Charmonium production in hot and dense matter

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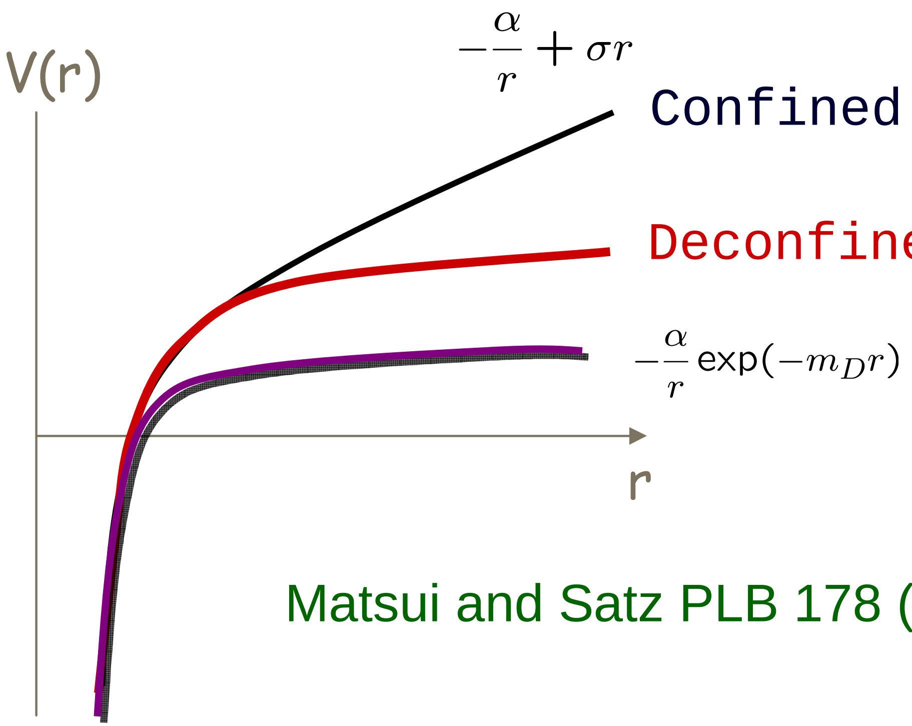
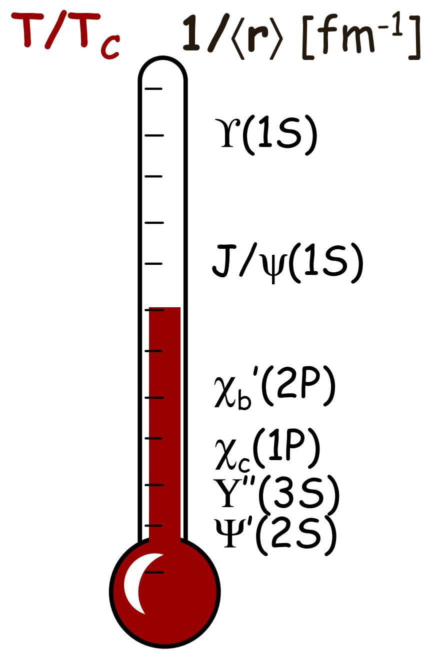
- Introduction : Deconfinement and charmonium suppression in HI collisions
- In-medium interaction of heavy quarks and quarkonium properties
(width and binding energy)
- Charmonium production in HI collisions : why some J/psi is produced @ RHIC ?
- Summary

Charm 2009, Heidelberg/Leimen, May 20-22, 2009

Color screening in QCD and quarkonia melting



Matsui and Satz PLB 178 (86) 416



Implicit assumptions :

- strong color screening above deconfinement
- validity of potential models
- formation time for charmonia << formation time of QGP
- very short time scale for decorrelating quark anti-quark pair

use quarkonia as thermometer of the matter created in RHIC

Tools for studying quarkonium at T>0

To explain the experimental data we need to know what happens to bound state at T>0 :

a) does it survive ?

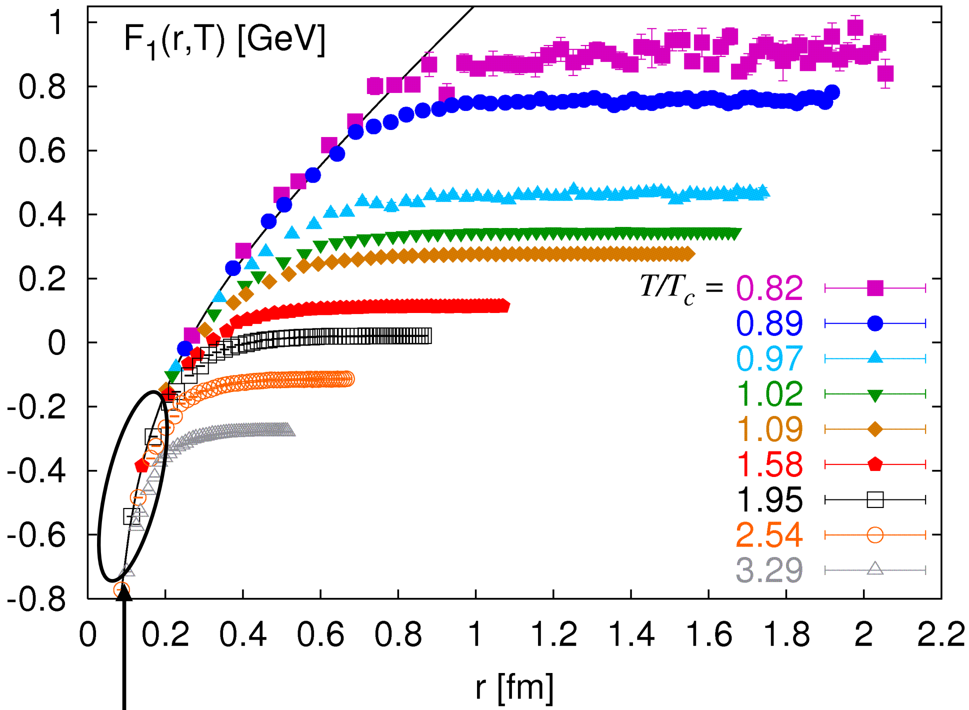
b) what its in-medium properties (mass, width) ?

