Heavy quarks as probes of the deconfined medium

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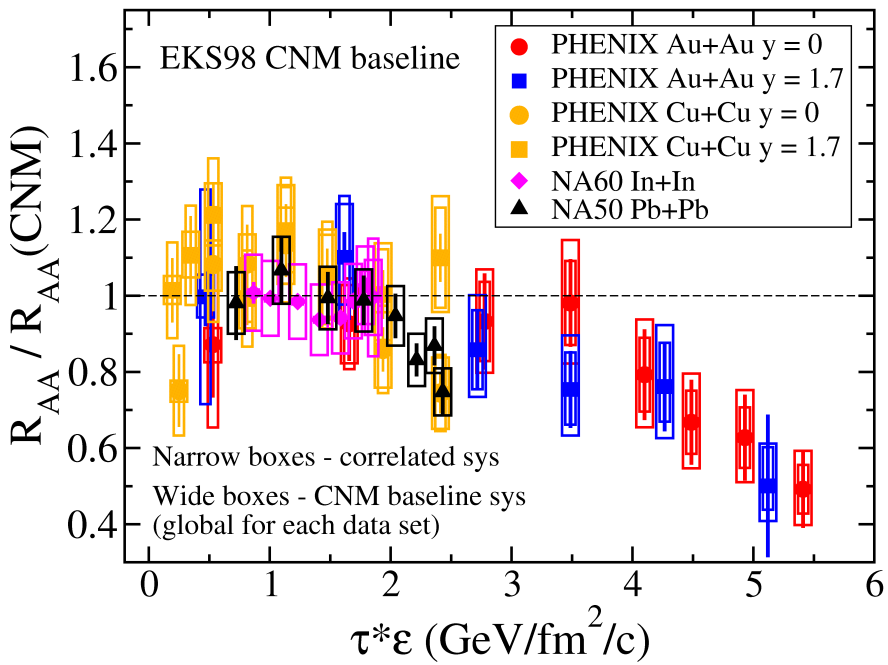
- Introduction : deconfinement at high temperatures, color screening and melting of mesons and lattice QCD at $T>0$
- Heavy meson correlation functions in lattice QCD and spectral functions
- Fluctuations and correlations of conserved charges as probe of deconfinement and hot medium
- Summary

Columbia University, March 8, 2010

Heavy flavor probes of the matter produced in RHIC

Nuclear modification factor for J/ψ production and non-photonic electrons from open charm (beauty) mesons

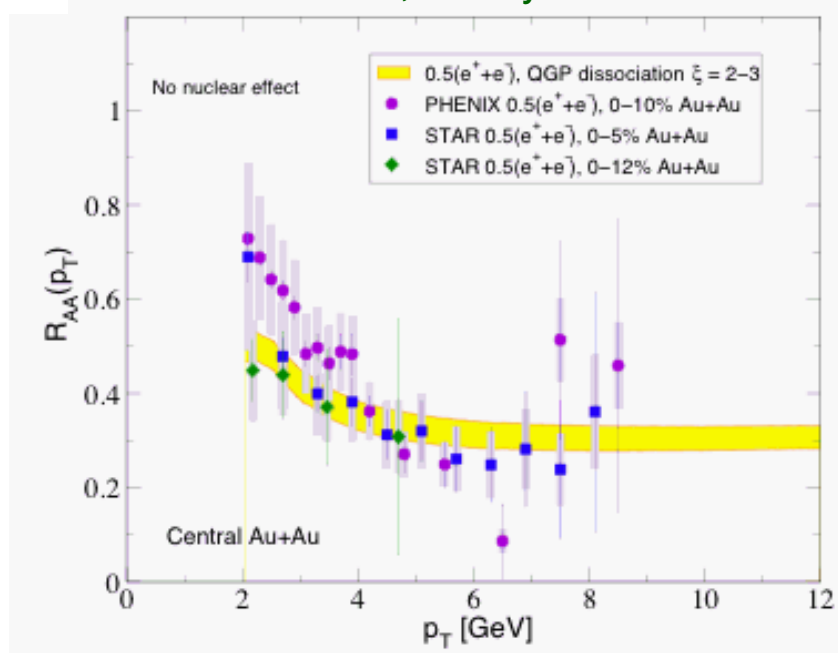
Frawley, talk at CATHIE-INT mini program'09, INT



Existence of heavy quarkonium states in the hot medium

Matsui and Satz, Kharzeev et al., ….

Vitev .et. al, J. Phys. G 34



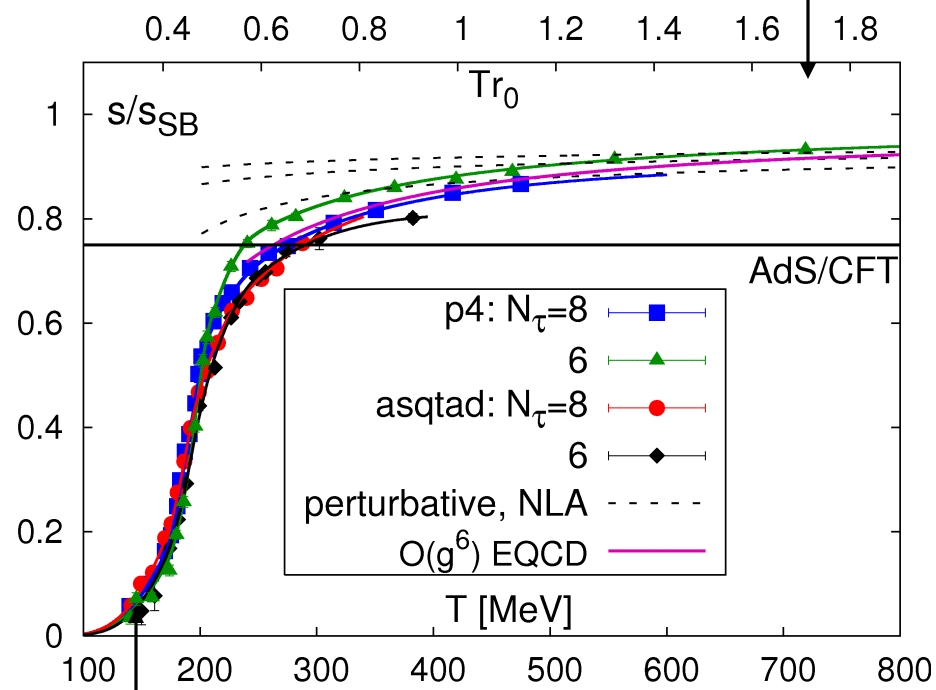
Too large energy loss of heavy quarks could be explained by heavy light bound states in the hot medium

Bellwied et al, Hees and Rapp …

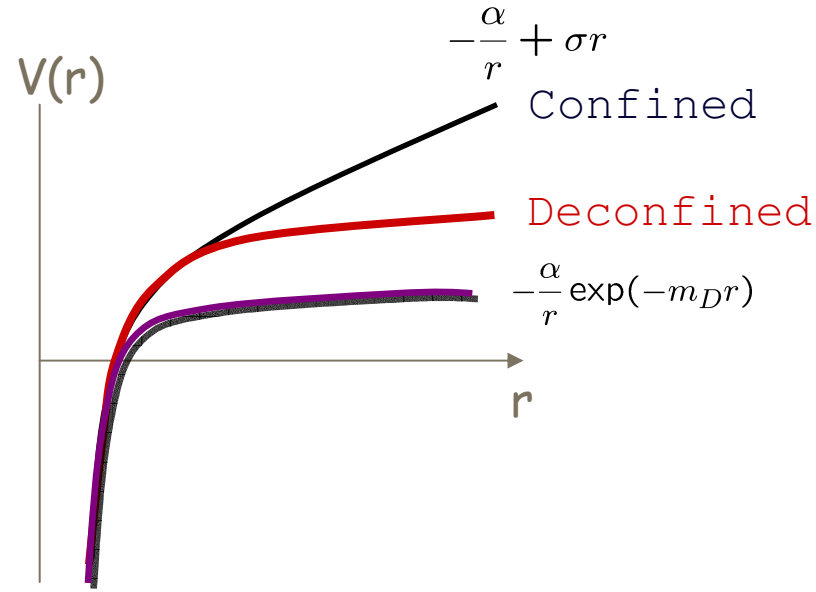
Color screening in QCD and quarkonia melting

free gas of quarks and gluons =
18 quark+18 anti-quarks +16 gluons =52 light d.o.f

P.P., NPA 830 (2009) 11



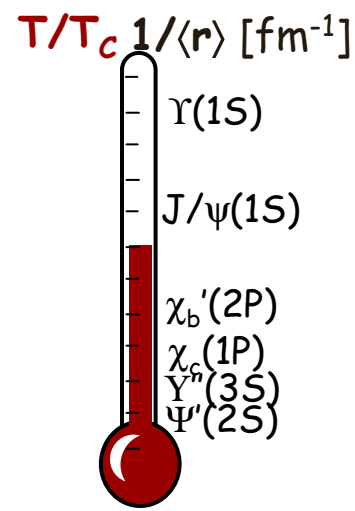
pion gas = 3 light d.o.f.



