Heavy Quarks and Quarkonia at finite temperature

New results from the Lattice

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Overview

- Thermodynamics of the static QQbar pair in full QCD
  with RIKEN-BNL-Columbia-Bielefeld Collaboration
  hep-lat/0610041 [to appear in PoS]

- Quarkonia correlators and spectral functions at zero and finite temperature
  with A.Jacovác(Budapest), P.Petreczky (BNL), A.Velytsky (UCLA)
  hep-lat/0611017 [to appear in PRD]

Method Description

- Large Scale Simulation on multi-teraflop QCDOC and APE
- P4 + Fat3 fermion action
- Previous studies - Asqtad, $N_t = 4, 6$, 3F and Bielefeld (3F, $N_t = 4$)
- Full QCD, *two* light and *one* strange dynamical quarks
- Physical strange quark mass
- Almost physical quark masses [0.1 strange quark mass]
- Scale setting via zero temperature heavy quark potential
- see talk by Frithjof Karsch

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Free Energies

Determined from Polyakov Loop correlations

$$F_1(|x|,T)/T = -\ln\langle \mathrm{Tr} L(\vec{x}) L^\dagger(0)\rangle [McLerran]$$

- Not really gauge invariant
- However very physical in Coloumb Gauge [Philipsen]
- Gauge invariant at infinite separation of Q and Qbar
- Renormalization required [Karsch et al]
- Assume that at very very short distances medium does not play any role
- Therefore everything is like at $T = 0$
- Do not forget to check

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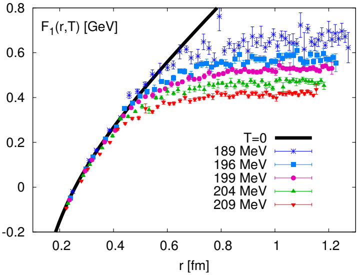
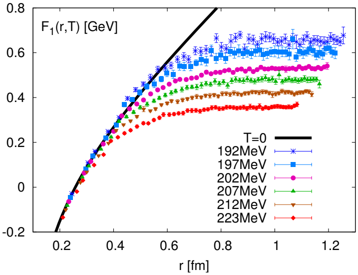
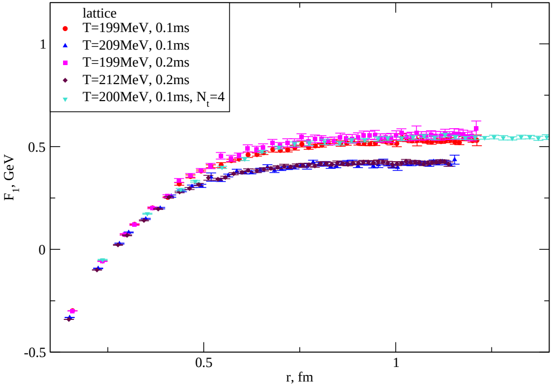




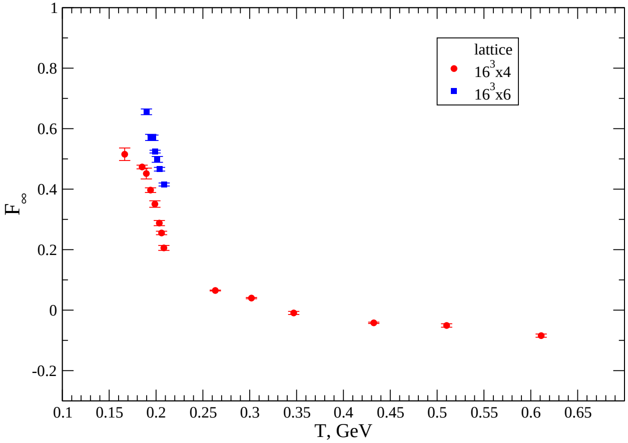
- No medium effects up to 0.3fm
- Strong effects at $r > 0.4 fm$

Checks and Balances: Scaling with m_q and N_t

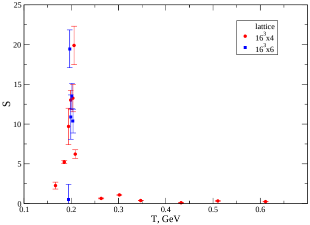


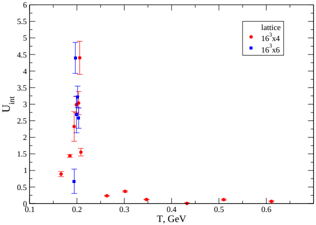
- Small cutoff effects
- Light quark mass scaling is also good

Free energy at infinite separation



Entropy and Internal Energy





- big jump in critical region
- in potential models would mean two or three-fold increase in effective mass
- food for thought.