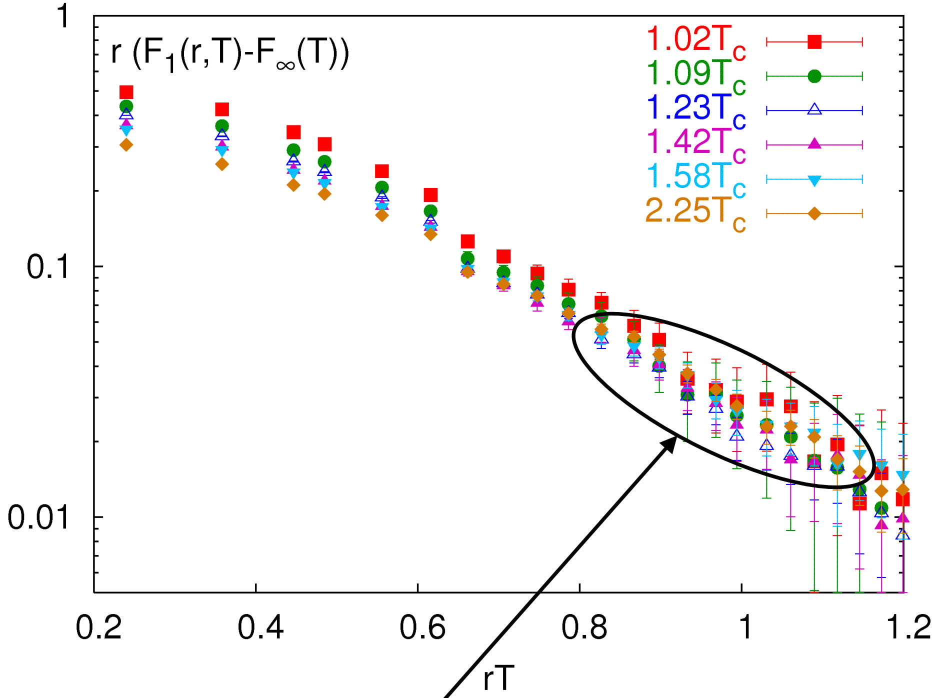
To answer these questions we can use :

- potential model + lattice QCD
  (how to justify ?)
- lattice calculations of Euclidean meson correlators and extraction of the spectral functions using MEM
  (the most straightforward but very difficult !)
- Effective field theory approach and pQCD
  (problematic close to the transition temperature)

Color screening in lattice QCD

RBC-Bielefeld Collaboration $(2+1)f\ QCD$, $16^3 \times 4$ lattices, $m_\pi \simeq 220$ MeV





$F_1(r,T)$ T-independent at short distances

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

Significant temperature dependence of the static quark anti-quark free energy for $r \simeq 0.3 - 0.5$ fm.

⇓

charmonium melting @ RHIC : Digal, P.P., Satz, 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 → $G(\tau,T)=D^{>}(-i\tau)$

⇧ Imaginary time ⇧ Real time

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

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

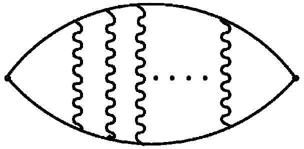
Experiment, dilepton rate

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

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

Quarkonium spectral functions in potential models

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



many gluon exchanges important near threshold

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

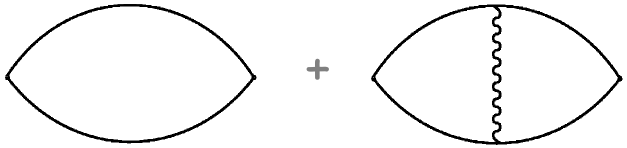
$$\sigma(E) = \frac{2N_c}{\pi}\,\mathrm{Im}\,G^{NR}(\vec{r},\vec{r}',E)_{\vec{r}=\vec{r}'=0}$$

