Study of heavy quark systems in a gluonic plasma

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Introduction

Heavy quarks: important probes of quark-gluon plasma

- quarkonia
- Heavy-light mesons: flow

Can flow of D, B, ... be understood as a diffusive process?
What do we know about quarkonia in equilibrium plasma?
Phenomenology in heavy ion collisions much harder

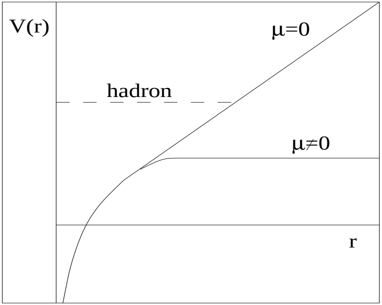
- Production: color octet passing through plasma?
- Coherent energy loss
- Time evolution of plasma
- Regeneration

(see arXiv:1403.8151 for discussion)

Quarkonia: finite temperature potential

Screening in plasma $\Longrightarrow$ reduced binding between $\bar{c}c$

T. Matsui & H. Satz, Phys. Lett. B 178 (1986) 416.



Free energy of a static $q\bar{q}$ pair at distance r

$$F_{T=0}(r) \sim -\frac{\alpha}{r} + \sigma r$$

$$F_{T>T_c}(r) \sim -\frac{\alpha(T)}{r} e^{-\mu(T) r}$$

A pattern of sequential suppression.
$\eta_c, J/\psi$ dissolves by 1.2 T_c

Karsch & Satz, 1991; Digal, Petreczky & Satz, 2001.

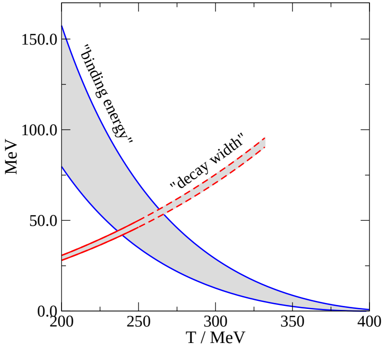
No theoretical ground for using $F_{T>T_c}(r)$ as potential.
Variations, like "internal energy" $U = \frac{\partial(F/T)}{\partial(1/T)}$ has been used.

Definition of potential

Can we write down a potential for, e.g., melting of the J/ψ peak in the dilepton channel?

$$V(r) = -\frac{4}{3}\alpha_s \left(\frac{e^{-m_D r}}{r} + m_D\right) - i\frac{8}{3}\alpha_s T\,\Phi(r)$$

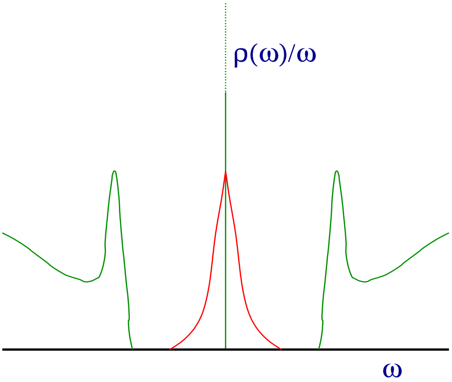
M. Laine, O. Philipsen, P. Romatschke and M. tassler, JHEP 0703 (2007) 054.



- Perturbative
- Have been attempts to calculate the potential non-perturbatively from lattice.
- *No justification for using $U(r,T)$ in quarkonia studies.*

Direct lattice study?

Problem at hand: find spectral function, e.g., $\rho_{\bar{c}\gamma_i c}(\omega)$ and the melting of the J/ψ peak in the dilepton channel.



Can we calculate ρ using lattice QCD?

Lattice analysis

- Study the Euclidean field theory on discretized space-time
- Can calculate $G_{\bar{c}\gamma_i c}(\tau) = \langle \bar{c}\gamma_i c(\tau)\ \bar{c}\gamma_i c(0)\rangle_T$ nonperturbatively, using numerical techniques
- Invert $G_{\bar{c}\gamma_i c}(\tau) \;=\; \int d\omega\, \rho(\omega)\, \frac{\cosh \omega(\tau - \frac{1}{2T})}{\sinh \frac{\omega}{2T}}$.
- Highly unstable in the discretized theory and with $G(\tau)$ of finite accuracy
- Maximum entropy method: use prior information to keep in check uncontrolled directions in search space.
- Widely used for charmonia.
- First studies: 1S charmonia survive till quite deep in plasma, while the 1P states dissolve early.

  Datta, Karsch, Petreczky, Wetzorke, 2004; Asakawa & Hatsuda, 2004

- But correlators are completely consistent with other scenarios.

  Umeda, 2007; Mocsy and Petreczky, 2007-2009.

