Hot Nuclear Matter Effects on Quarkonia

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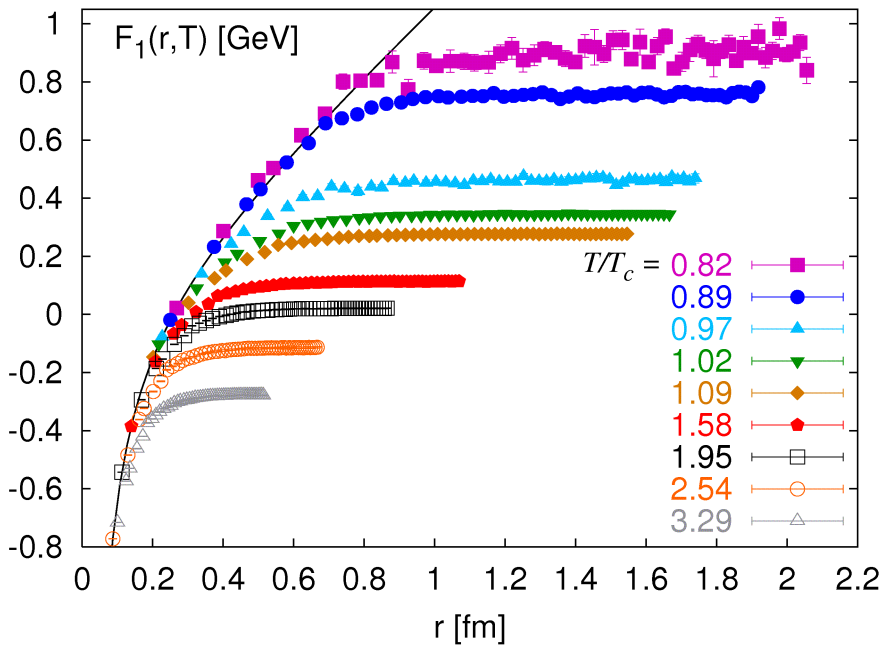
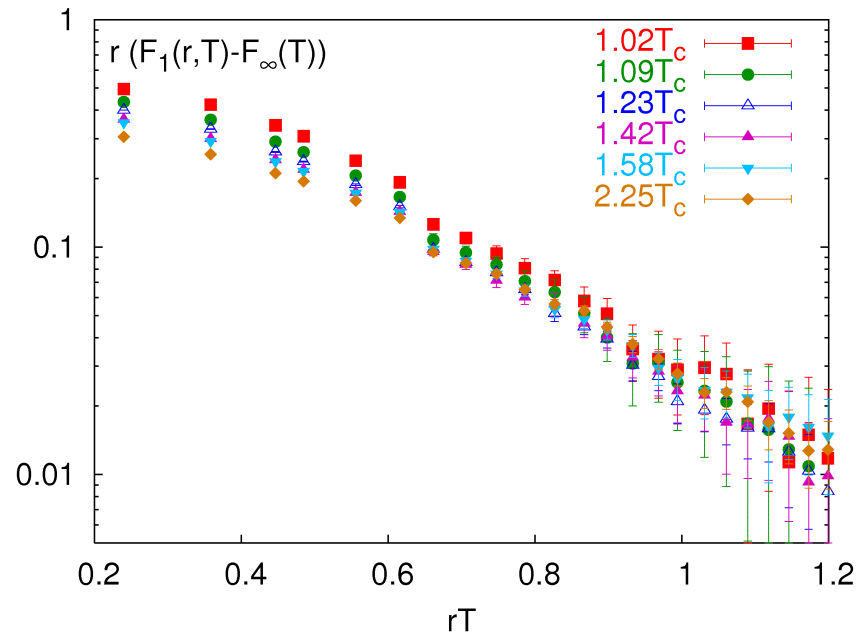
- Introduction : Deconfinement at high temperature and color screening
- Quarkonium correlators and spectral functions from lattice
- Quarkonium spectral functions in potential models
- Effective field theory approach for heavy quark bound states
- Conclusions and Outlook

AGS & RHIC User's Meeting, May 27, 2008

Color screening in QCD and quarkonia melting

RBC-Bielefeld Collaboration $16^3 \times 4$, $24^3 \times 6$ lattices, $m_\pi \simeq 200$ MeV





Strong temperature dependence of the static quark anti-quark correlators

$F_1(r,T)$ scales with T and is exponentially screened for $r > 0.8/T$

Does this imply quarkonium melting ?

Matsui and Satz PLB 178 (86) 416

see also

Digal et al, PLB 514 (01) 57 ; PRD 64 (01) 094015,

Meson correlators and spectral functions

$$G(\tau,\vec{p},T)=\int d^3x\, e^{i\vec{p}\cdot\vec{x}}\left\langle J_H(\tau,\vec{x})\, J_H{}^{+}(0,0)\right\rangle,\quad J_H(\tau,\vec{x})=\bar{q}(\tau,\vec{x})\Gamma_H q(\tau,\vec{x})$$

$$\Gamma_H = 1,\ \gamma_5,\ \gamma_\mu,\ \gamma_5\cdot\gamma_\mu$$

γ_5 : Pseudo – scalar(PS) $\rightarrow \eta_c\ (^1S_0)$

1 : Scalar(SC) $\rightarrow \chi_{c0}\ (^3P_0)$

γ_μ : Vector(VC) $\rightarrow J/\psi\ (^3S_1)$

$\gamma_5\gamma_\mu$: Axial – Vector(AX) $\rightarrow \chi_{c1}\ (^3P_1)$

LGT $\rightarrow$ $\boxed{G(\tau,T)=D^{>}(-i\tau)}$

Imaginary time Real time

$$\frac{D^{>}(\omega)-D^{<}(\omega)}{2\pi}=\frac{1}{\pi}\,\mathrm{Im}\,D_R(\omega)=\sigma(\omega)$$