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

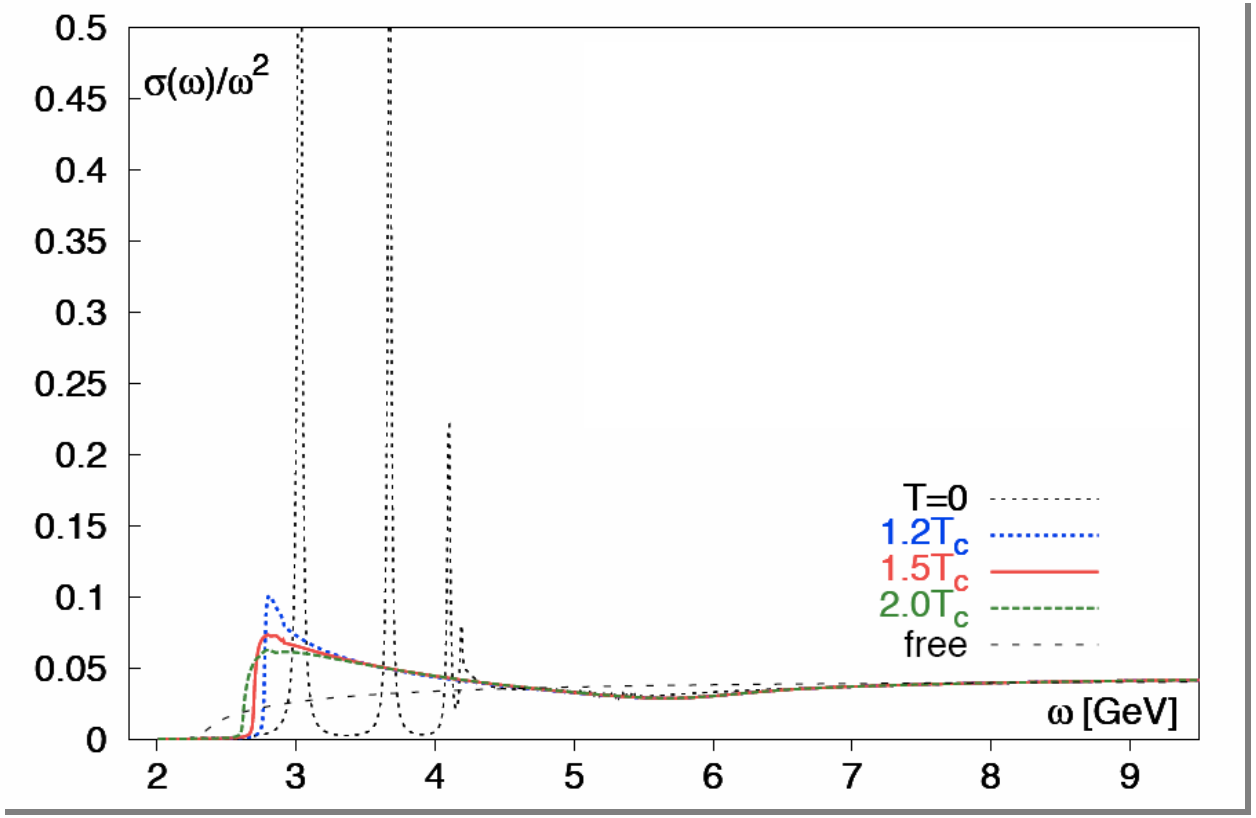


$$\sigma_{pert} \cong \omega^2 \frac{3}{8\pi}\left(1 + \frac{11}{3\pi}\alpha_s\right)$$

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

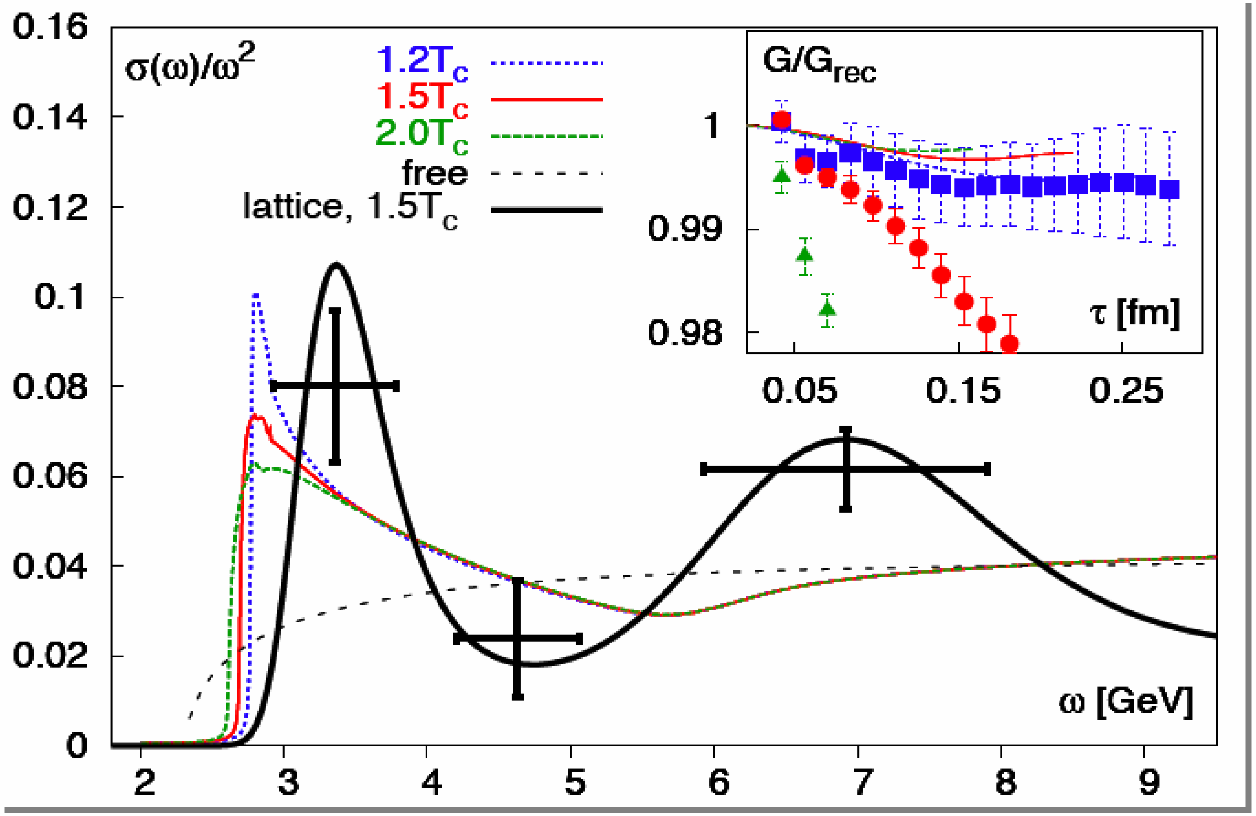
Mócsy, P.P., PRL 99 (07) 211602, PRD77 (08) 014501, EPJC ST 155 (08) 101

η_c



- resonance-like structures disappear already by $1.2T_c$
- strong threshold enhancement above free case indication of correlations