Matsui and Satz PLB 178 (86) 416

interactions become short range

melting of heavy quarkonium states



Finite Temperature QCD and its Lattice Formulation

$$\langle O \rangle = \mathrm{Tr} O e^{-\beta H - \mu N}$$

evolution operator in imaginary time

$$\beta = 1/T$$

$$\langle O \rangle = \int \mathcal{D}A_\mu \mathcal{D}\psi \mathcal{D}\bar{\psi} O e^{-\int_0^\beta d\tau d^3x \mathcal{L}_{QCD}}$$

$$A_\mu(0,\mathbf{x}) = A_\mu(\beta,\mathbf{x}) \;\; \psi(0,\mathbf{x}) = -\psi(\beta,\mathbf{x})$$

Integral over functions → Lattice → integral with very large (but finite) dimension (> 1000000)

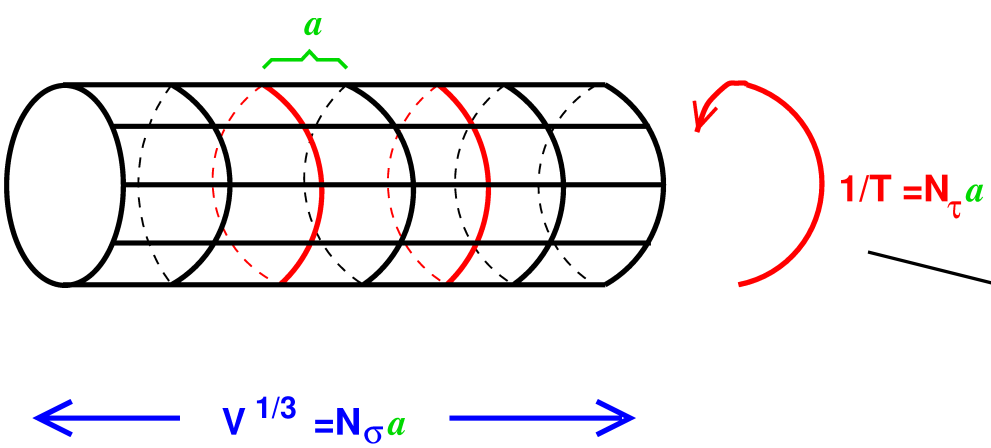
$$\langle O \rangle = \int \prod_x dU_\mu(x) O(detM[U]) e^{-\sum_x S_G[U(x)]}, U_\mu(x) = e^{igaA_\mu(x)}$$

Quenched approximation : $detM = 1$

continuum limit

$N_\tau \to \infty$, N_σ/N_τ fixed

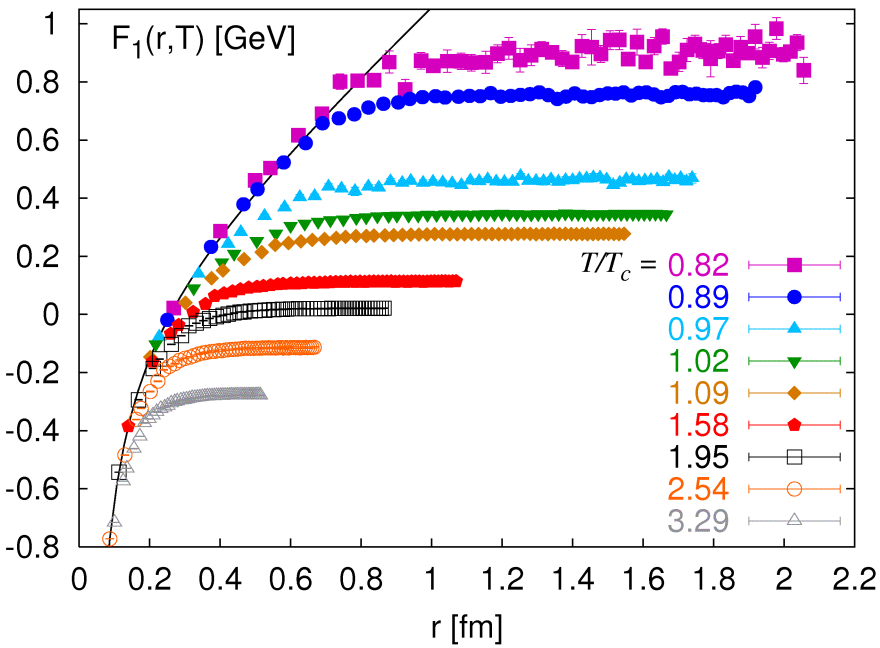
Costs : $\sim a^{-7} \sim N_\tau^7$



difficult to study real time properties:
spectral functions,
transport coefficients

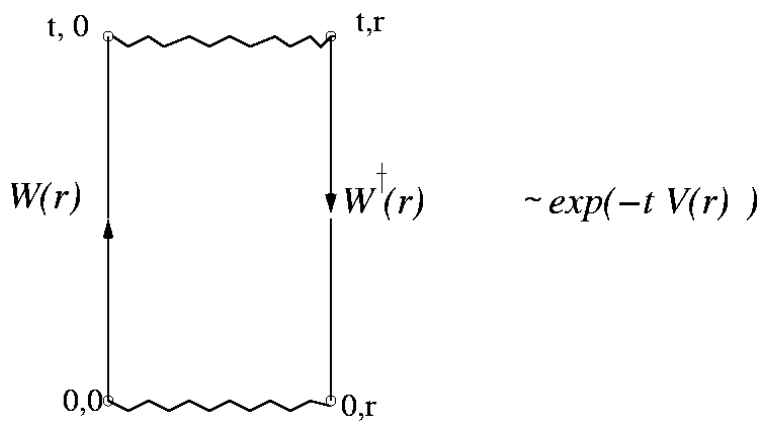
Color screening in lattice QCD

P.P., arXiv:1001.5284 $(2+1)f\ QCD,\ 16^3 \times 4$ lattices, $m_\pi \simeq 220$ MeV



Infinitely heavy quark anti-quark pair :

$$W(r) = \mathcal{P}\exp(ig\int_0^{1/T} d\tau A_0(r,\tau))$$



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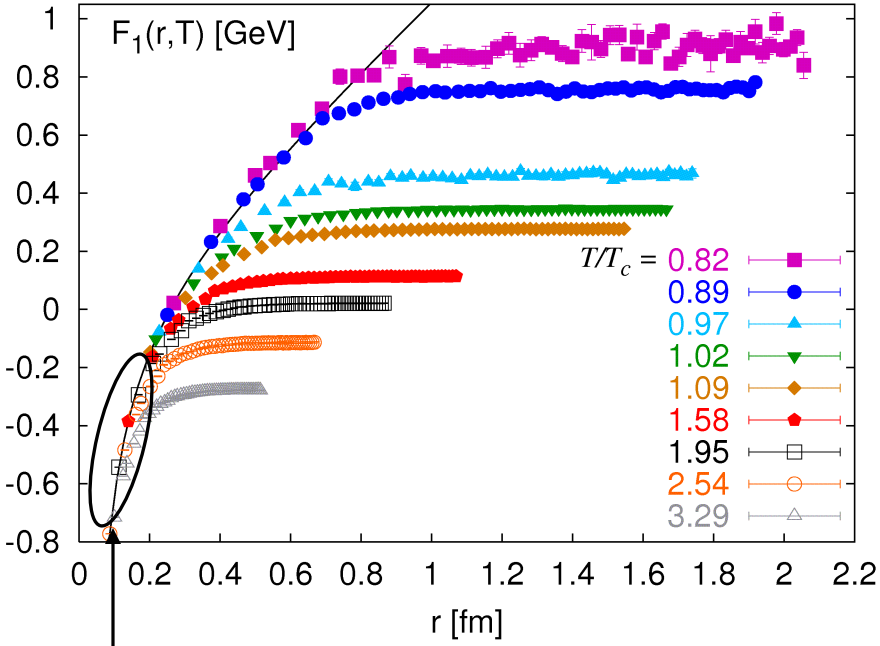
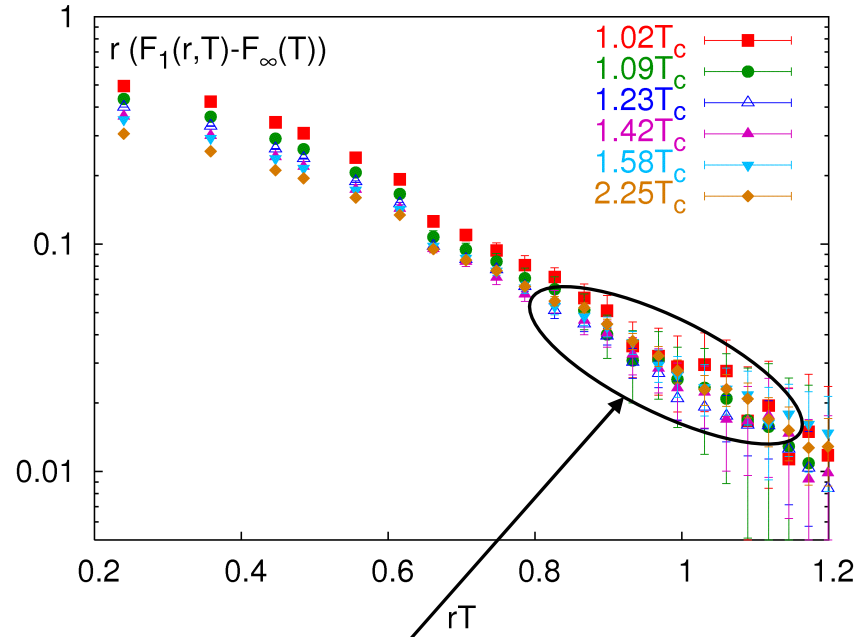




$F_1(r,T)$ T-independent at short distances

$F_1(r,T)$ 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.