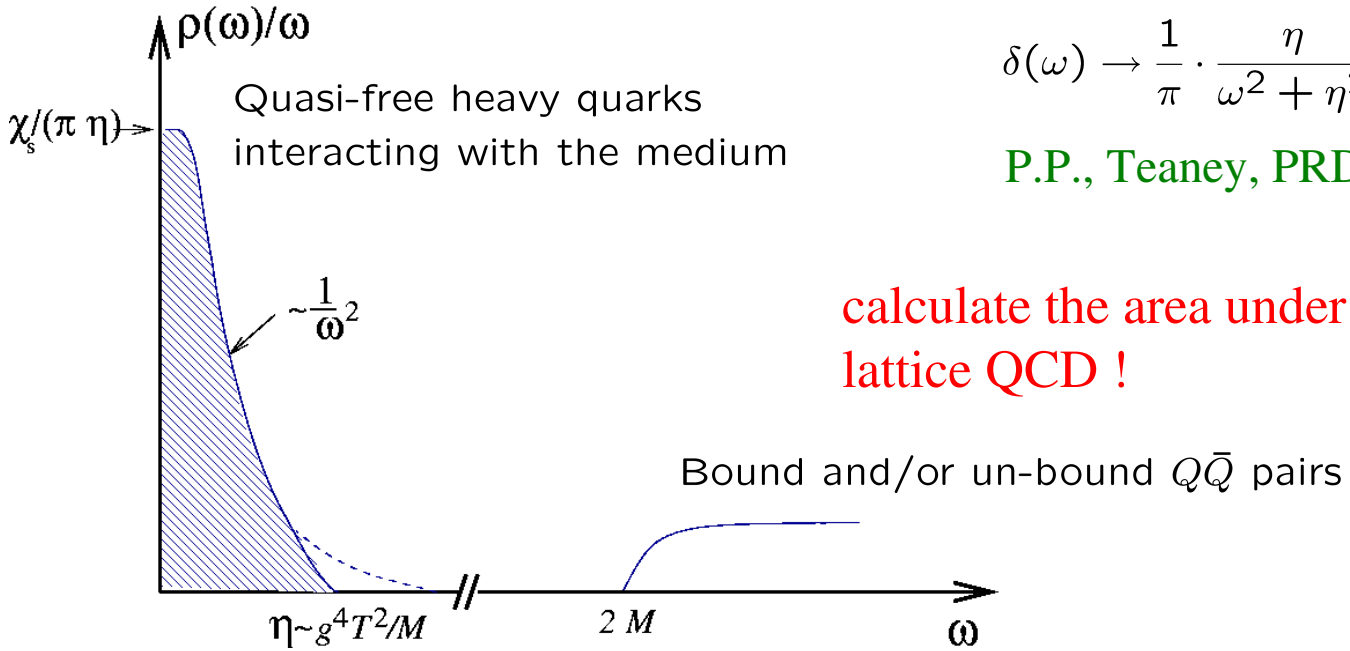
$$\boxed{\frac{\mathrm{d}W}{\mathrm{d}\omega\mathrm{d}^3p}=\frac{5\alpha^2}{27\pi^2}\frac{1}{\omega^2(\mathrm{e}^{\omega/T}-1)}\sigma_V(\omega,\vec{p},T)}$$

Experiment, dilepton rate

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

$G(\tau,\vec{p},T)$ $\Rightarrow$ MEM $\Rightarrow$ $\sigma(\omega,\vec{p},T)$

Quarkonium spectral functions above deconfinement



interactions :

$$\delta(\omega) \to \frac{1}{\pi} \cdot \frac{\eta}{\omega^2 + \eta^2} \qquad \eta = \frac{T}{M}\frac{1}{D} \ll T$$

P.P., Teaney, PRD 73 (2006) 014508

calculate the area under the peak using lattice QCD !

E.g. free theory :

$$\sigma_V^{ii}(\omega) = \theta(\omega^2 - 4M^2)\frac{1}{4\pi^2}\omega^2\sqrt{1 - \frac{4M^2}{\omega^2}} + \chi(T)\left(\frac{T}{M}\right)\omega\delta(\omega)$$

$$\sigma^{\text{high}}(\omega, T) \quad + \quad \sigma^{\text{low}}(\omega, T)$$

$$\chi(T) = \frac{6}{\pi^2}\int_0^\infty dp p^2 \left(-\frac{\partial n_F}{\partial E_p}\right)$$

quark number susceptibility

$$G_i(\tau, T) = G_i^{\text{low}}(\tau, T) + G_i^{\text{high}}(\tau, T)$$

$$G^{\text{low}}(\tau) \simeq \chi^i(T)T$$

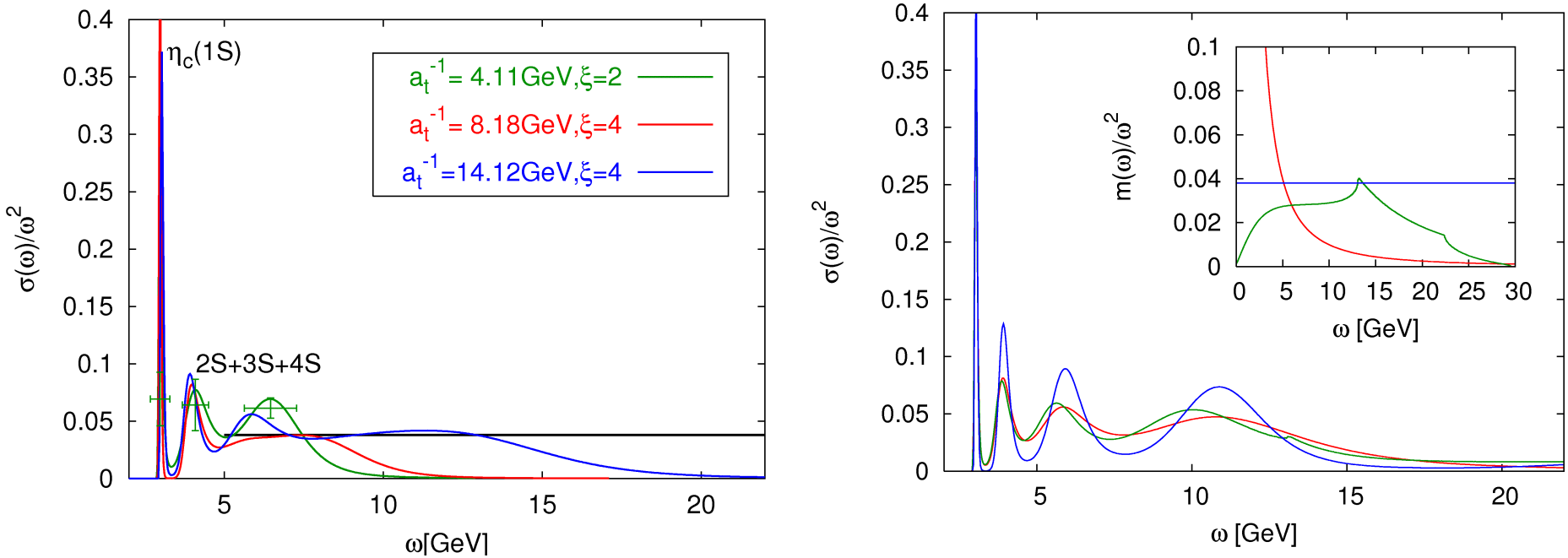
zero mode contribution

Charmonia spectral functions at T=0

Anisotropic lattices: $16^3 \times 64, \xi = 2$ $16^3 \times 96, \xi = 4$, $24^3 \times 160, \xi = 4$
$L_s = 1.35 - 1.54$fm, #configs=500-930;
Wilson gauge action and Fermilab heavy quark action

Jakovác, P.P., Petrov, Velytsky, PRD 75 (07) 014506

Pseudo-scalar (PS) $\rightarrow$ S-states



For $\omega > 5$ GeV the spectral function is sensitive to lattice cut-off ;
Strong default model dependence in the continuum region