Renormalized Polyakov Loop

- Very nice oder parameter in pure glue
- Still interesting in full QCD
- Loved by model-builders
- Needs renormalization [also see Pisarski way]
- But we define it through already renormalized F_1 [Karsch et al]

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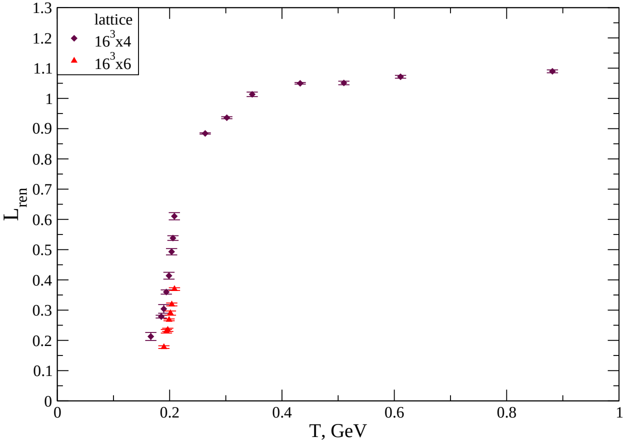
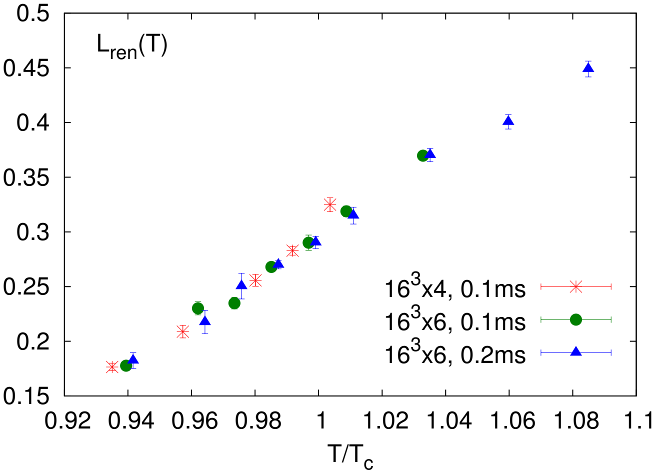
Renormalized Polyakov Loop in physical units



Renormalized Polyakov Loop Scaling



Reconstruction of the Spectral Function

- $G(\tau,\vec{p}) = \int_0^\infty d\omega \sigma(\omega,T) K(\omega,\tau,T)$
- $O(10)$ data and $O(100)$ degrees of freedom to reconstruct.
- Bayesian technique: find $\sigma(\omega,T)$ that maximizes $P[\sigma|DH]$.
  - D data
  - H prior knowledge: $\sigma(\omega,T) > 0$

New implementation of Maximum Entropy Method: [hep-lat/0611017]

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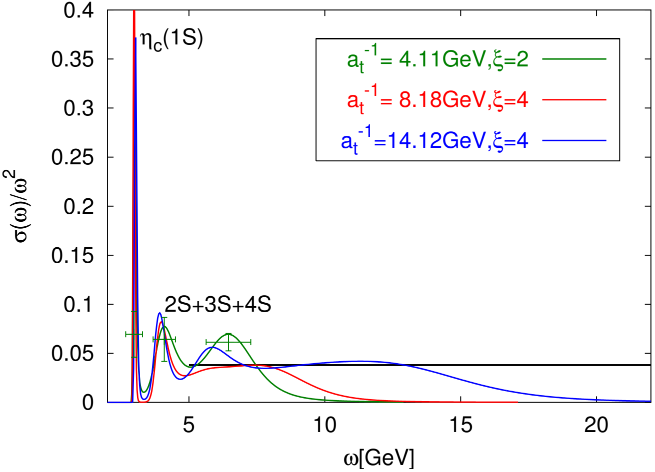
Charmonium: $T = 0$



- visible excited states
- First time we see continuum!

Charmonium: $T > 0$

$$G(\tau,\vec{p}) = \int_0^\infty d\omega \sigma K(\omega,\tau), \quad K(\omega,\tau) = \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)}.$$

$$G_{recon}(\tau,T) = \int_0^\infty d\omega \sigma(\omega, T=0) K(\tau,\omega,T)$$

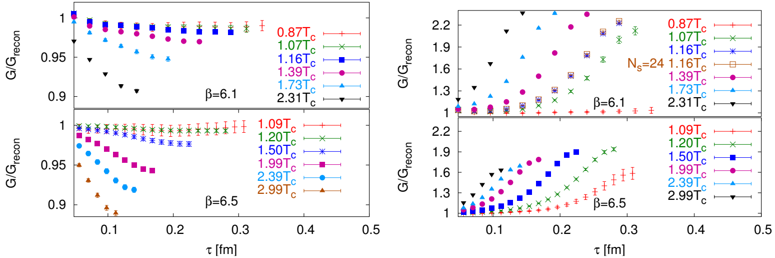
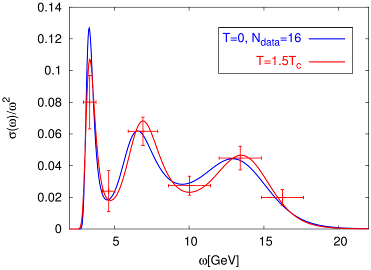
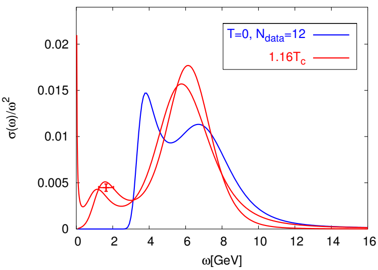


Figure: The ratio $G(\tau, T)/G_{recon}(\tau, T)$ of charmonium for (pseudo)scalar channel at $a_t^{-2} = 8.18$ and 14.11GeV at different temperatures.