This imply quarkonium melting ?
Digal, P.P., Satz, PLB 514 (01) 57 ; PRD 64 (01) 094015,

Meson correlators and spectral functions

$$G(\tau,\vec{p}) = \int d^3x e^{i\vec{p}\vec{x}} \langle J_H(\tau,\vec{x}) J_H^\dagger(0,0)\rangle \qquad J_H(\tau,\vec{x} = \bar{q}(\tau,\vec{x})\Gamma_H q(\tau,\vec{x})$$

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

γ_5 : Pseudo – scalar(PS) $\rightarrow \eta_c\ (^1S_0)$ $\qquad$ 1 : Scalar(SC) $\rightarrow \chi_{c0}\ (^3P_0)$

γ_μ : Vector(VC) $\rightarrow J/\psi\ (^3S_1)$ $\qquad$ $\gamma_5\gamma_\mu$: Axial – Vector(AX) $\rightarrow \chi_{c1}\ (^3P_1)$

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

Imaginary time $\qquad$ Real time

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

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

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

Spatial correlation functions more sensitive to the low frequency behavior :

$$G(z) = \int dxdy \int_0^{1/T} d\tau \langle J_H(\tau,\vec{x}) J_H^\dagger(0,0)\rangle|_{z\rightarrow\infty} \sim \exp(-M_s z)$$

$$G(z) = \int_{-\infty}^{\infty} dp_z e^{ip_z z} \int_0^\infty d\omega \frac{\sigma(\omega,0,0,p_z)}{\omega}$$

Charmonia spectral functions at T=0

Quenched approximation

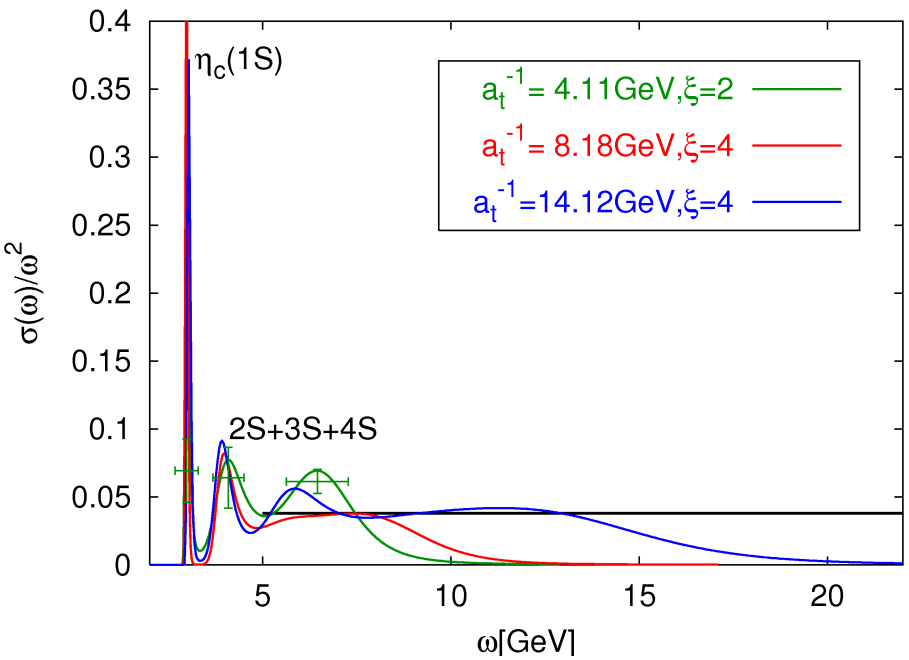
Anisotropic lattices: $16^3 \times 64, \xi = 2$ $16^3 \times 96, \xi = 4$, $24^3 \times 160, \xi = 4$

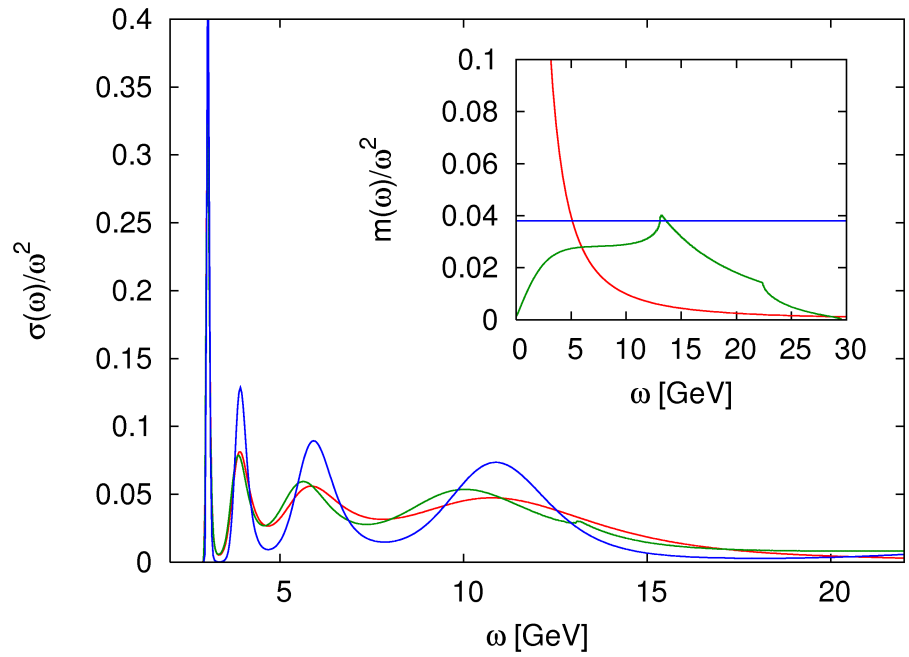
$L_s = 1.35 - 1.54$fm, #configs=500-930;