Charmonia correlators at T>0

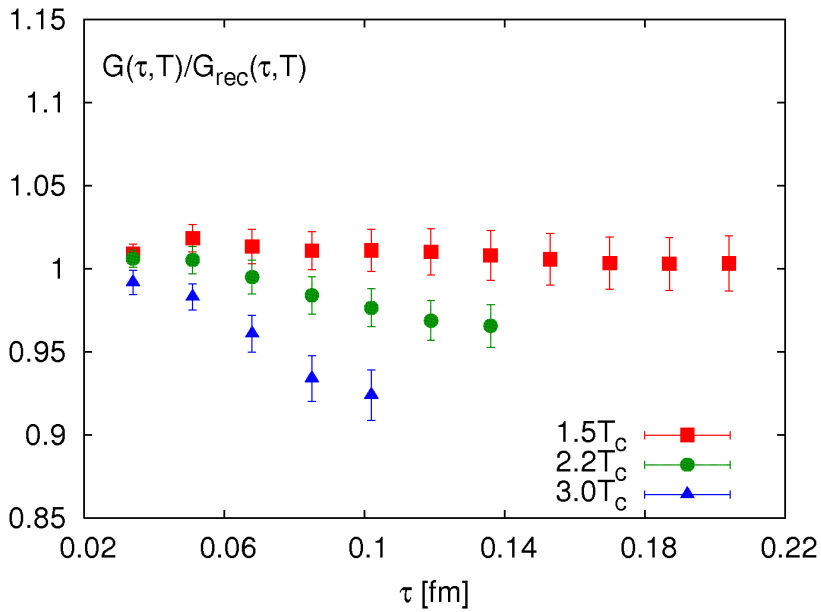
temperature dependene of $G(\tau,T)$

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

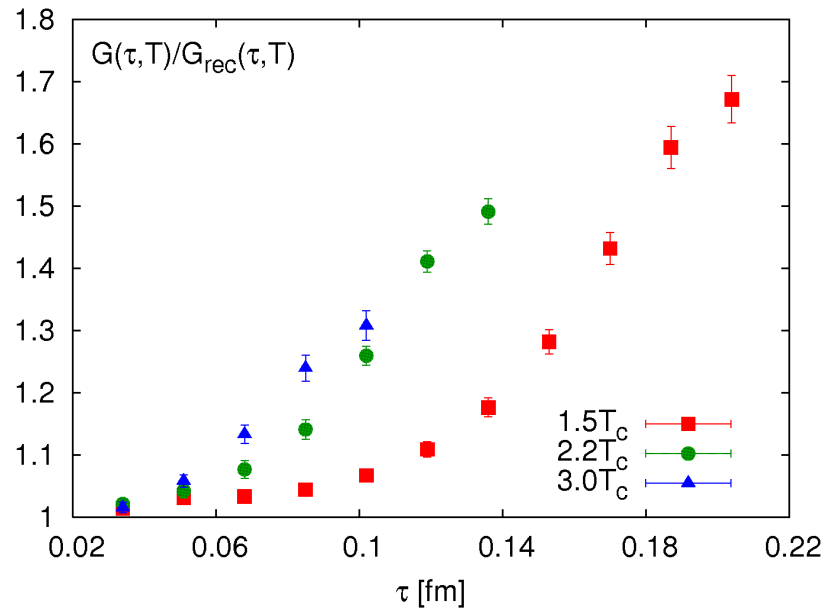
If there is no T-dependence in the spectral function, $G(\tau,T)/G_{recon}(\tau,T)=1$

$$G_{recon}(\tau,T)=\int_0^\infty d\omega\sigma(\omega,T=0)\frac{\cosh(\omega\cdot(\tau-\frac{1}{2T})}{\sinh(\omega/(2T)}$$

Pseudo-scalar



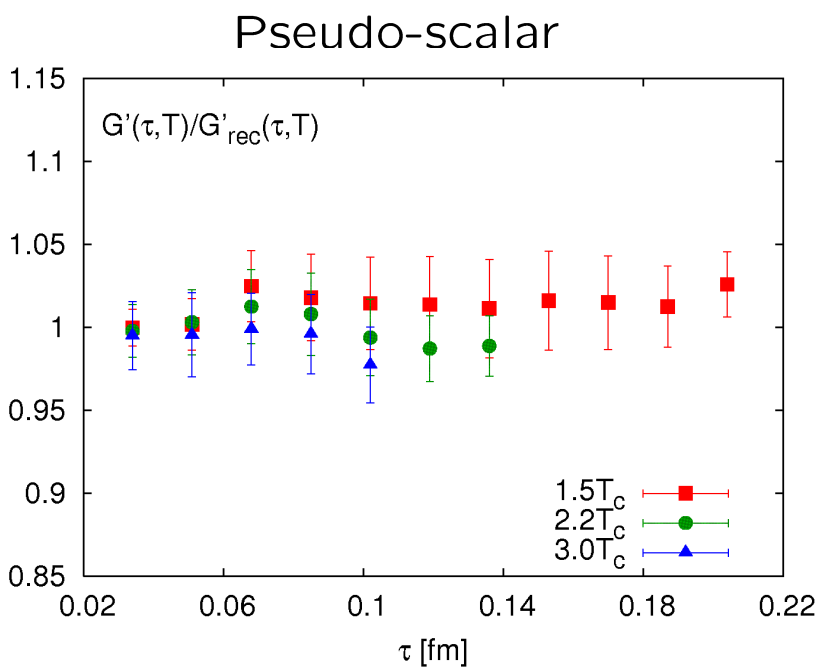
Scalar

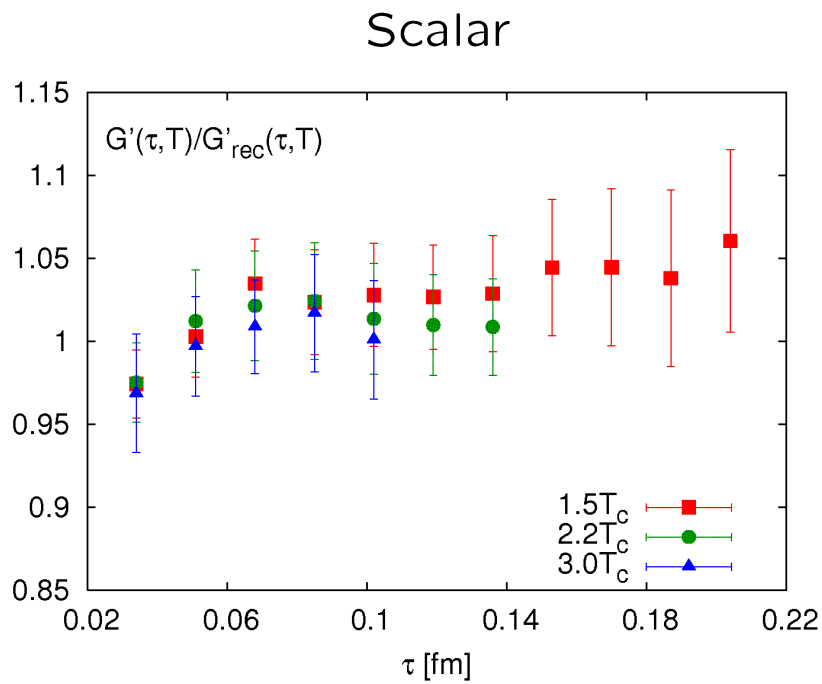


Datta et al, PRD 69 (04) 094507

Charmonia correlators at T>0

zero mode contribution is not present in the time derivative of the correlator
Umeda, PRD 75 (2007) 094502





No change in the derivative of the scalar quarkonium correlator up to $3T_c$!
Almost the entire temperature dependence of the scalar correlators is given by the zero mode contribution !

