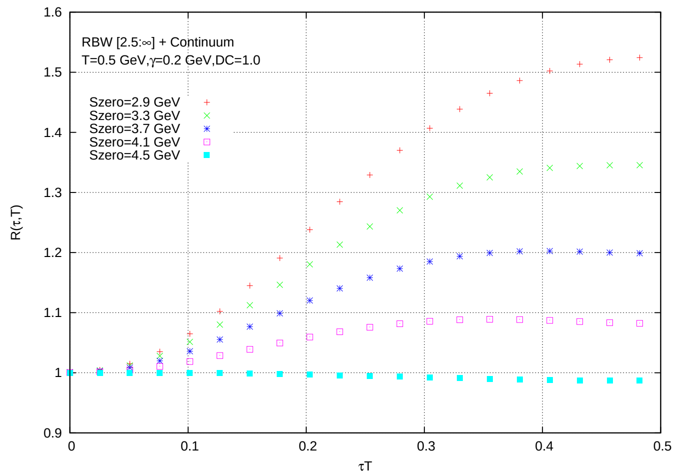
continuum threshold $\sim$ open charm threshold

for $T > T_c$, M_D decreases
(decrease with T of $F(T, r = \infty)$ in heavy quark lattice studies)

what happens for decreasing continuum threshold $s(T) < s_0$?

correlator ratio increases
rapidly with decreasing $s(T)$



competing effects:

– increase γ $\Rightarrow$ $R(\tau, T) \Downarrow$

– decrease $s(T)$ $\Rightarrow$ $R(\tau, T) \Uparrow$

decrease of continuum threshold affects χ_c at lower T
than J/ψ or η_c

hence possible; R_χ increases with τ
$R_{J/\psi}$ decreases with τ

check in detail

Still missing:

$\omega = 0$ contribution to spectrum at $T \neq 0$:

c and $\bar{c}$ annihilate & "heat the medium"

contribution to spectral function:

$$\sigma_0(\omega) = T\ a(T)\ \omega\ \delta(\omega)$$

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we're tuning, stay tuned...

last word not yet known

$\Rightarrow$ talk of <u>Agnes Mocsy</u> for alternative