Bottomonia from lattice

- Study of bottomonia difficult as large discretization error ($m_b a \sim 1$)
- Study using NRQCD: $\Upsilon(1S)$ and $\eta_b(1S)$ survive till $> 2T_c$
  However, large width: $\sim$ 300 MeV at 1.5 T_c

  G. Aarts, et al., JHEP 1111 (2011), 103; JHEP 1312 (2013) 064.
- χ_{b_0}, χ_{b_1} drastically modified in the plasma.

  Aarts et al.
- Much smaller width of $\Upsilon(1S)$ found in a recent study.

  S. Kim, P. Petreczky and A. Rothkopf, arXiv:1310.6461.
- Would be good to have a different kind of analysis. Even qualitative insight will be valuable.

Relativistic bottom in gluon plasma

- NRQCD: discretization error difficult to control.
- We study relativistic bottom.
- Gluonic plasma: can use sufficiently fine lattices, $a = 9.7$ and 13 GeV, and nonperturbatively $\mathcal{O}(a)$ improved bottom action.
- For thermal decay of bottomonia, thermal quarks not expected to be important.

D. Kharzeev & H. Satz, Phys. Lett. B334 (1994) 155

- Study "subtracted correlator" $G(\tau) - G(1/2T)$
- Subtraction required to isolate the diffusion peak at low ω

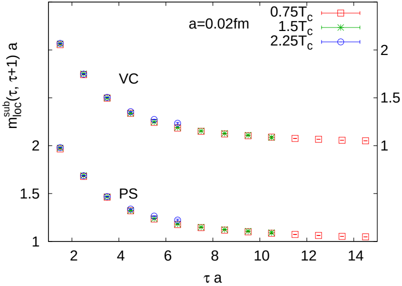
Umeda 2007; Datta & Petreczky 2008; Petreczky 2009

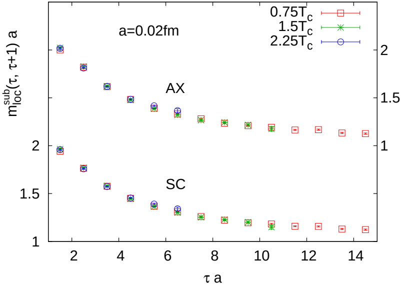
- Diffusion part has been calculated using lattice QCD.

Francis, et al., arXiv:1311.3759.
Banerjee, Datta, Gavai, Majumdar, Phys. Rev. D 85 (2012) 014510..

"Subtracted" Local masses

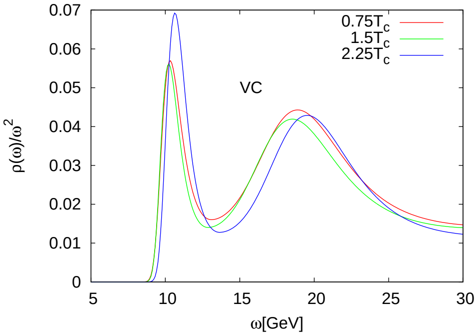
"Local masses" : if correlation caused by a single stable particle, what is its mass?





No dramatic change on crossing T_c

Spectral function using MEM



ρ using maximum entropy method and free theory result as prior information.

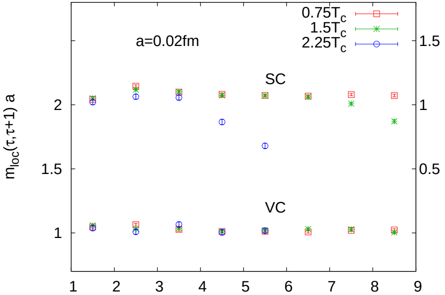
Sensitive to prior information.

Also not suitable for extraction of width.

Smeared correlators

Use Gaussian smeared currents, to isolate the behavior of the lowest state

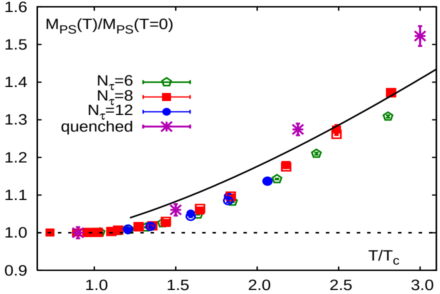
Note: this current does not directly connect to dilepton channel.



A (questionable) Breit-Wigner form gives $\Gamma < 0.1T$ for $\Upsilon(1S)$ at 1.5 T_c.

Spatial "screening" correlator

"Screening correlator": measures screening of $\bar{b}\Gamma b$ source.
Study of correlator easier, but interpretation in terms of spectral function more difficult.



Indicative of dissolution of J/ψ around $T \sim 1.5\,T_c$.

Karsch, Laermann, Mukherjee, Petreczky, PRD 85('12) 114501

Quenched study

Similar behavior observed earlier in quenched QCD, where spatial correlator was seen to show temperature effect already at 1.1 T_c. Change in screening mass does not directly imply ground state modification.