Datta, P.P., Quark Matter 2008, arXiv:0805.1174

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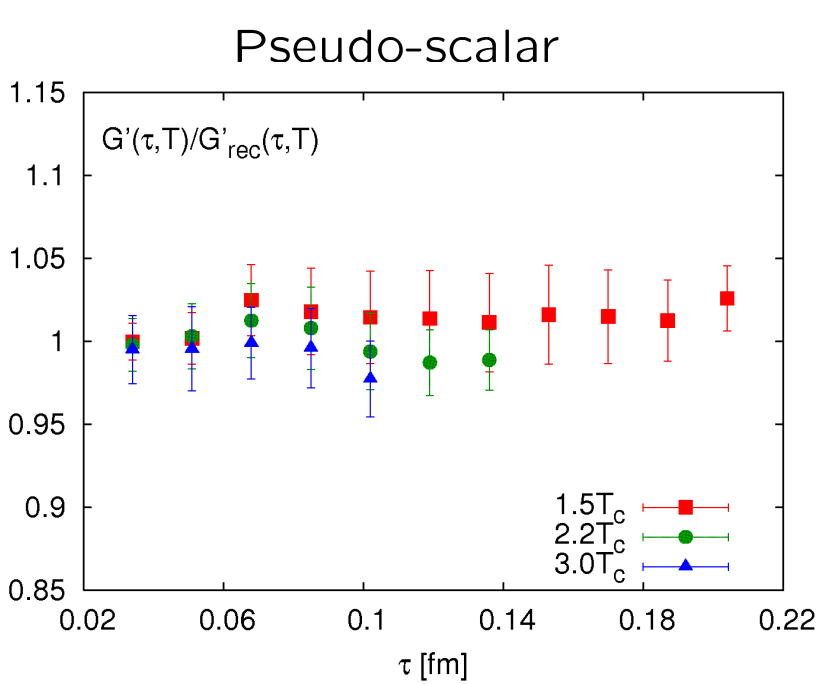

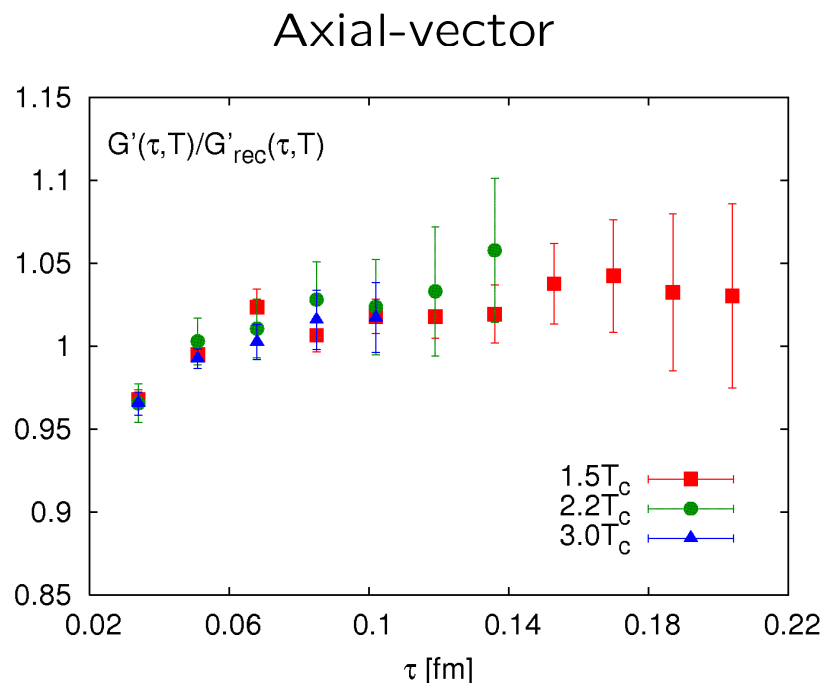

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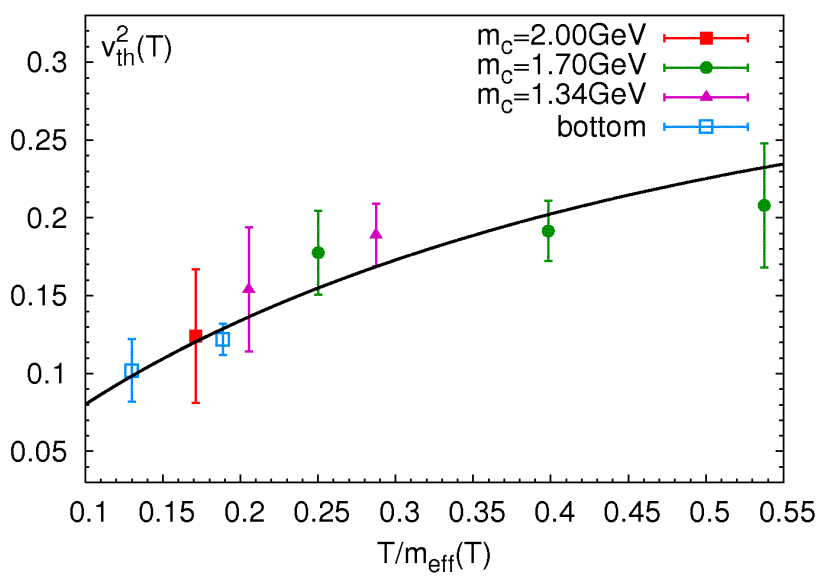
Estimating the zero mode contribution

$$G^{\text{low}}(\tau,T) = G(\tau,T) - G_{rec}(\tau,T)$$

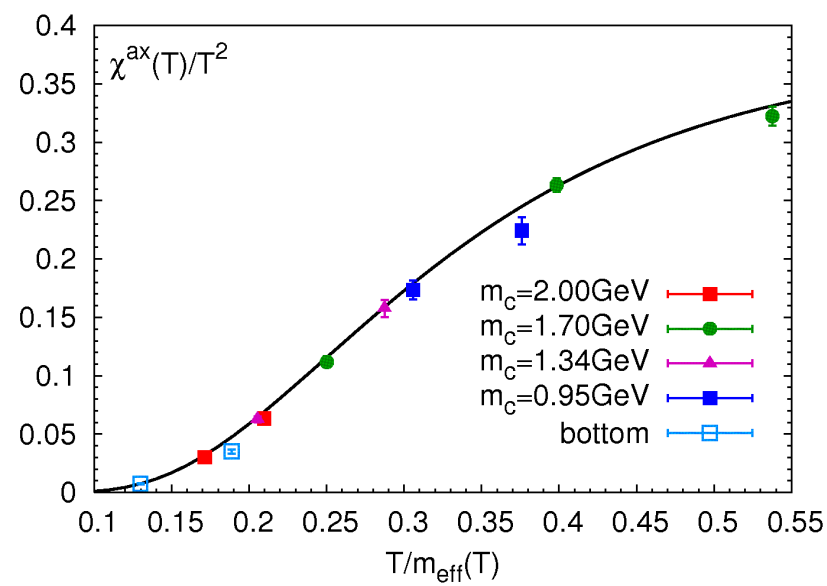
$G_i^{\text{low}}(\tau,T)$ is τ-idependent within errors and