η_c

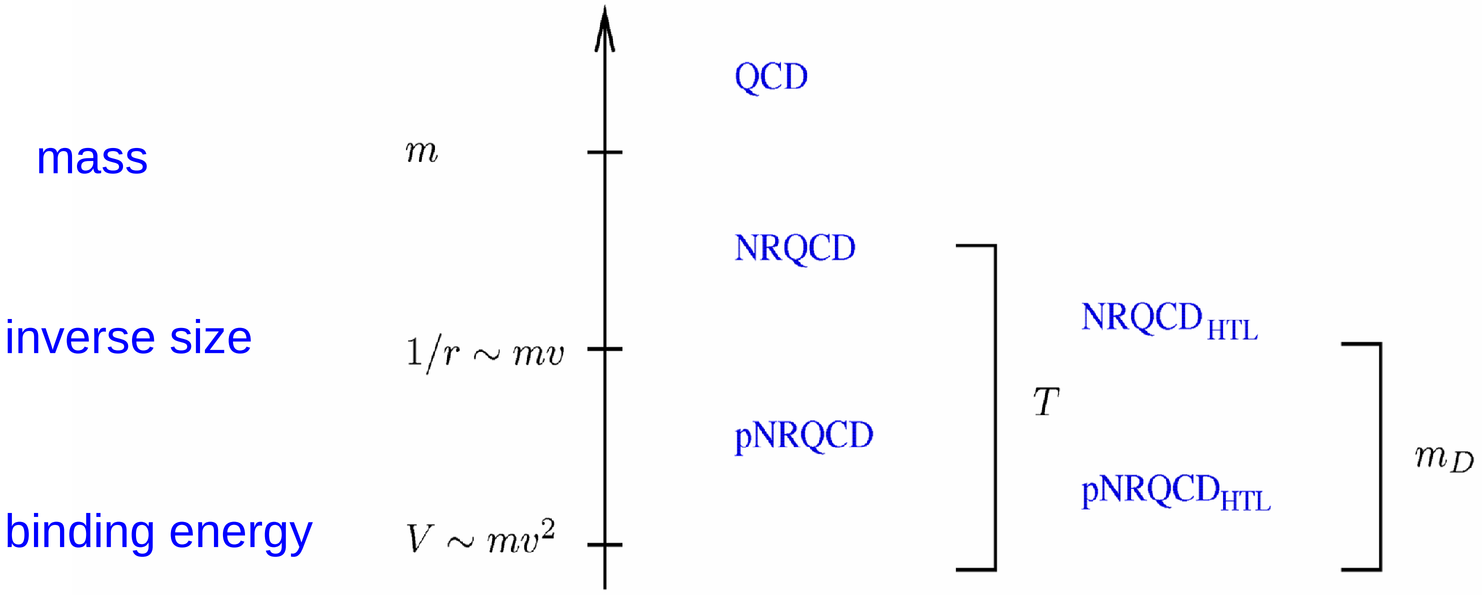


- resonance-like structures disappear already by $1.2T_c$
- strong threshold enhancement above free case indication of correlations
- height of bump in lattice and model are similar

•The correlators do not change significantly despite the melting of the bound states

Effective field theory approach for heavy quark bound states and potential models

The heavy quark mass provides a hierarchy of different energy scales



The scale separation allows to construct sequence of effective field theories: NRQCD, pNRQCD

potential model appears as the 0th approximation of the pNRQCD

pNRQCD at finite temperature for static quarks

EFT for energy scale $\Delta V = (V_o - V_s), mv^2 \ll 1/r,\ T,\ m_D$

Ultrasoft 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

$$+ \int d^3r \ \mathrm{Tr} \left\{ \mathrm{S}^\dagger \left[i\partial_0 - \frac{-\nabla^2}{m^2} - V_s(r,T) \right] \mathrm{S} + \mathrm{O}^\dagger \left[iD_0 - \frac{-\nabla^2}{m^2} - V_o(r,T) \right] \mathrm{O} \right\}$$

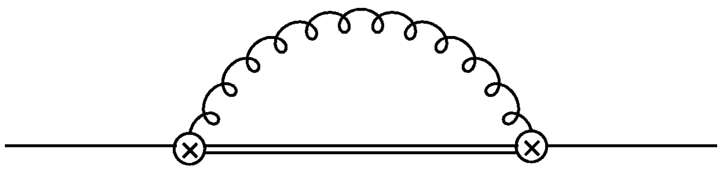
$$+ V_A \,\mathrm{Tr} \left\{ \mathrm{O}^\dagger \vec{r} \cdot g\vec{E}\, \mathrm{S} + \mathrm{S}^\dagger \vec{r} \cdot g\vec{E}\, \mathrm{O} \right\} + \frac{V_B}{2} \mathrm{Tr} \left\{ \mathrm{O}^\dagger \vec{r} \cdot g\vec{E}\, \mathrm{O} + \mathrm{O}^\dagger \mathrm{O} \vec{r} \cdot g\vec{E} \right\}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

potential is the matching parameter of EFT !

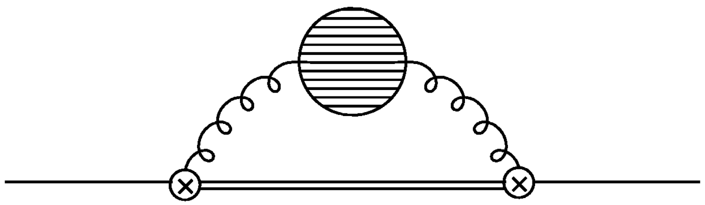
Free field equation: $(i\partial_0 - \frac{-\nabla^2}{m^2} - V_s(r,T))S = 0$

If $\Delta V \sim \alpha_s/r \ll T,\ m_D$ there are thermal contribution to the potentials

singlet-octet transition :



Landau damping :



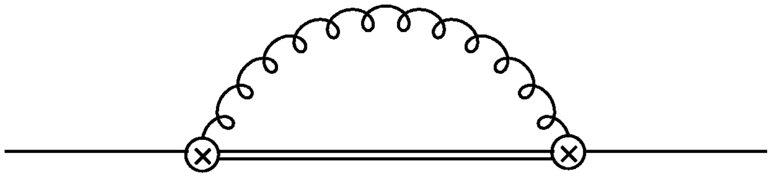
Brambilla, Ghiglieri, P.P., Vairo arXiv:0804.0993 [hep-ph]