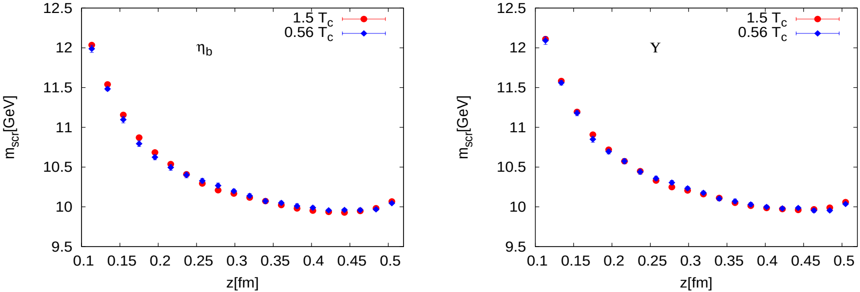
$$G(z, T) = \int \frac{dk_z}{\pi} e^{ik_z z} \int d\omega \frac{\rho(\omega, k_\perp = 0, k_z)}{\omega}$$

E.g., one can have a spectral function peak
$\delta(\omega^2 - A^2(T)\vec{p}^2) \Rrightarrow m_{\mathrm{scr}}(T) = m/A(T)$
Also difficult to distinguish between different forms of modification.

Datta, Karsch, Petreczky, Wetzorke, PRD ('04)

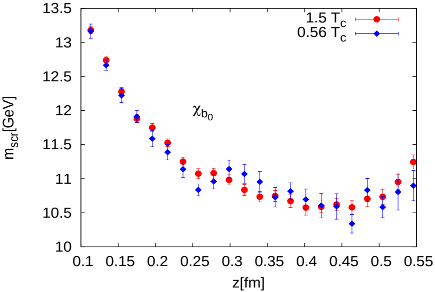
Screening of $\bar{b}b$ charges

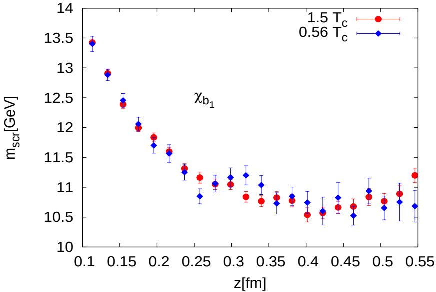
What does the screening correlator tell us about $\bar{b}b$ mesons?



Expectedly, no modification of 1S screening length at 1.5 T_c.

Screening of $\bar{b}b$ charges

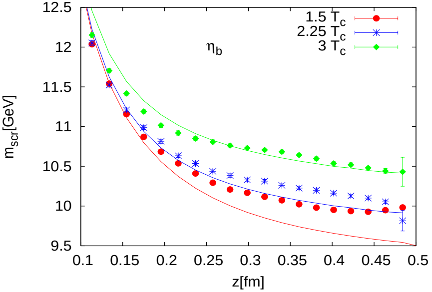


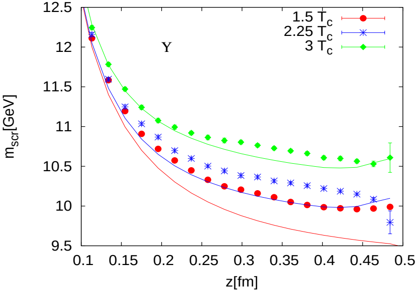


Interestingly, no modification of χ_b screening length at 1.5 T_c either.

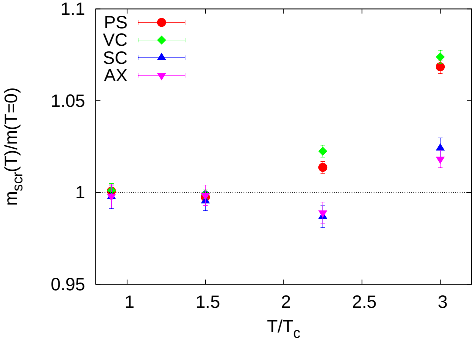
Screening of 1S $\bar{b}b$ above T_c

At 2.25 T_c, the 1S states also show a temperature dependence.





Combined plot of screening mass of $\bar{b}b$ sources



Discussion

- Study of quarkonia melting on lattice is a nontrivial problem.
- Combination of fine lattices and maximum entropy based analysis is the leading strategy now.
  But important to explore, in particular, other analysis strategies, and utilize the other theoretical results.
- We look at details of the Matsubara correlator for both point and smeared currents, as well as spatial screening correlators, to study bottomonia in plasma.
- $\Upsilon(1S)$ survives till above 2 T_c in gluonic plasma, with very little width at 1.5 T_c.
- Larger modification of the χ_b states, but survival of the peak in plasma till temperatures in excess of 1.5 T_c.