$\chi_i(T) \simeq G_i^{\text{low}}(\tau = 1/(2T),T)$

Vector



Axial-vector

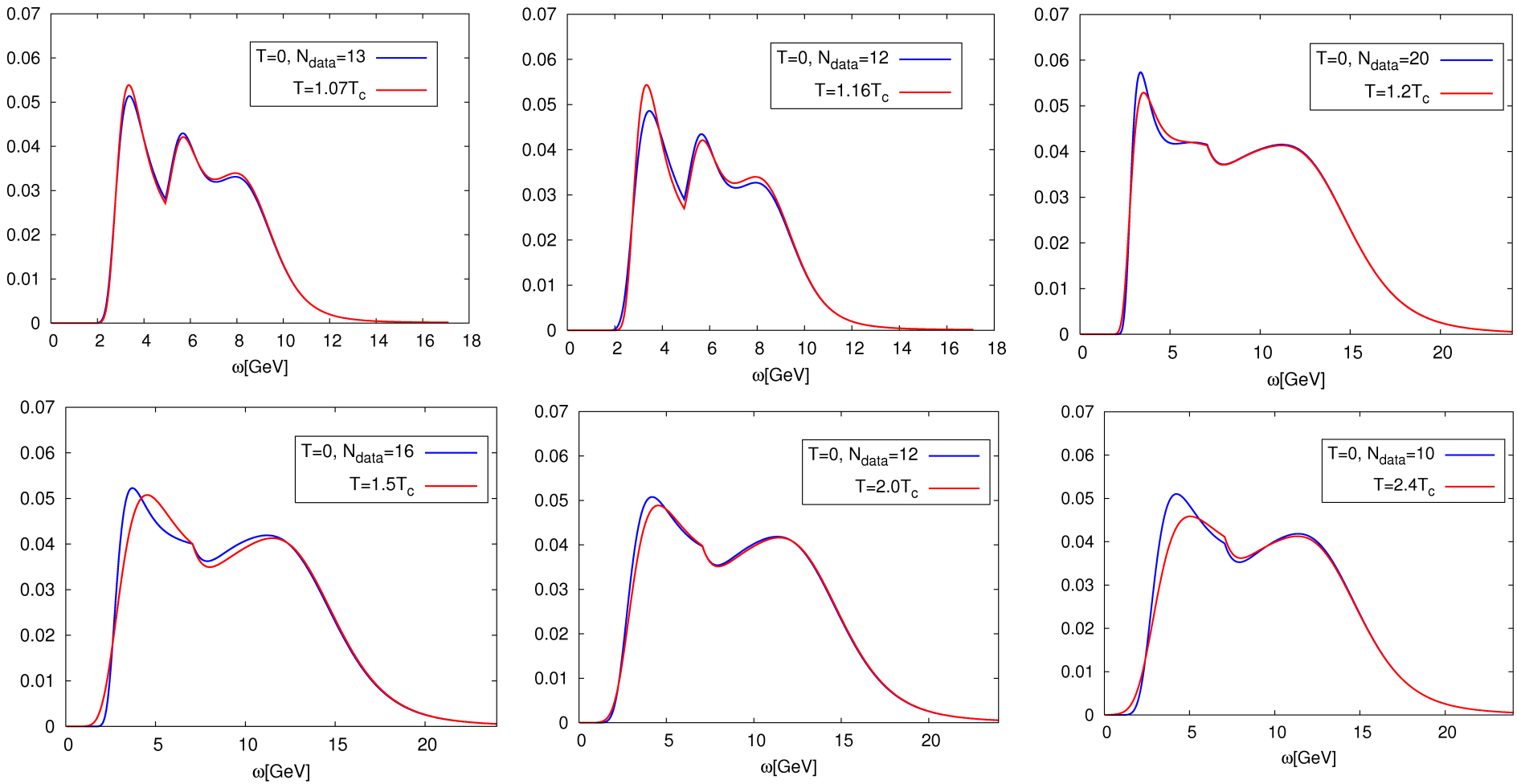


$$G_{Vii}^{\text{low}}/G_{00} \simeq \frac{\int d^3p \frac{p_i^2}{E_p^2} e^{-E_p/T}}{\int d^3p e^{-E_p/T}} \simeq v_{th}^2$$

Datta, P.P., Quark Matter 2008, arXiv:0805.1174

Charmonium spectral functions at finite temperature

Jakovác, P.P., Petrov, Velytsky, PRD 75 (07) 014506



no large T-dependence but details are not resolved

Lessons from lattice calculation of quarkonium correlators :

• The dominant source of the T-dependence of the quarkonium correlators comes from the zero mode contribution, i.e. the low energy part

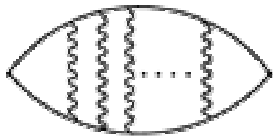
• The high energy part of the quarkonium correlators which carries information about bound states shows almost no T-dependence up to 3Tc even for P-waves (do P-wave quarkonia survive at high temperatures ?)

• The zero mode contribution can be well understood in terms of gas of quasi-free quarks with some effective mass

• Although spectral functions extracted from MEM do not show large T-dependence details (like bound state peaks) are not well resolved in the deconfined phase with current lattice data

Quarkonium spectral functions in potential models

$\omega \sim M_{J/\psi}$, s_0 nonrelativistic



many gluon exchanges important near threshold

$$\left[-\frac{1}{m}\nabla^2 + V(\vec{r}) + E\right] G^{NR}(\vec{r},\vec{r}\,',E) = \delta^3(\vec{r}-\vec{r}\,')$$

$$\sigma(E) = \frac{2N_c}{\pi}\,\mathrm{Im}\,G^{NR}(\vec{r},\vec{r}\,',E)_{\vec{r}=\vec{r}\,'=0}$$

S-wave

$$\sigma(E) = \frac{2N_c}{\pi}\frac{1}{m^2}\vec{\nabla}\cdot\vec{\nabla}'\,\mathrm{Im}\,G^{NR}(\vec{r},\vec{r}\,',E)_{\vec{r}=\vec{r}\,'=0}$$