The potential for $r < 1/T < 1/m_D$:

$$QCD \;\; {}^{1/r}\!\rightarrow pNRQCD \;\; {}^{T}\!\rightarrow pNQRCD_{HTL} \;\; {}^{m_D}\!\rightarrow pNRQCD_{therm}$$

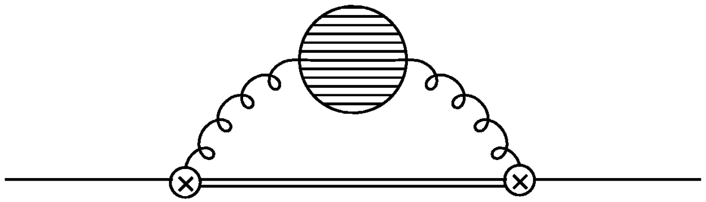
Re$V_s(r,T)$ | Im$V_s(r,T)$

$-C_F\frac{\alpha_s}{r}$ | 0



$\Delta V = V_o - V_s$

T: $g^2T^3r^2 \times \frac{\Delta V}{T} \sim \alpha_s^2 T^2 r$ | $g^2T^3r^2 \times \left(\frac{\Delta V}{T}\right)^2 \sim \alpha_s^3 T$

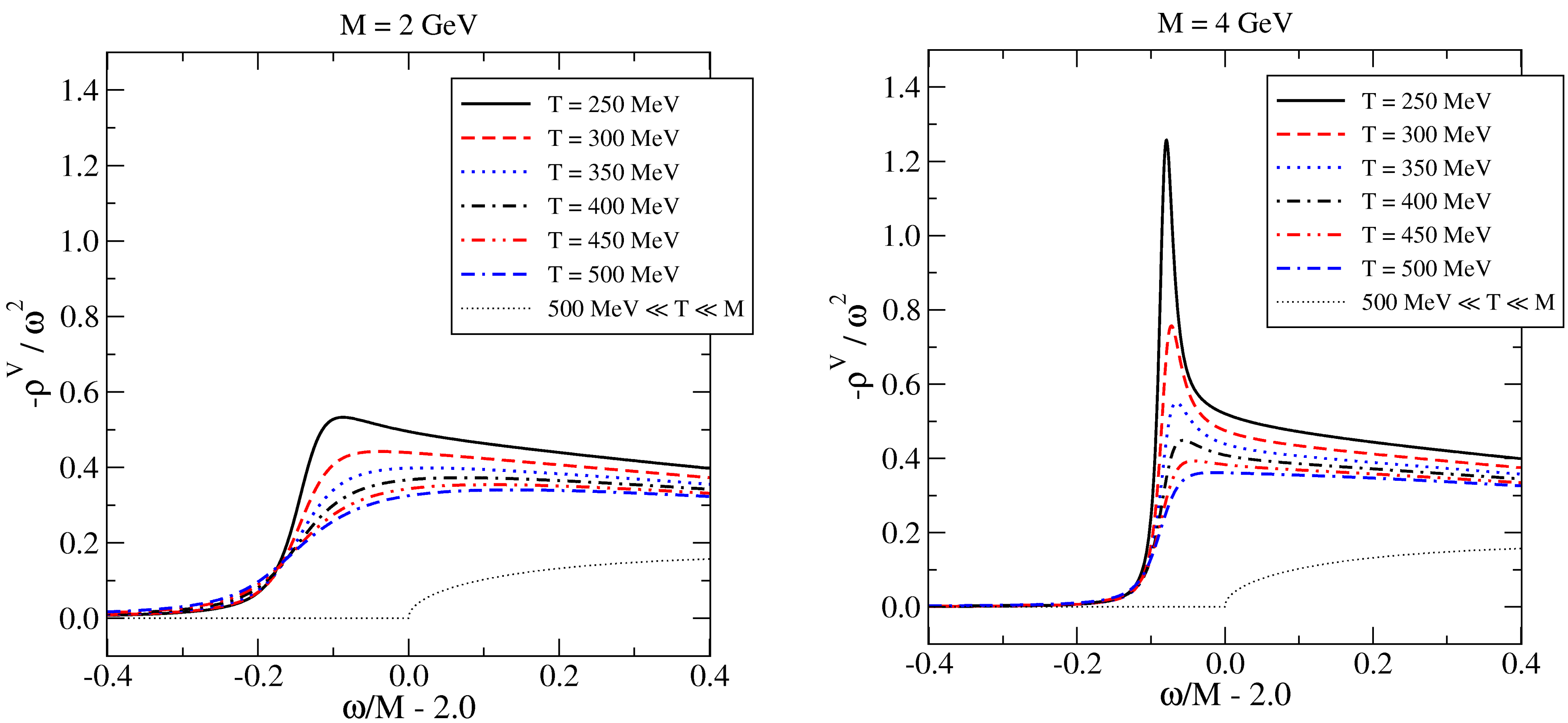


T: $g^2T^3r^2 \times \left(\frac{m_D}{T}\right)^2$ | $g^2T^3r^2 \times \left(\frac{m_D}{T}\right)^2$

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

Spectral functions with complex potential ?