- 1S (left) shows very little dependence on temperature
- hard to accomodate in potential models [see Agnes Moszcy talk]
- 1P is very temperature-dependent

Summary

- Interaction in hot medium gets screened at increasingly short distances
- Scaling is good to very good
- Free energy has a sharp drop at the transition
- Entropy and Internal Energy have sharp peak
- The $1S$ (η_c, J/ψ) charmonium states **exist** as a resonance at $T \simeq 1.5T_c$.
- Can define and calculate Renormalized Polyakov Loop
- $1P$ (ξ_{c0}, ξ_{c1}) charmonium states **dissolve** at $1.1T_c$.

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β	5.7	5.9	6.1	6.1	6.5
$N_s^2 \times N_t$	$8^3 \times 64$	$16^3 \times 64$	$16^3 \times 64$	$16^3 \times 96$	$24^3 \times 160$
$(\xi,\ \xi_0)$	(2,1.655)	(2,1.691)	(2,1.718)	(4,3.211)	(4,3.3166)
r_0/a_s	2.414(8)	3.690(11)	5.207(29)	5.189(21)	8.96(4)
a_t^{-1}[Gev]	1.905	2.913	4.110	8.181	14.12
L_s [fm]	1.66	2.17	1.54	1.54	1.34
configs	2000	1560	930	500	160

Table: Simulation parameters for charmonium at zero temperature.

Correlators and Spectral Functions

Point meson operator

$$J_H(t,x) = \bar{q}(t,x)\Gamma_H q(t,x),$$

where $\Gamma_H = 1, \gamma_5, \gamma_\mu, \gamma_5\gamma_\mu, \gamma_\mu\gamma_\nu$.

Meson states in different channels:

Γ	$^{2S+1}L_J$	J^{PC}	$c\bar{c}$ (n=1)	$c\bar{c}$ (n=2)	$b\bar{b}(n=1)$ (n=1)	$b\bar{b}(n=2)$ (n=2)
γ_5	$^1S_0$	0^{-+}	η_c	η_c'	η_b	η_b'
γ_s	$^3S_1$	1^{--}	J/ψ	ψ'	$\Upsilon(1S)$	$\Upsilon(2S)$
$\gamma_s\gamma_{s'}$	$^1P_1$	1^{+-}	h_c		h_b	
1	$^3P_0$	0^{++}	χ_{c0}		$\chi_{b0}(1P)$	$\chi_{b0}(2S)$
$\gamma_5\gamma_s$	$^3P_1$	1^{++}	χ_{c1}		$\chi_{b1}(1P)$	$\chi_{b1}(2P)$
		2^{++}	χ_{c2}		$\chi_{b2}(1P)$	$\chi_{b2}(2P)$

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The spectral function

$$\sigma_H(p_0,\vec{p}) = \frac{1}{2\pi}(D_H^>(p_0,\vec{p}) - D_H^<(p_0,\vec{p})) = \frac{1}{\pi} Im D_H^R(p_0,\vec{p})$$

$$D_H^{>(<)}(p_0,\vec{p}) = \int \frac{d^4p}{(2\pi)^4} e^{ip.x} D_H^{>(<)}(x_0,\vec{x}) \quad (2)$$

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The Euclidean propagator

$$G_H(\tau,\vec{p}) = \int d^3x e^{i\vec{p}.\vec{x}} \langle T_\tau J_H(\tau,\vec{x}) J_H(0,\vec{0})\rangle$$

is related to the spectral function through the integral representation

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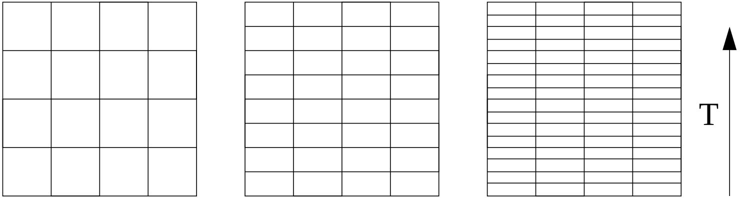

- Anisotropic lattice $\xi = a_s/a_\tau = 2$ and 4.
- Standard Wilson action in the gauge sector
- Anisotropic clover improved action for heavy fermions
- Quenched approximation

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