P-wave

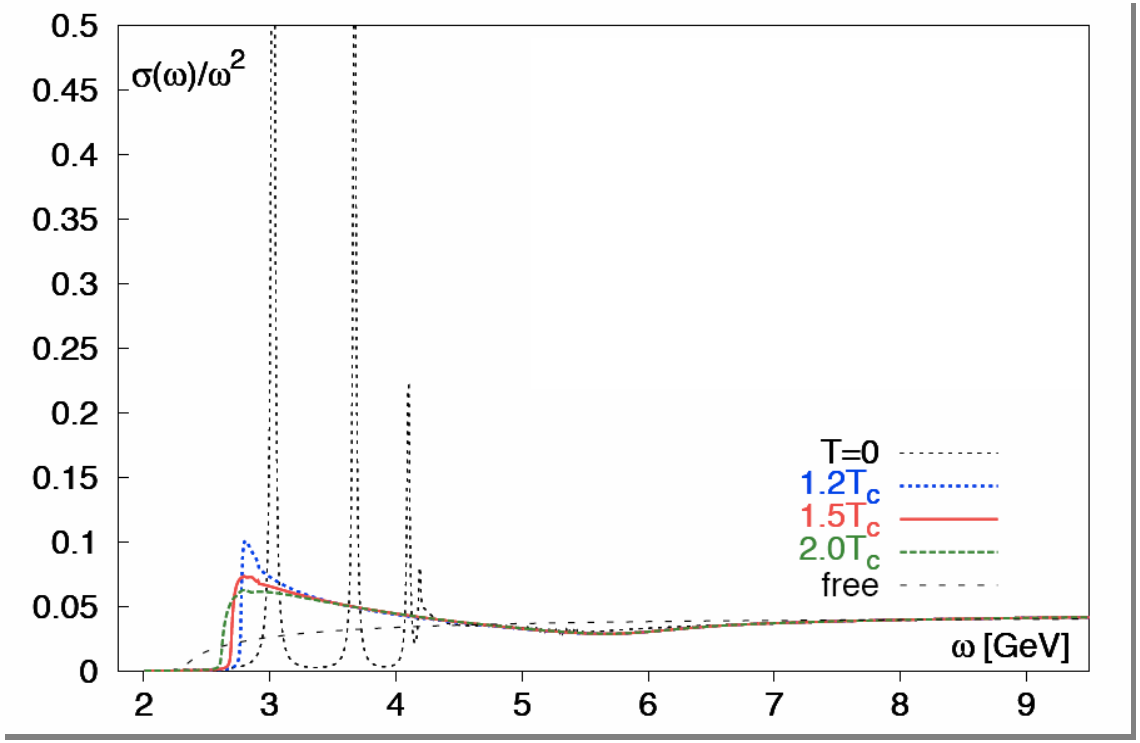
$\omega >> s_0$ perturbative

$$\sigma_{pert} \cong \omega^2 \frac{3}{8\pi}\left(1 + \frac{11}{3\pi}\alpha_s\right)$$

use lattice data on the quark anti-quark free energy to construct the potential

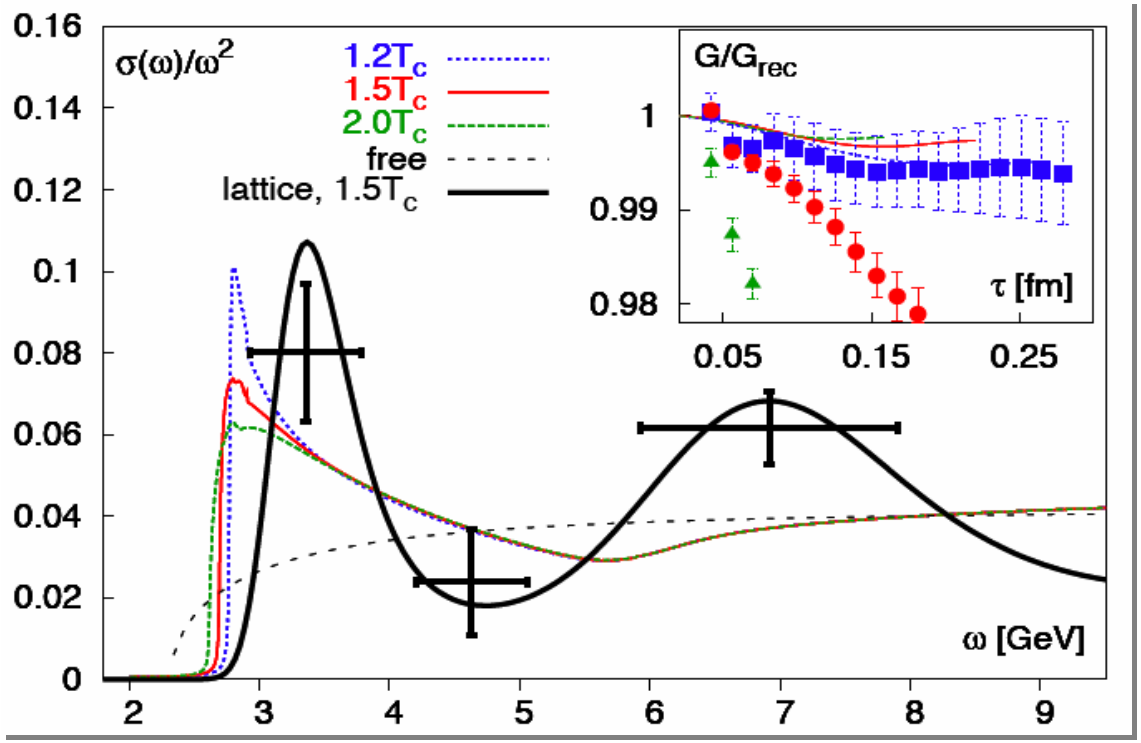
Mócsy, P.P., PRL 99 (07) 211602, PRD77 (08) 014501, EPJC ST 155 (08) 101

η_c



- resonance-like structures disappear already by $1.2T_c$
- strong threshold enhancement above free case indication of correlations
- height of bump in lattice and model are similar
- The correlators do not change significantly despite the melting of the bound states

η_c



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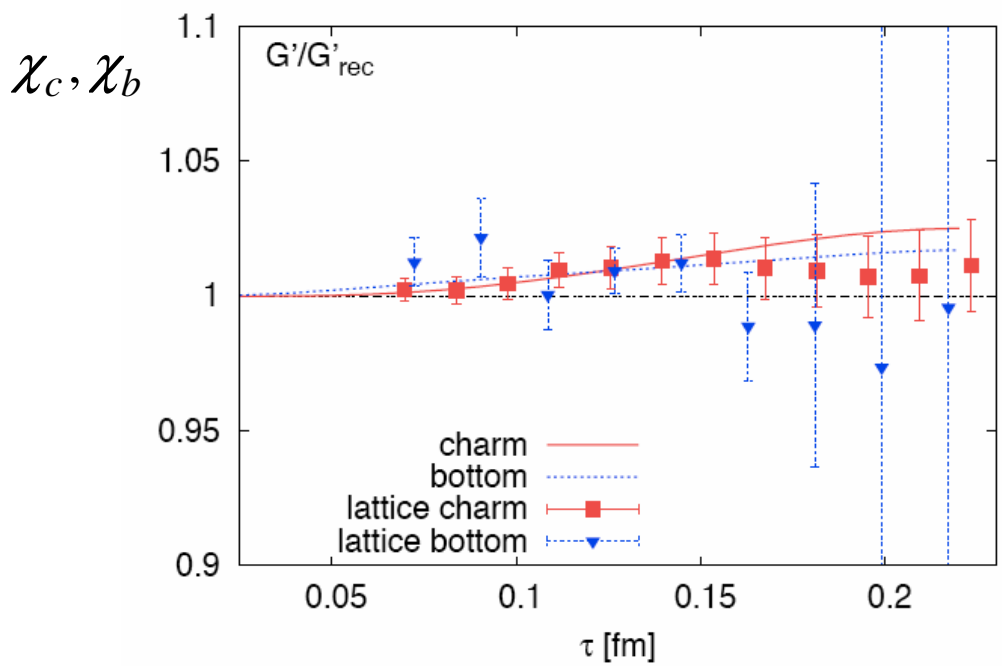