Burnier, Laine, Vepsalainen JHEP 0801 (08) 043



The imaginary part of the potential washes out the bound state peak making it a mere threshold enhancement even for b-quarks !
Large threshold enhancement is observed

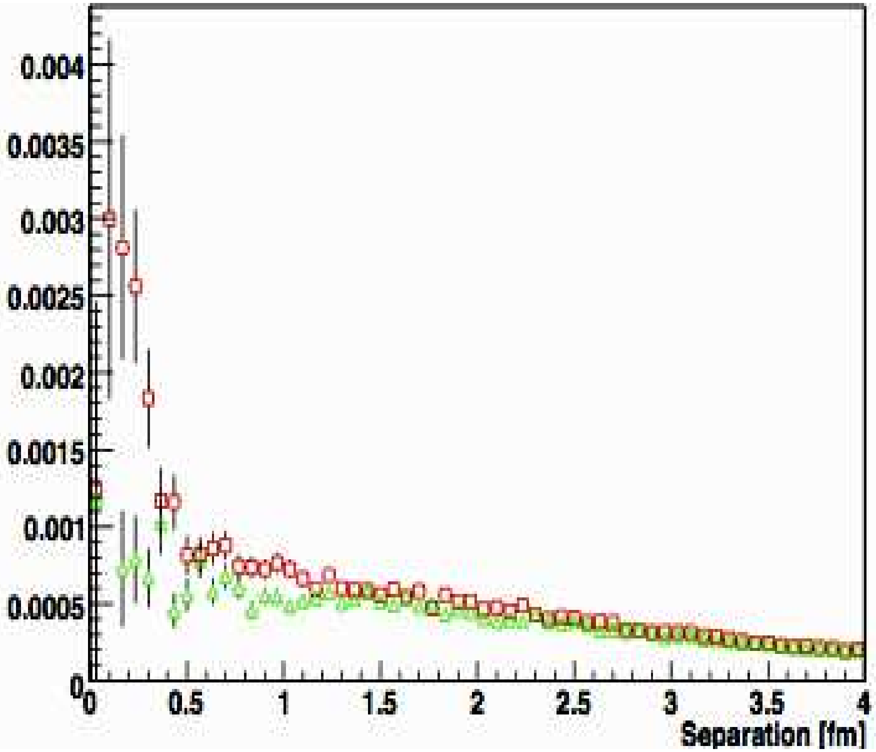
Dynamical model for charmonium suppression at RHIC

Charmonium is form inside the deconfined medium (QGP formation < *1fm* @ RHIC)
The charmonium yield at RHIC is determined not only by the in-medium interaction of charm quark and anti-quark but also by the in-medium charm difussion (drag)
Svetitsky PRD37 (88) 2484

attractive force between ccbar

$$\frac{d\mathbf{p}}{dt} = -\eta\mathbf{p} + \xi - \nabla U$$

$$\frac{d\mathbf{r}}{dt} = \frac{\mathbf{p}}{m_c}$$



1) diffusion constant from analysis of open charm yield
Moore, Teaney, PRC71 (05) 064904

2) the bulk matter is simulated by 2+1d hydro (*e=p/3*)

3) *U* is taken from lattice QCD

4) initial charm distribution from PYTHIA

5) not the most realistic choice of U

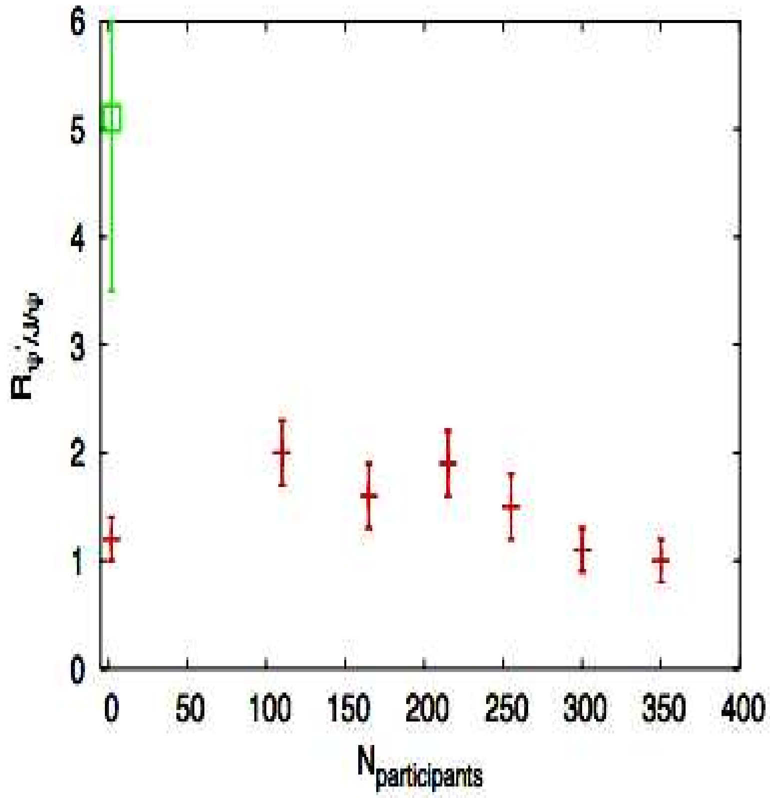
6) projecting onto quantum mechanical bound states is problematic

Young, Shuryak, arXiv:0803.2866 [nucl-th]

Ratio of psi’ to J/psi (mock thermal equilibrium):

we form the *double* ratios, at two relative energies corresponding to ψ' and J/ψ masses (minus $2m_{charm}$)

$$R_{\psi'/J\psi} = \frac{f(.8\text{ GeV})}{f_0(.8\text{ GeV})} \Big/ \frac{f(.3\text{ GeV})}{f_0(.3\text{ GeV})}$$