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

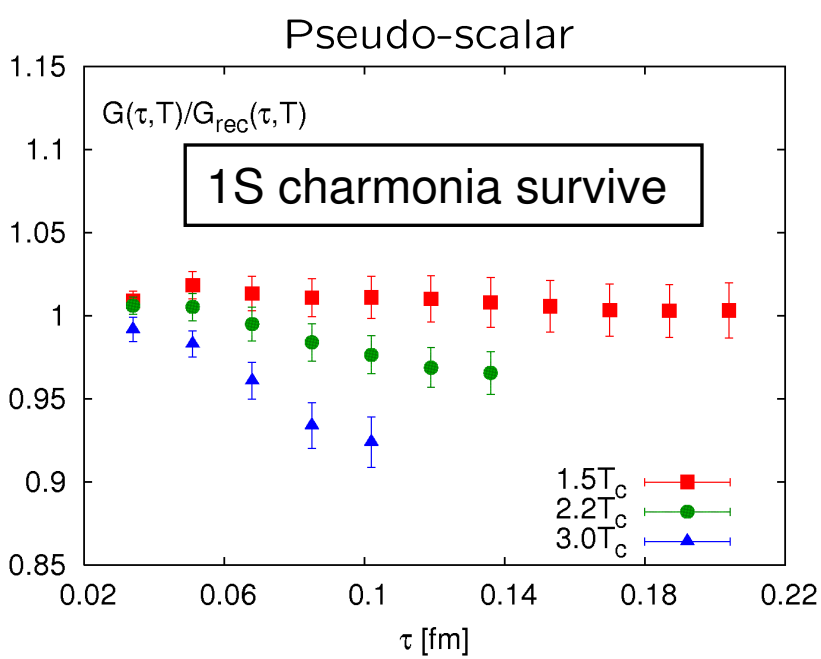
Charmonia correlators at T>0

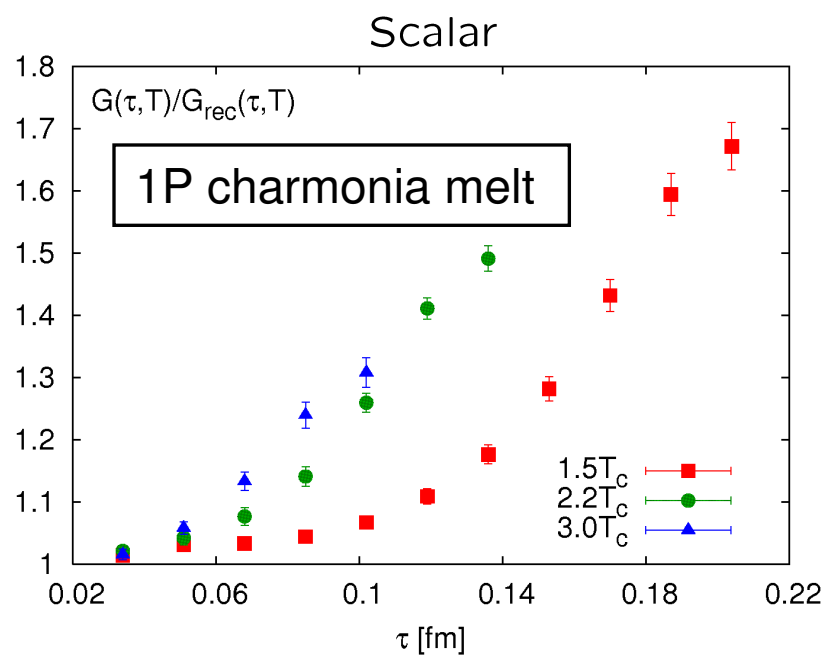
temperature dependene of $G(\tau,T)$

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

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

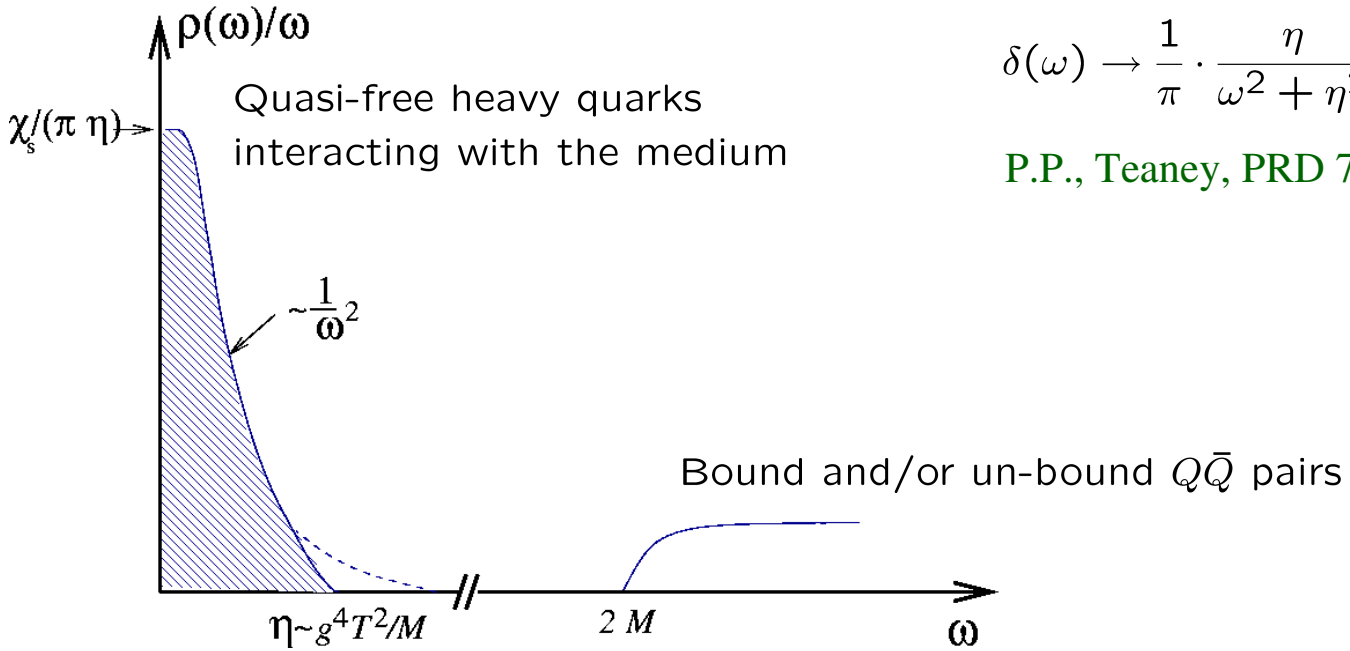
$$G_{recon}(\tau,T)=\int_0^\infty d\omega\sigma(\omega,T=0)\frac{\cosh(\omega\cdot(\tau-\frac{1}{2T}))}{\sinh(\omega/(2T))}$$





Datta, Karsch, P.P., Wetzorke, PRD 69 (04) 094507

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

E.g. free theory :

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

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

quark number susceptibility

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

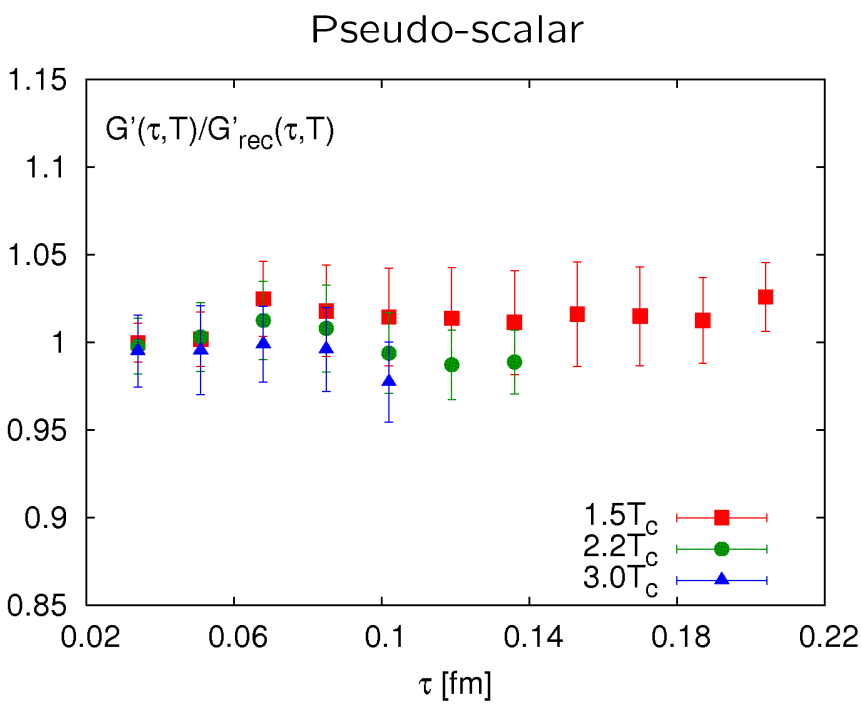
$$G_i(\tau, T) = G_i^{\text{low}}(\tau, T) + G_i^{\text{high}}(\tau, T)$$

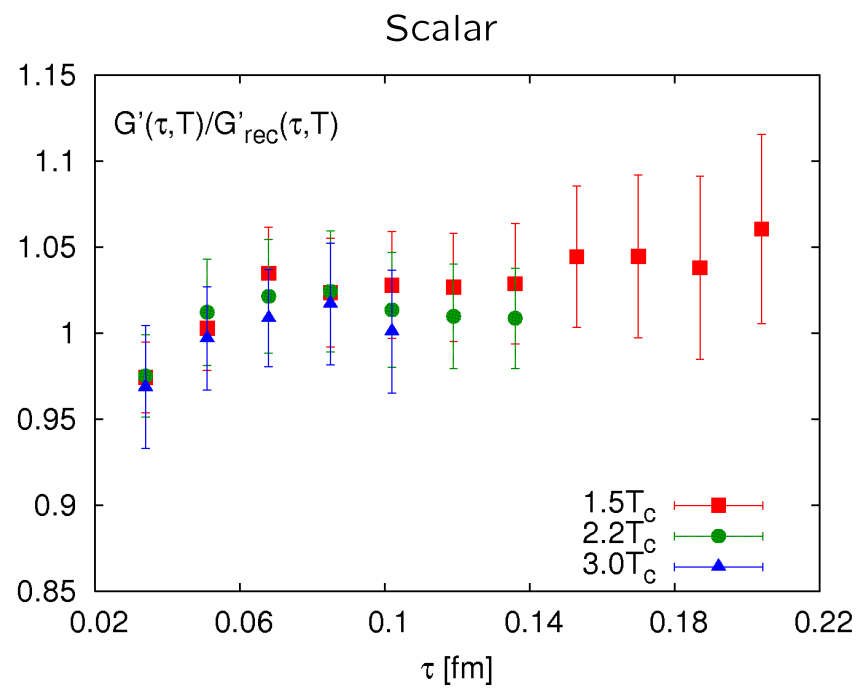
$$G^{\text{low}}(\tau) \simeq \chi^i(T)T$$

zero mode contribution

Charmonia correlators at T>0

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



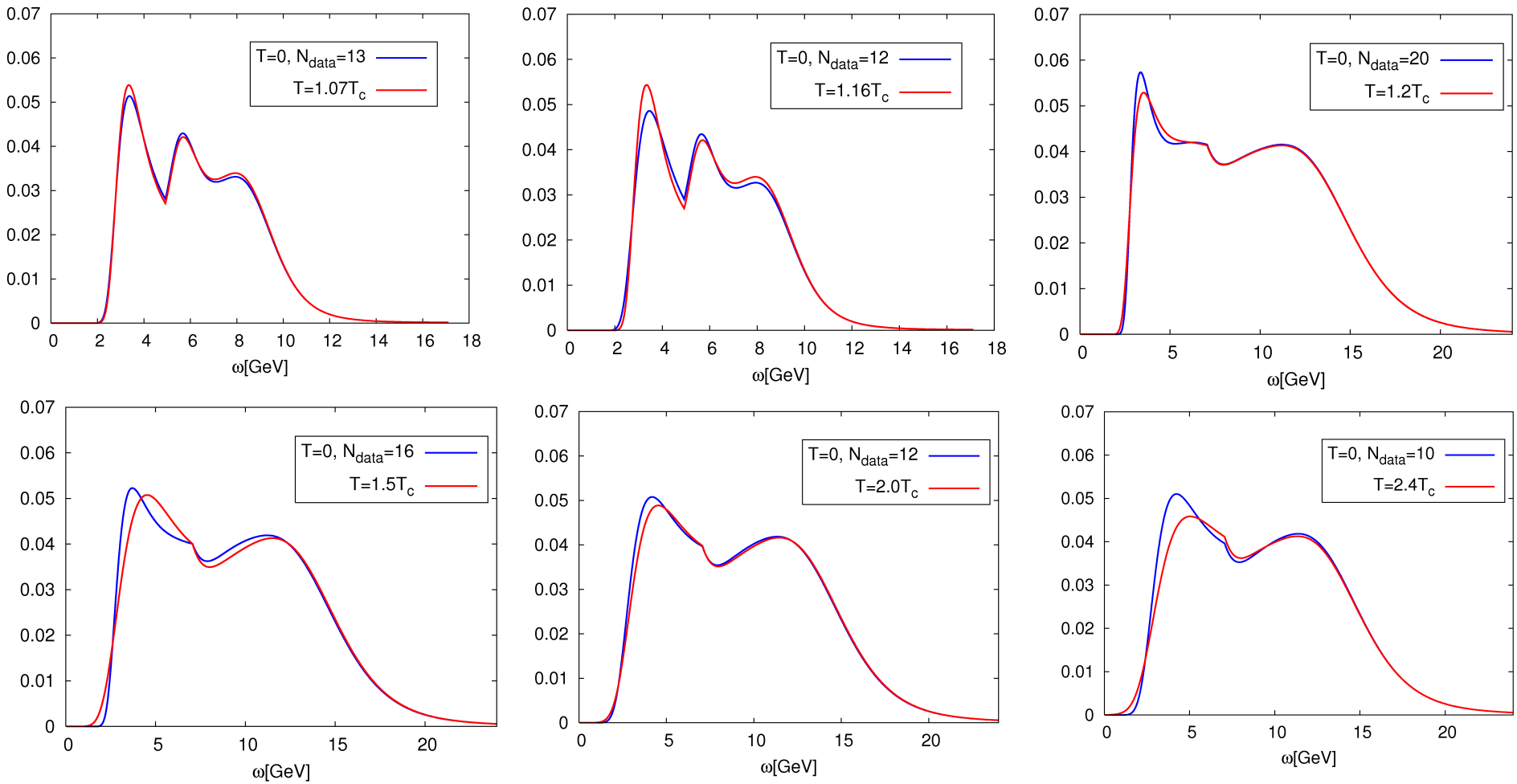


No change in the derivative of the scalar quarkonium correlator up to $3T_c$!
Almost the entire temperature dependence of the scalar correlators is given by the zero mode contribution !