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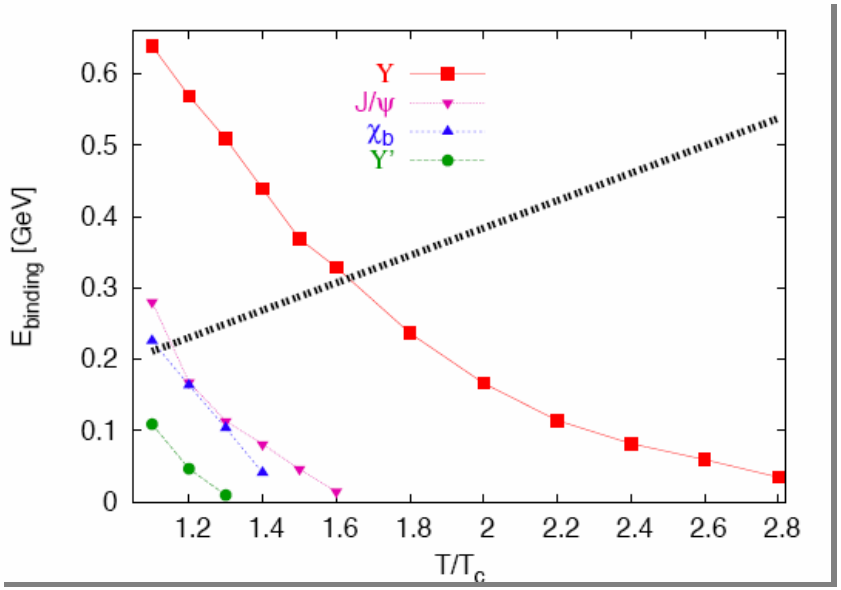
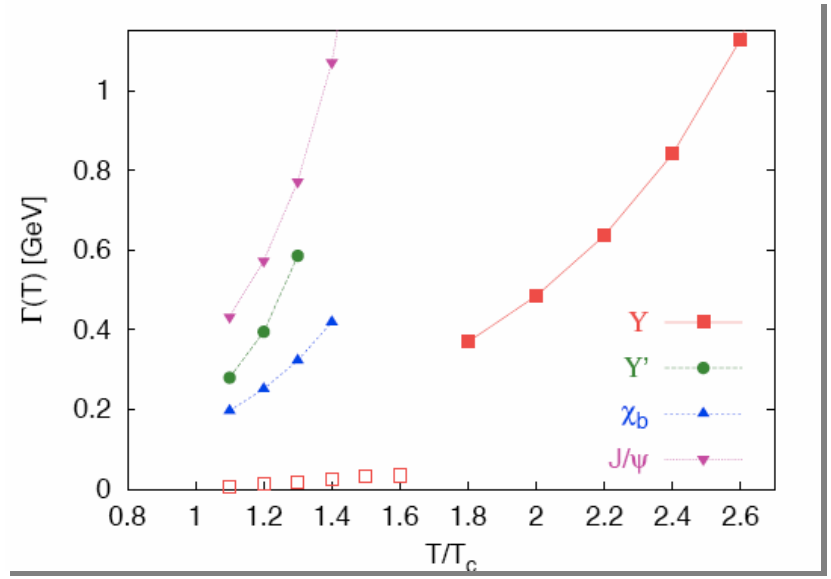
Quarkonium binding energy and thermal width

Using lattice data on the static quark anti-quark free energy in 2+1f QCD the binding energy of different quarkonium states can be estimated

Mócsy, P.P., PRL 99 (07) 211602



Kharzeev, McLerran, Satz, PLB356 (95) 349



$$\Gamma(T) \geq 2E_{bin}(T)$$

state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

Lessons from potential models with screening :

• potential model calculations which use the quark anti-quark free energy calculated on the lattice predict that all bound state melt at temperatures smaller than 1.3Tc except the 1S bottomonium, which melts at 2Tc

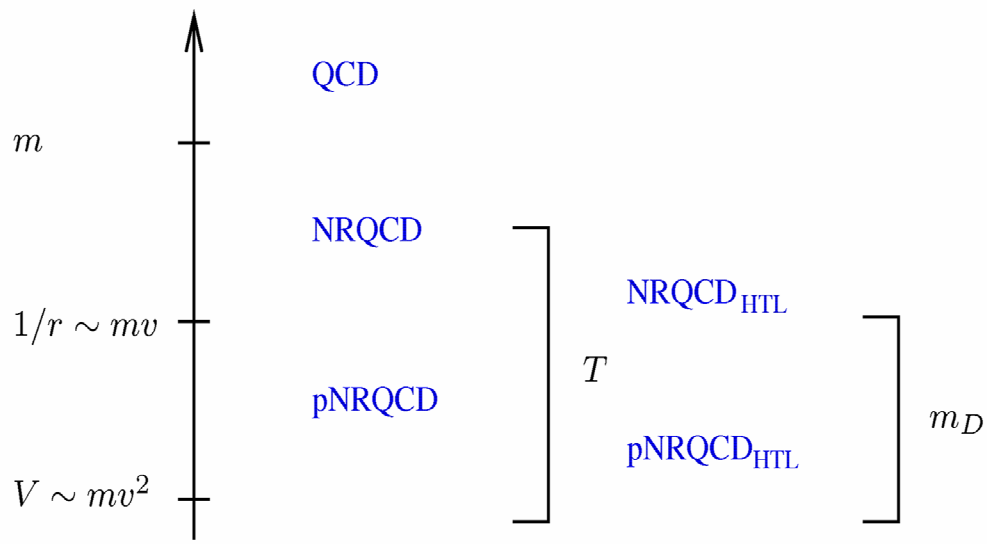
state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

Mócsy, P.P., PRL 99 (07) 211602

• there is a large threshold enhancement in the quarkonium spectral functions even at high temperatures, which compensates for absence of bound states resulting in temperature independent quarkonium correlators for both S- and P-waves in complete agreement with lattice results on quarkonium correlators !