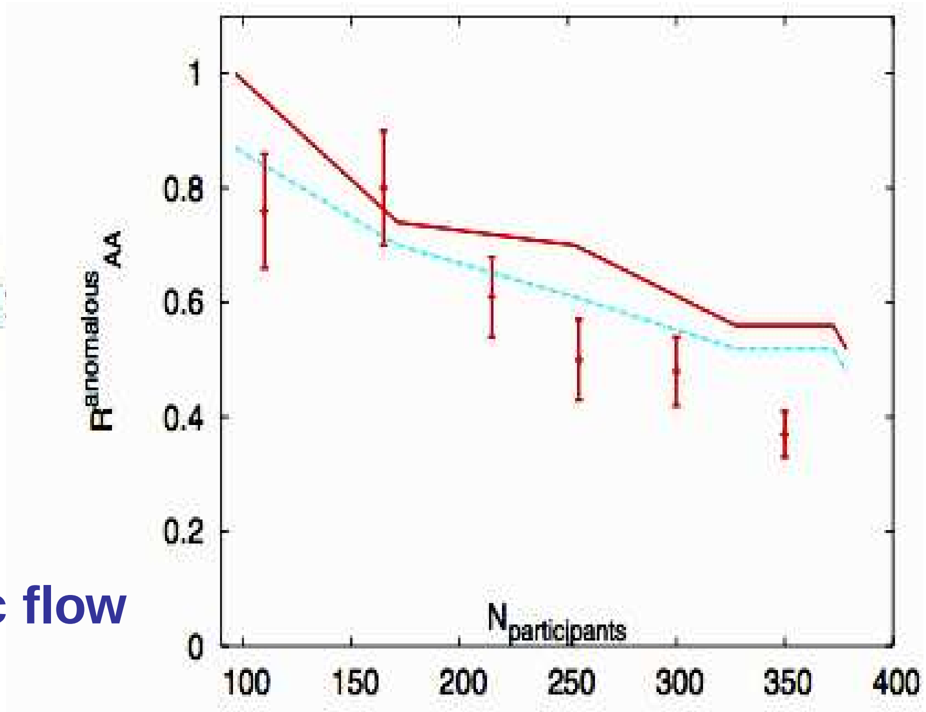


$R_{\psi'/J\psi} \rightarrow 1$: thermal equilibrium observed by NA50.

due to quasi-equlibrium and not true thermal equlibrium

Feed-down from excited states :

$$N_{J/\psi}^{final} = N_{J/\psi}^{direct}\left[1 + R_{\psi'/\psi}\sum_i \left(\frac{g_i}{3}\right)\exp\left(-\frac{\Delta M_i}{T}\right)B_i\left(\right.\right]$$



Open questions :

What are pt, y distributions and anisotropic flow of J/psi from the Langevin dynamics ?

Summary

- Most likely charmonium states dissolve in QGP due thermal effects : thermal activation to octet states, screening, Landau-damping

- However, ccbar pairs remain correlated due to strong attraction at short distances (seen as threshold enhancement in the spectral functions and tiny *T*-dependence of the Euclidean correlators

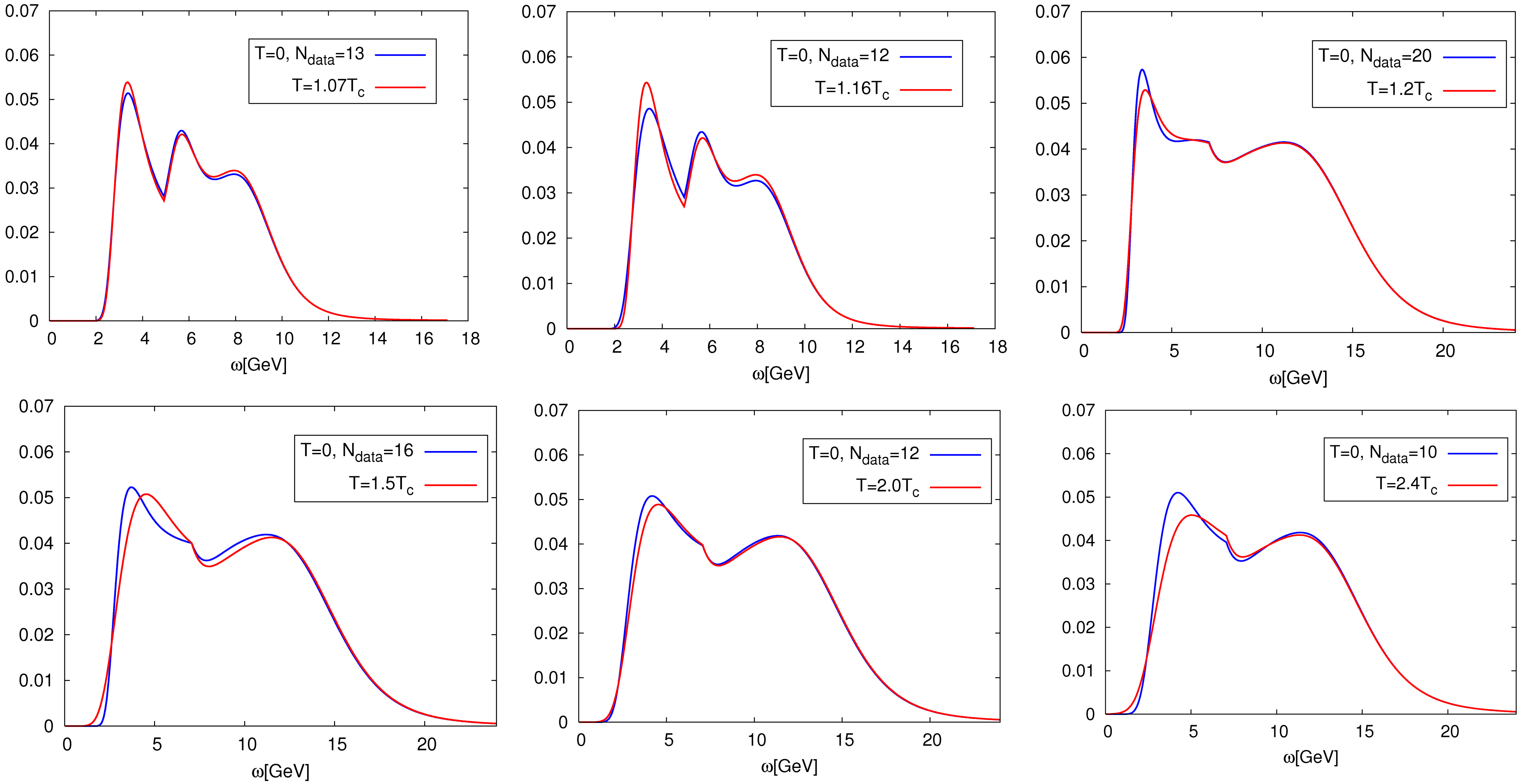
- What can we learn from charmonium measurements : ?
  - attractive interaction of heavy quarks in QGP (sQGP ?)
  - diffusion of heavy quarks in QGP
  - system lifetime