P.P., EPJ C62 (2009) 85

Charmonium spectral functions at finite temperature

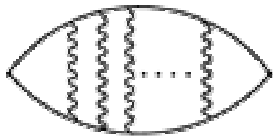
Jakovác, P.P., Petrov, Velytsky, PRD 75 (07) 014506



no large T-dependence but details are not resolved

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

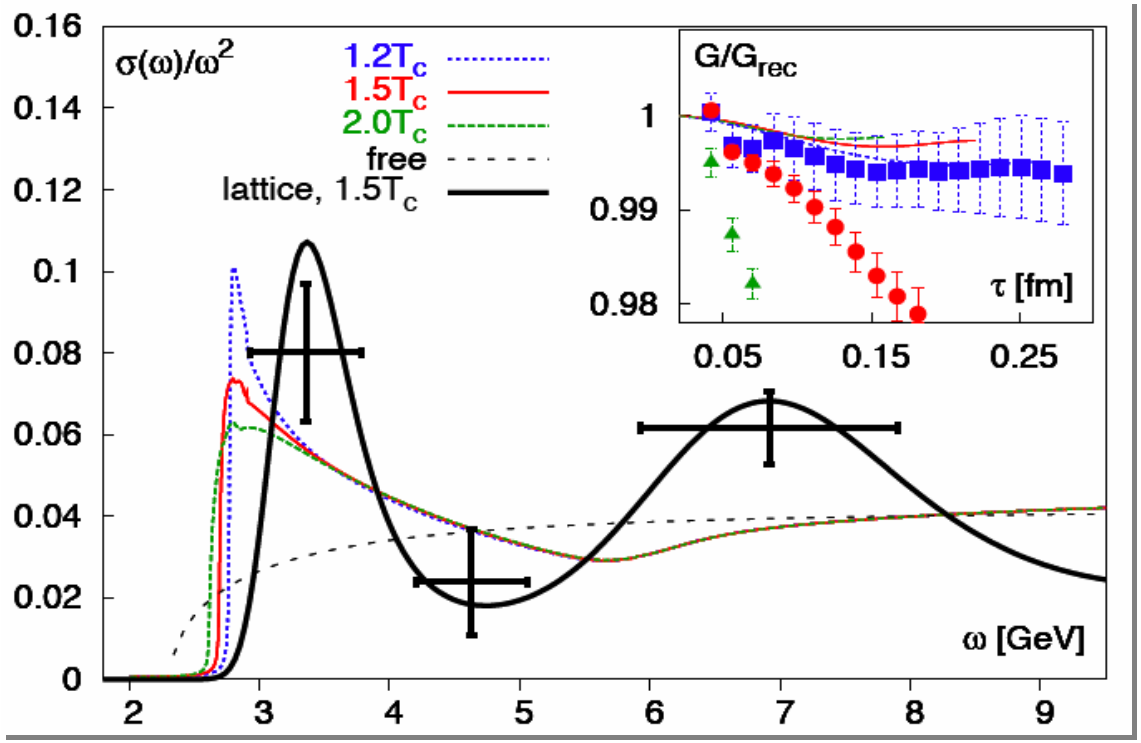
$\omega >> s_0$ perturbative

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

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

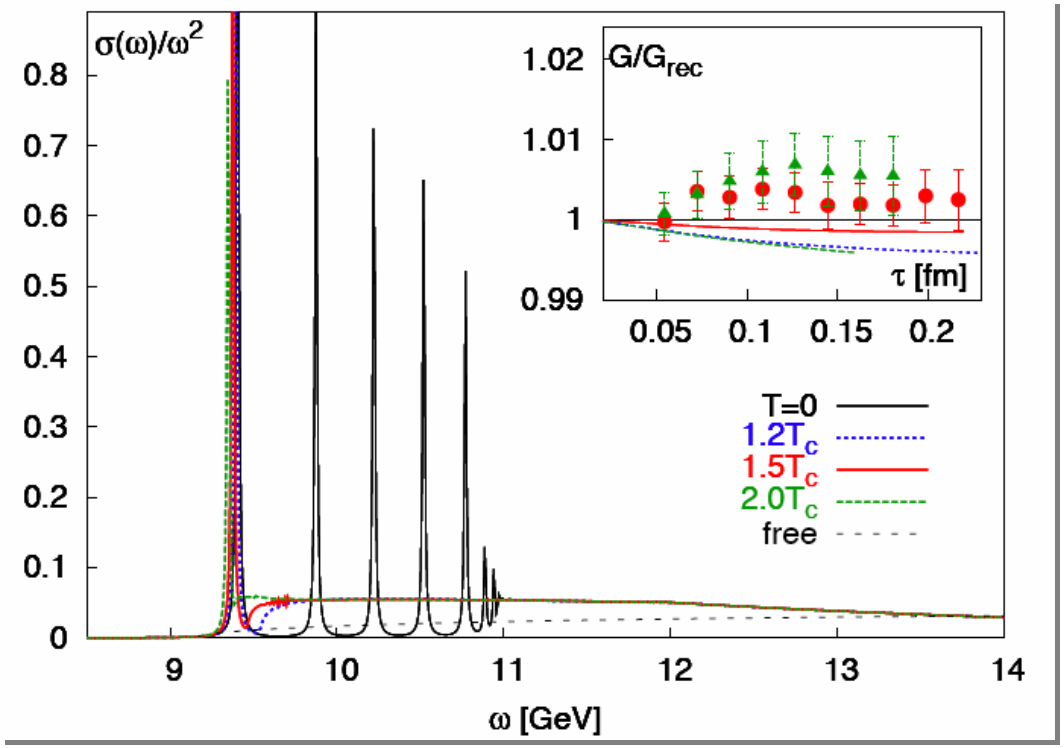
Mócsy, P.P., PRL 99 (07) 211602, PRD77 (08) 014501, EPJC ST 155 (08) 101

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_b

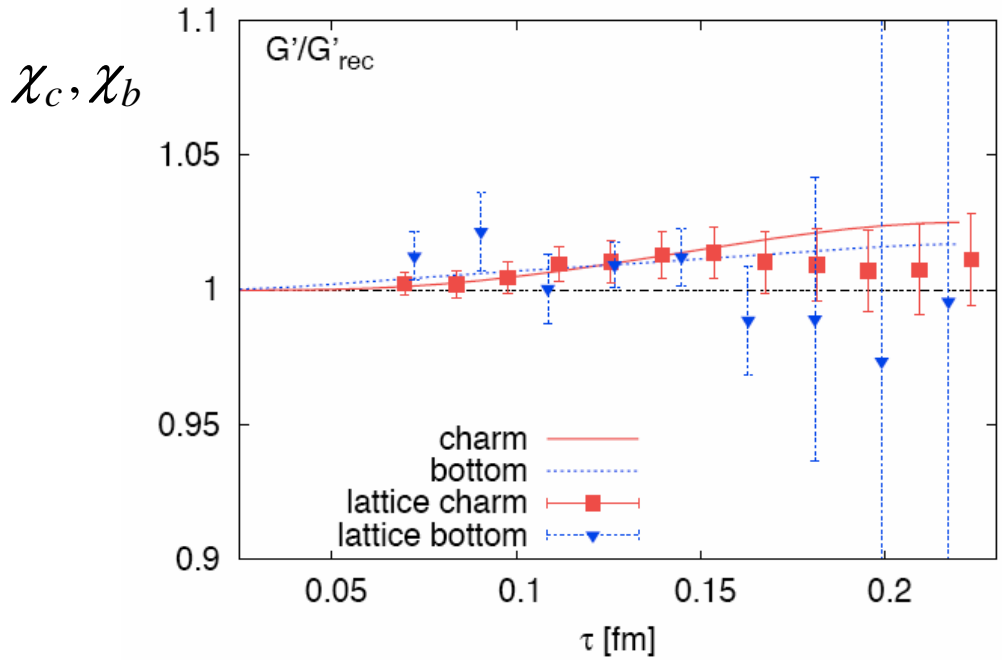


ground state bottomonium survives deconfinement

other states dissolved

medium modification of the 1S peak is small

agreement found with lattice correlators



- all P-states disappear already by $1.2T_c$

but the derivatives of the of the correlators don not show any significant T-dependence

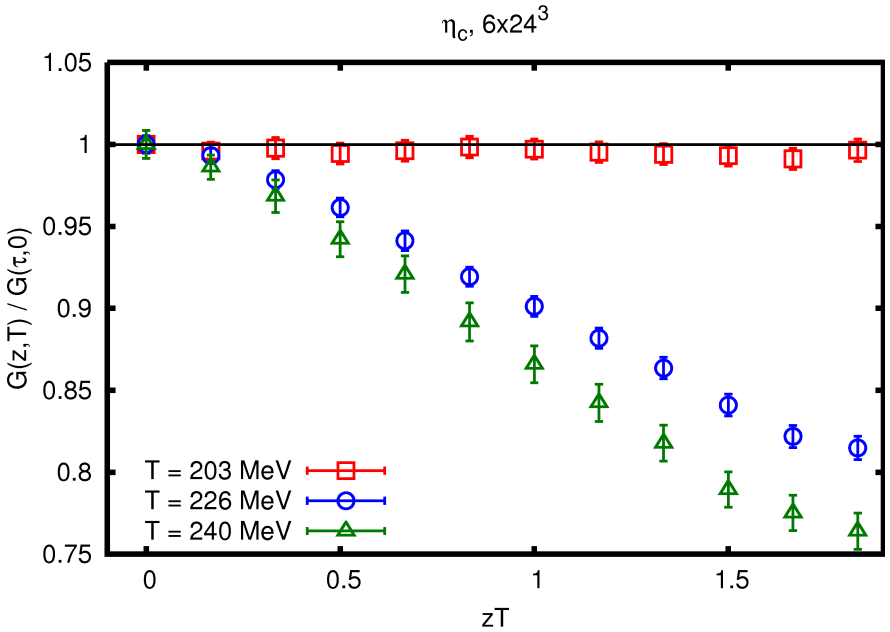
Estimates for the dissociation temperatures from potential models:

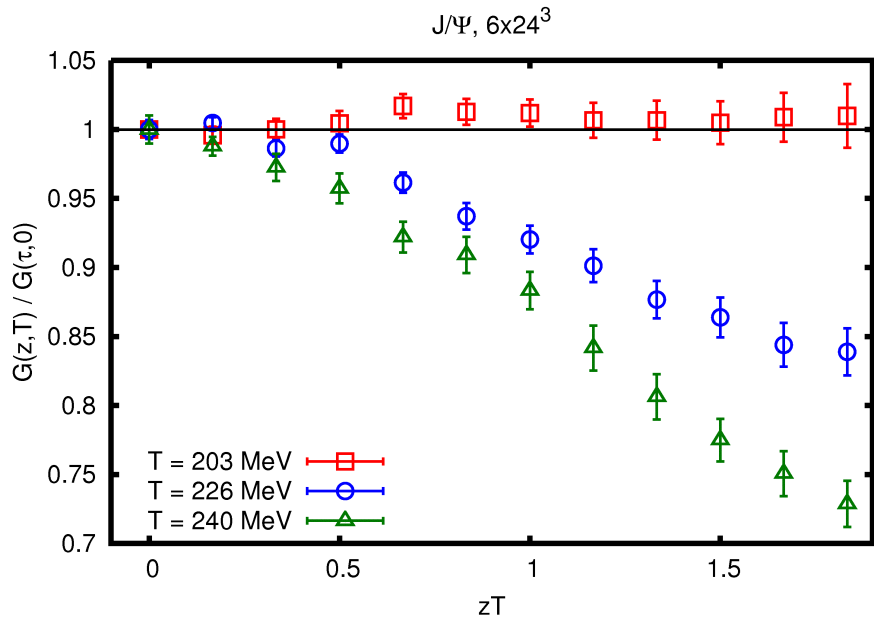
Mócsy, P.P., PRL 99 (07) 211602

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

Spatial correlation function of heavy quarkonium

RBC-Bielefeld Collaboration
Mukherjee, talk at CATHIE-TECHQM workshop, BNL, Dec. 2009





indication for strong modification of the quarkonium spectral functions compatible with melting of 1S charmonium states

Spatial correlation function of heavy quarkonium

RBC-Bielefeld Collaboration
Mukherjee, talk at CATHIE-TECHQM workshop, BNL, Dec. 2009

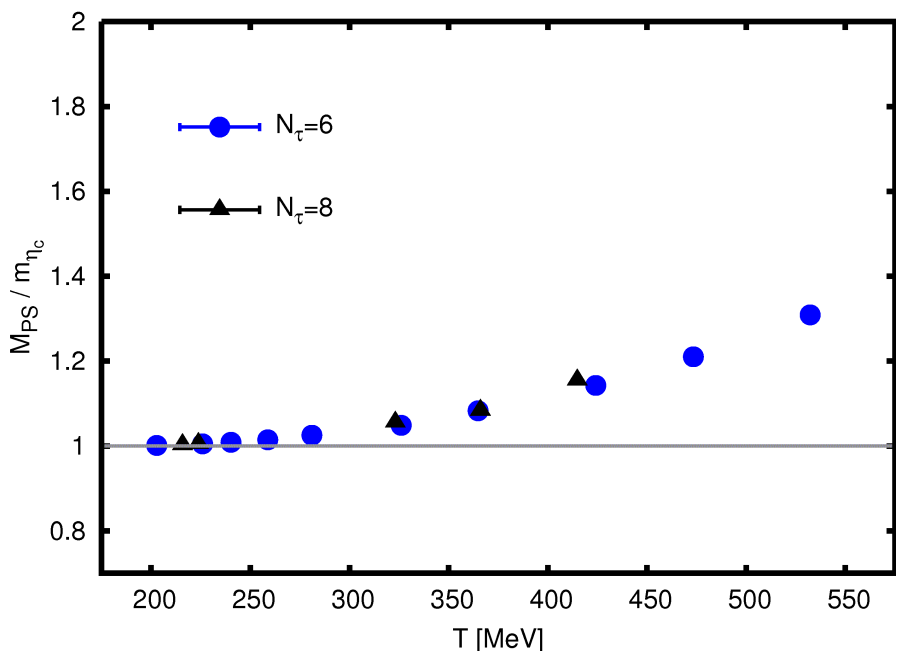
low T : narrow peak approximation

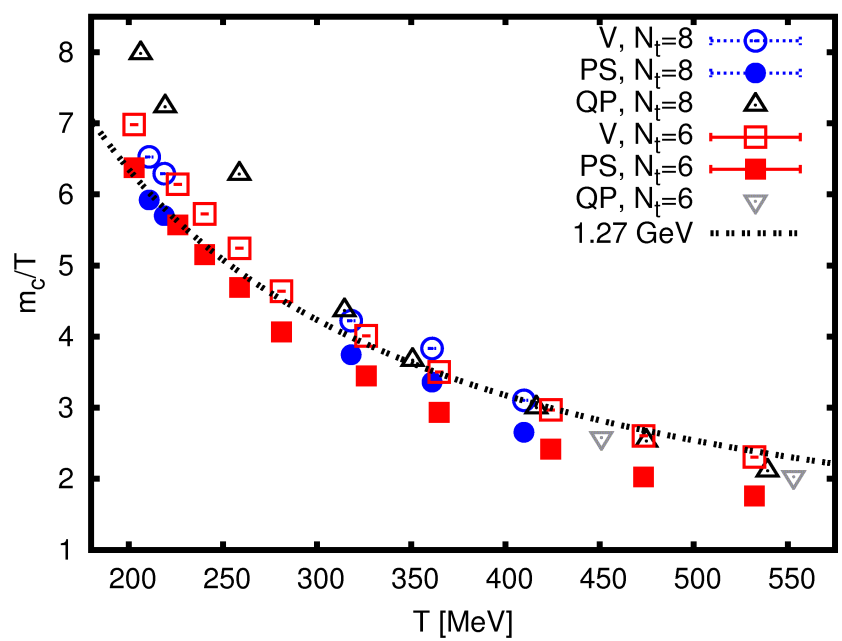
$$\sigma(\omega, \vec{p}) \sim \delta(\omega^2 - \vec{p}^2 - M^2(T))$$

$$M_s(T) \sim M(T)$$

high T : unbound quark anti-quark pair

$$M_s(T) = 2\sqrt{(\pi T)^2 + m_c^2(T)}$$





For *T>300*MeV lattice results on screening masses suggest unbound pairs

What has been learned from meson correlators ?

• Correlation function of static mesons (free energy of static quarks) indicate strong color screening effects at distances comparable to quarkonium size

• Study of quarkonium spectral functions in potential models show that most of quarkonium states are dissolved at temperatures $1.2T_c$ or $T \approx 240MeV$

• Melting of quarkonium states does not lead to large change of the Euclidean time meson correlation functions, the T-dependence of the Euclidean time meson correlation function is dominated by the zero mode contribution

• Spatial meson correlation functions are sensitive to the in-medium modification of the spectral functions they indicate melting of charmonium states at $T \approx (220\text{-}240)\ MeV$ and can be understood in terms of propagation of unbound quark anti-quark pair for $T > 300MeV$

QCD thermodynamics at non-zero chemical potential

Taylor expansion :

$$\frac{p(T,\mu_B,\mu_Q,\mu_S,\mu_c)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!l!} \chi_{ijk}^{BQS} \left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_Q}{T}\right)^j \left(\frac{\mu_S}{T}\right)^k \left(\frac{\mu_c}{T}\right)^l$$

hadronic

$$\frac{p(T,\mu_u,\mu_d,\mu_s,\mu_c)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!l!} \chi_{ijkl}^{uds} \left(\frac{\mu_u}{T}\right)^i \left(\frac{\mu_d}{T}\right)^j \left(\frac{\mu_s}{T}\right)^k \left(\frac{\mu_c}{T}\right)^l$$

quark

$$\chi_{ijk}^{abc} = \frac{\partial^i}{\partial\hat{\mu}_a^i}\frac{\partial^j}{\partial\hat{\mu}_b^j}\frac{\partial^k}{\partial\hat{\mu}_c^k}\frac{\partial^l}{\partial\hat{\mu}_d^l}\frac{1}{VT^3} \ln Z(T,V,\mu_a,\mu_b,\mu_c,\mu_d)|_{\mu_a=\mu_b=\mu_c=\mu_d=0},$$

$$\hat{\mu}_X = \mu_X/T$$

Taylor expansion coefficients give the fluctuations and correlations of conserved charges, e.g.

$$\chi_2^X = \frac{1}{VT^3}(\langle X^2\rangle - \langle X\rangle^2) \qquad \chi_{11}^{XY} = \frac{1}{VT^3}(\langle XY\rangle - \langle X\rangle\langle Y\rangle)$$