Effective field theory approach for heavy quark bound states

The heavy quark mass provides a hierarchy of different energy scales
there are also different thermal scales in the weak coupling regime



○ Brambilla Pineda Soto Vairo RMP 77(05)1423

We assume that bound states exist for

- $T \ll m$
- $1/r \sim mv \gtrsim m_D$

Brambilla, Ghiglieri, P.P., Vairo arXiv:0804.0993 [hep-ph]

Light quark and gluons

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \sum_{i=1}^{n_f} \bar{q}_i \, i \not{D} q_i$$

Singlet $Q\bar{Q}$ field

Octet $Q\bar{Q}$ field

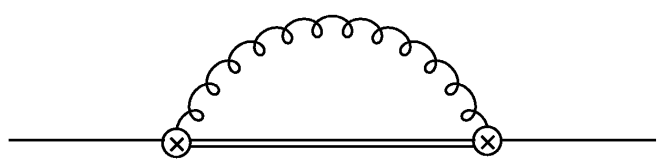
$$+ \int d^3r \; \mathrm{Tr} \left\{ \mathsf{S}^\dagger \left[i\partial_0 + V_s(r,T) \right] \mathsf{S} + \mathsf{O}^\dagger \left[iD_0 - V_o(r,T) \right] \mathsf{O} \right\}$$

$$+ V_A \, \mathrm{Tr} \left\{ \mathsf{O}^\dagger \vec{r} \cdot g\vec{E} \, \mathsf{S} + \mathsf{S}^\dagger \vec{r} \cdot g\vec{E} \, \mathsf{O} \right\} + \frac{V_B}{2} \mathrm{Tr} \left\{ \mathsf{O}^\dagger \vec{r} \cdot g\vec{E} \, \mathsf{O} + \mathsf{O}^\dagger \mathsf{O} \vec{r} \cdot g\vec{E} \right\} + \ldots$$

potential is the matching parameter of EFT !

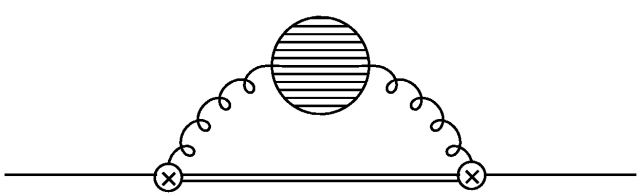
Free field equation: $(i\partial_0 + V_s(r,T))S = 0$

	$\mathrm{Re}V_s(r,T)$	$\mathrm{Im}V_s(r,T)$
singlet-octet transition :	$g^2T^3r^2 \times \frac{\delta V}{T}$	$g^2T^3r^2 \times \left(\frac{\delta V}{T}\right)^2$



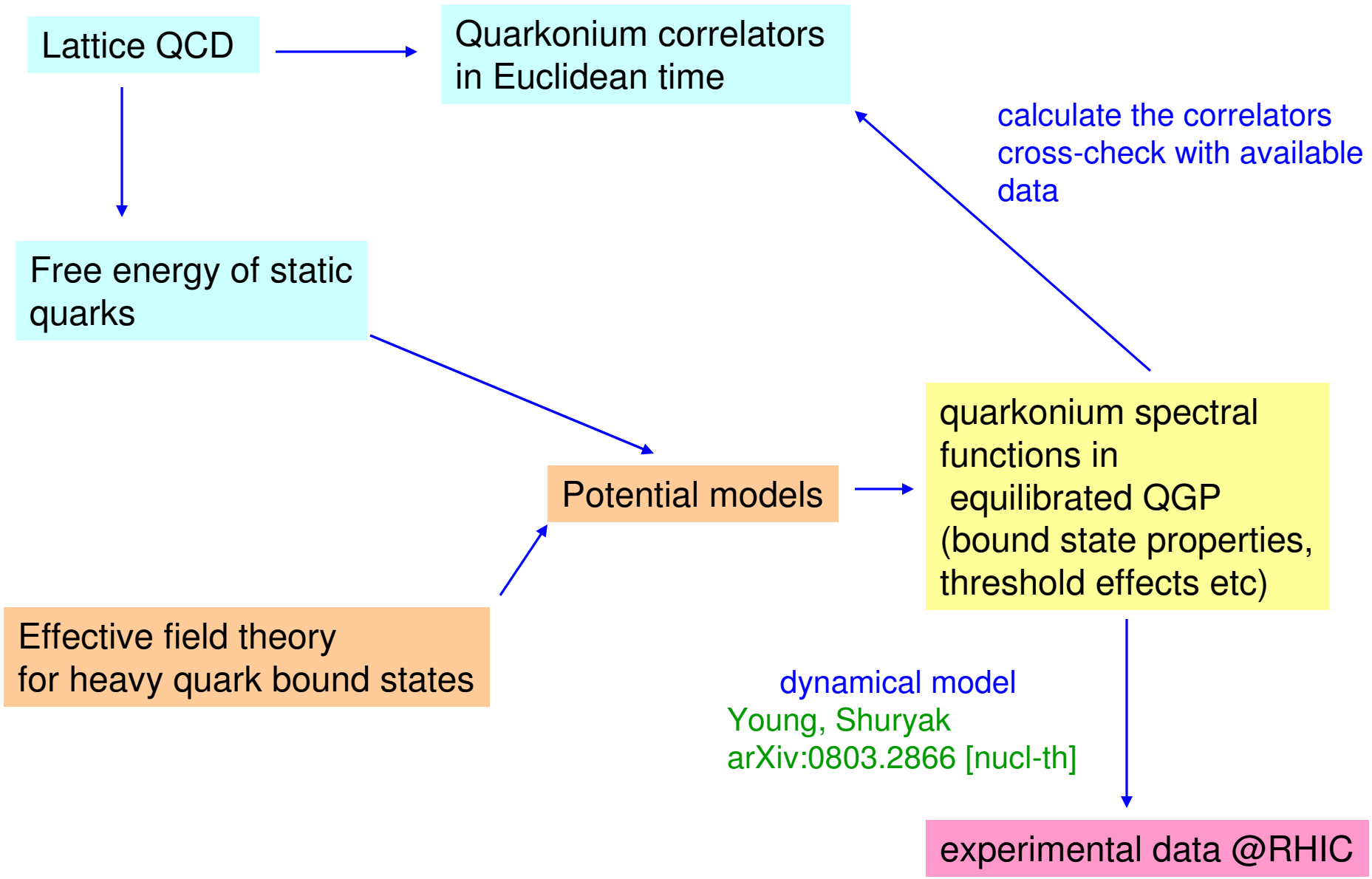
$$\delta V = V_o - V_s$$

Landau damping :	$g^2T^3r^2 \times \frac{m_D}{T}$	$g^2T^3r^2 \times \left(\frac{m_D}{T}\right)^2$



Brambilla, Ghiglieri, P.P., Vairo arXiv:0804.0993 [hep-ph]

Outlook


Lattice QCD
Quarkonium correlators in Euclidean time
calculate the correlators
cross-check with available data
Free energy of static quarks
Potential models
quarkonium spectral functions in equilibrated QGP (bound state properties, threshold effects etc)
Effective field theory for heavy quark bound states
dynamical model
Young, Shuryak
arXiv:0803.2866 [nucl-th]
experimental data @RHIC