- Dynamic models including the attractive interaction between quarks and diffusion of heavy quarks can in principle describe the moderate J/psi suppression observed at RHIC
  - problems are in details : exact form of interaction, cold nuclear matter effects etc
  - closer connection to fundamental QCD is needed

- Suppression @ LHC > Suppression @ RHIC > Suppression @ SPS (experimentally confirmed up to RHIC energies)

Back-up: Charmonium spectral functions at finite temperature

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



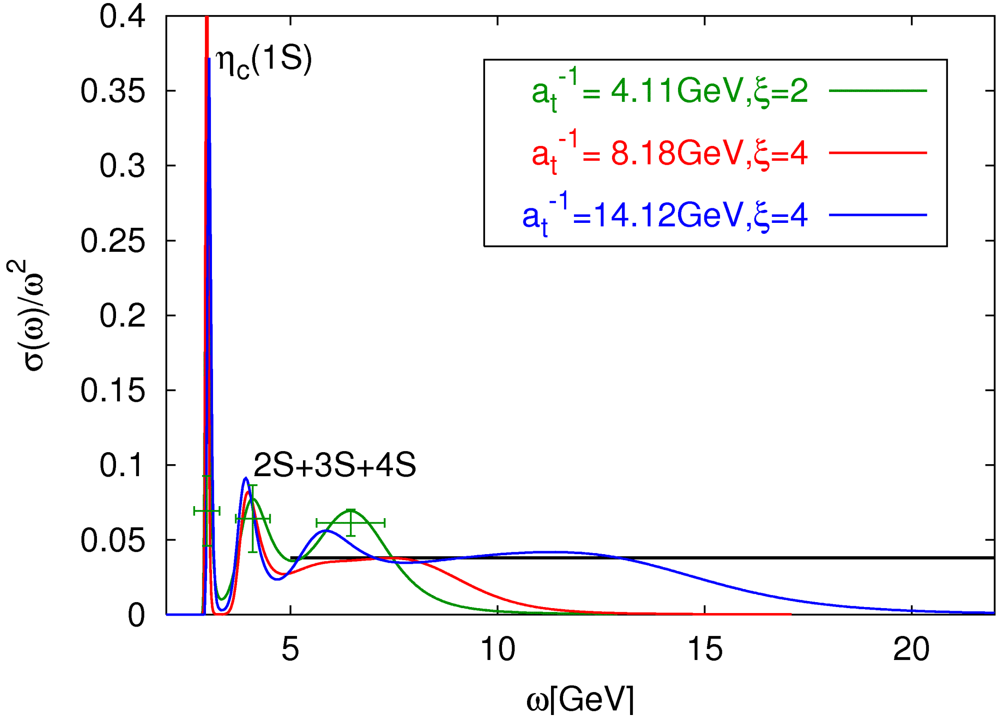
no large T-dependence but details are not resolved

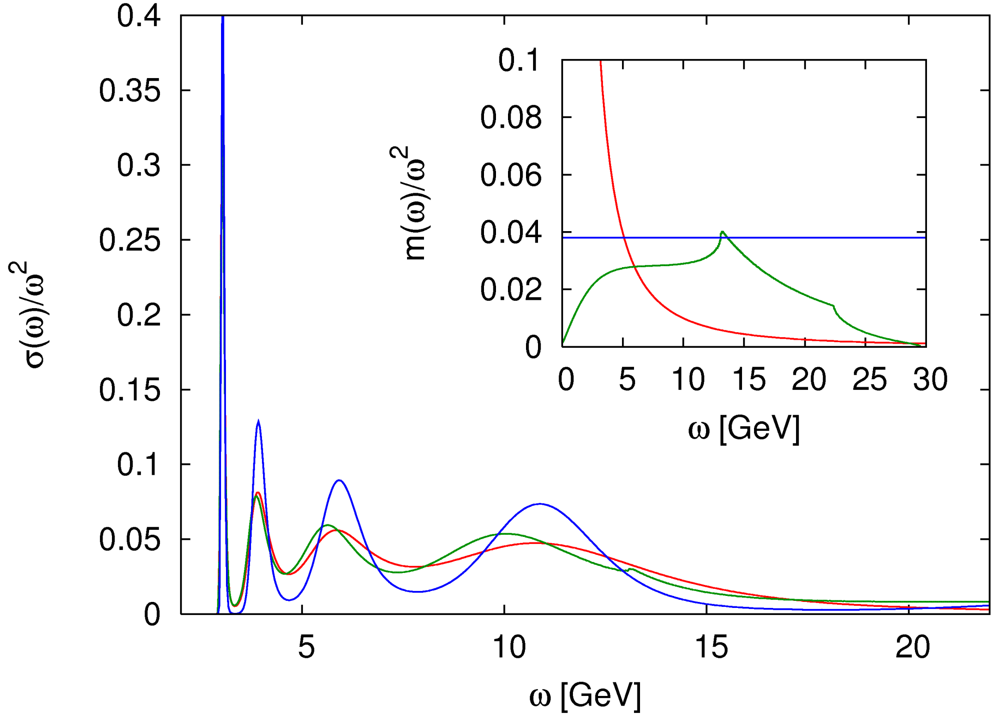
Back-up: Charmonia spectral functions at T=0

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