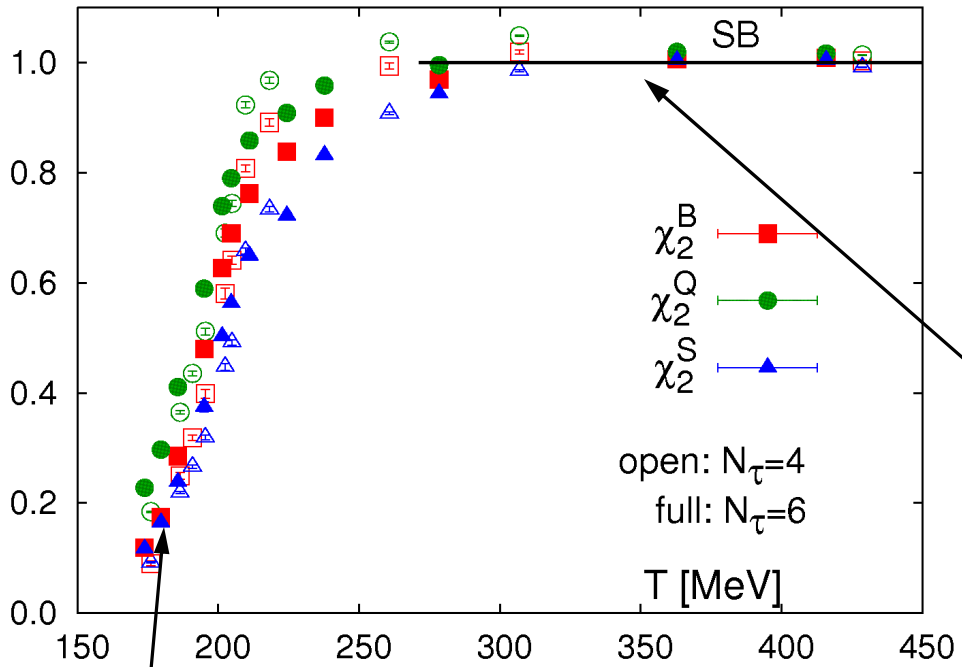
Deconfinement : fluctuations of conserved charges

$$\chi_2^B = \frac{1}{VT^3}(\langle B^2\rangle - \langle B\rangle^2)$$ baryon number

Cheng et al., arXiv:0811.1006

$$\chi_2^Q = \frac{1}{VT^3}(\langle Q^2\rangle - \langle Q\rangle^2)$$ electric charge

$$\chi_2^S = \frac{1}{VT^3}(\langle S^2\rangle - \langle S\rangle^2)$$ strange quark number



Ideal gas of quarks :

$$\chi_2^B{}_{\rm SB} = \frac{1}{3} \quad \chi_2^Q{}_{\rm SB} = \frac{2}{3}$$

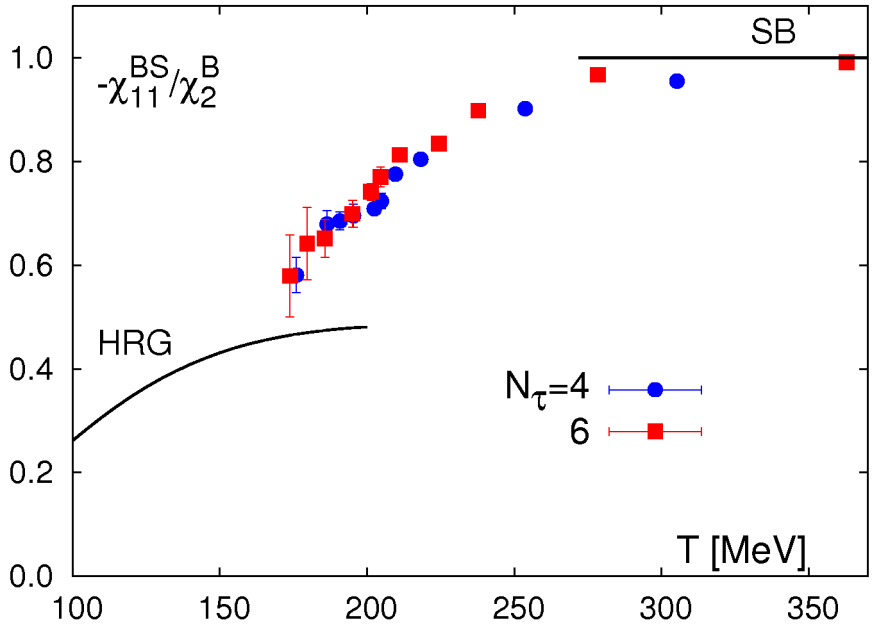
$$\chi_2^S{}_{\rm SB} = 1$$

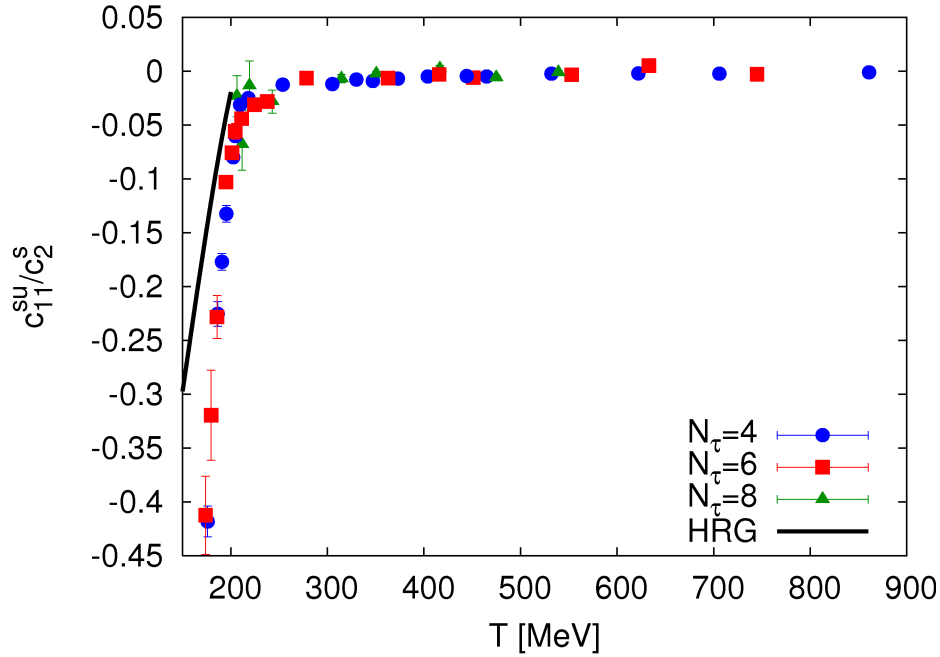
conserved charges carried by light quarks

conserved charges are carried by massive hadrons

Deconfinement : correlations of conserved charges

Cheng et al., arXiv:0811.1006, P.P, Hegde, Velytsky, PoS LAT2009 159



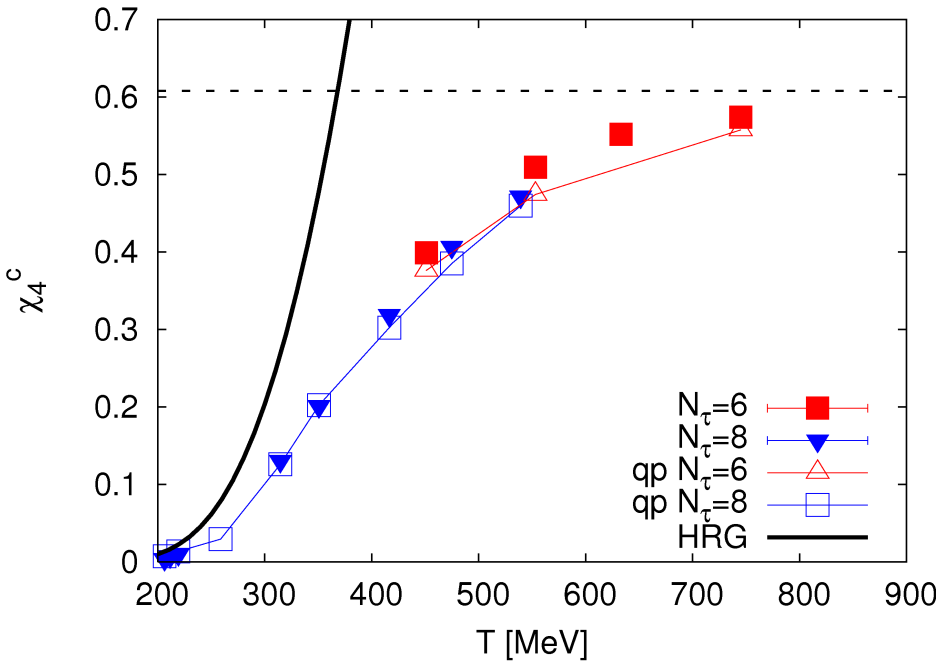


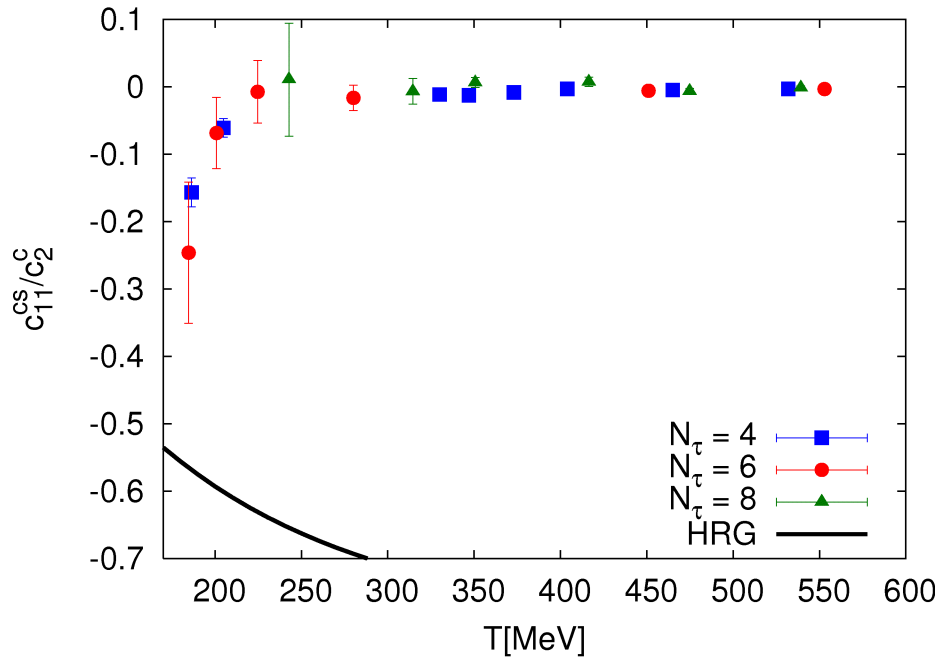
correlations of conserved charges at low temperatures can be qualitatively understood in terms of hadron resonance gas model

hadrons can carry different quark flavors => different quark flavors are correlated in the hadronic phase

quarks are un-bound at high temperatures => no correlations between different quark flavors

Charm fluctuations and correlations





Charm fluctuations can be well understood in terms of effective quark degrees of freedom for *T>300*MeV

Charm-strange and charm-light quark fluctuations vanish for *T>250*MeV indicating that heavy-light mesons dissolve at these temperatures

Summary

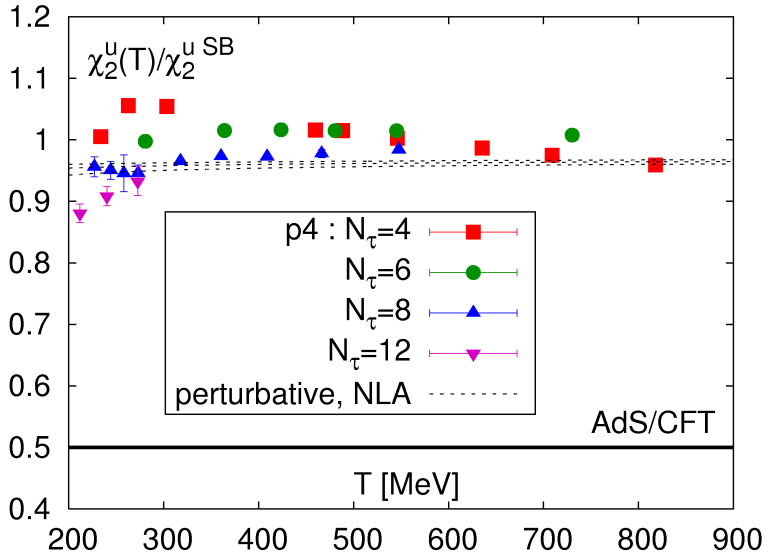
Lattice calculations of static quark anti-quark correlation functions, temporal and spatial meson correlation function exclude existence of charmonium bound states at temperatures above 300MeV.

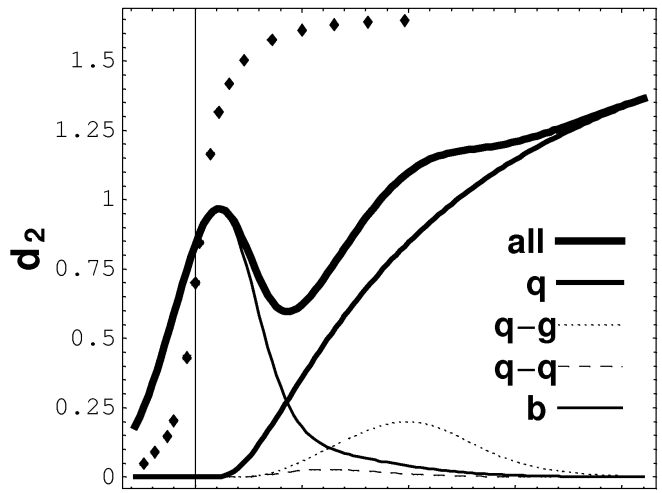
There are indications from various quantities calculated on the lattice that charmonium states melt at temperatures (220-240)MeV

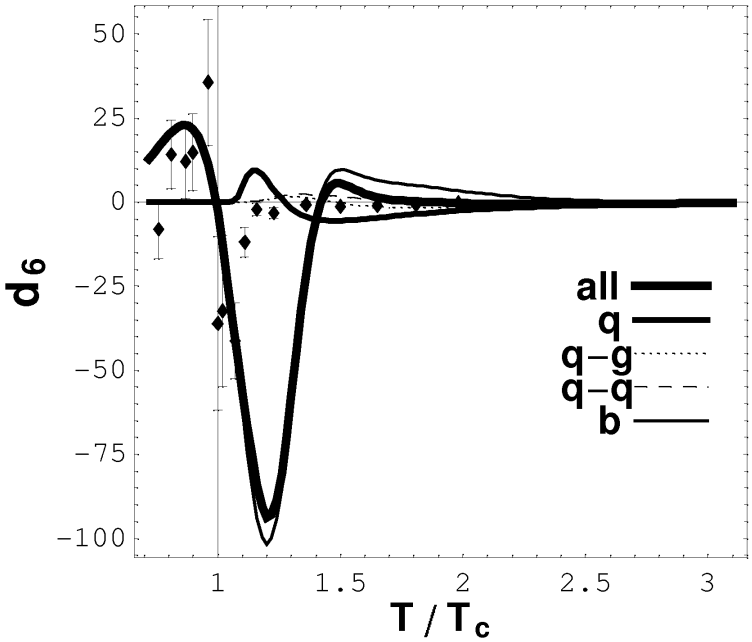
Melting of quarkonium states does not lead to large change of temporal meson correlation functions therefore will be difficult to observe directly on the lattice

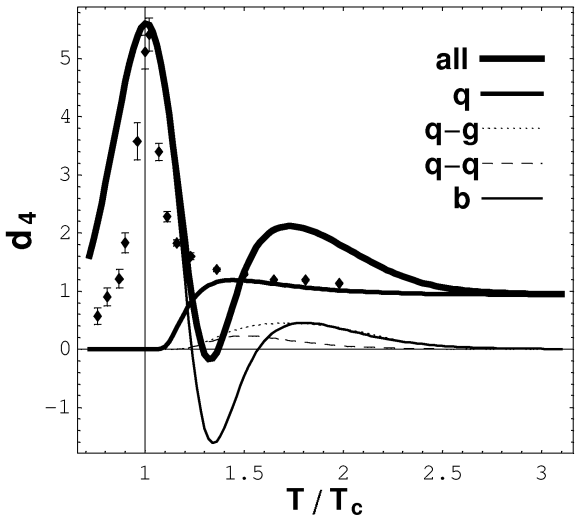
Fluctuations and correlations of conserved charges are sensitive probes of the relevant degrees of freedom at high temperatures, in the charm sector they indicate the melting of heavy light mesons at temperatures of about 220MeV

Back-up slides:







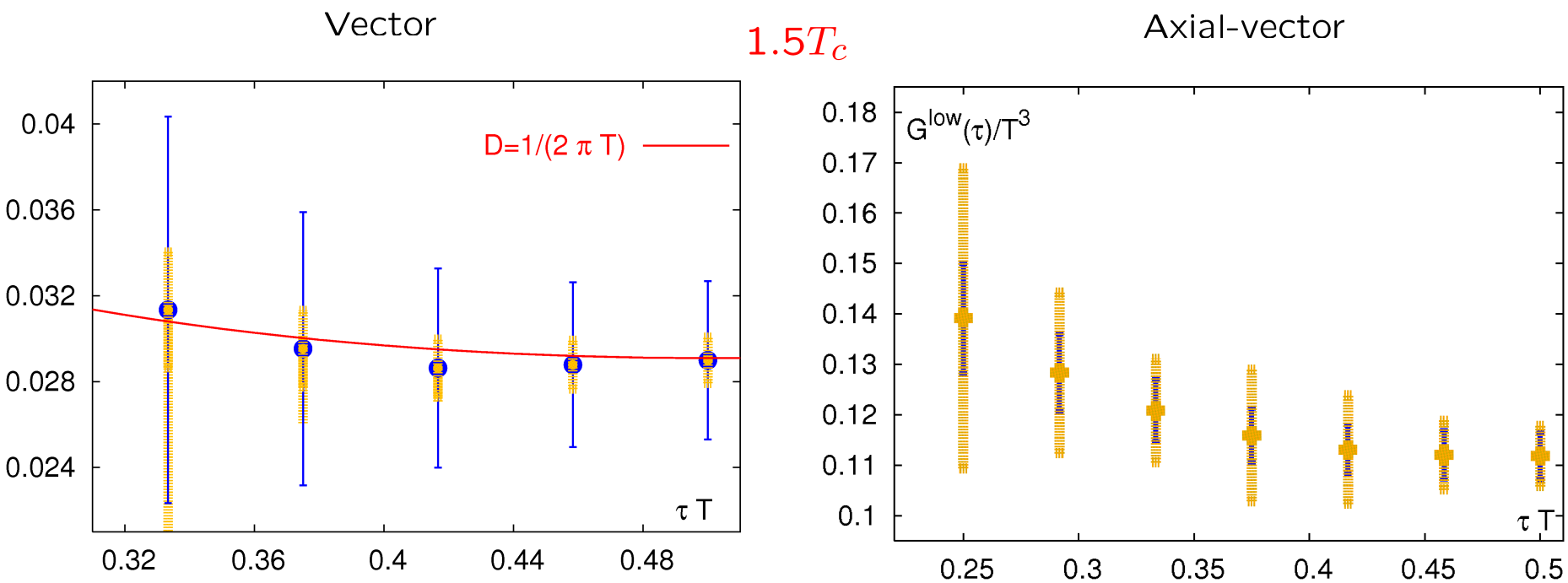


sQGP scenario,
Liao, Shuryak,PRD 73 (06) 014509

Estimating the zero mode contribution

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

$1.5T_c$



The curvature of $G_i^{\text{low}}(\tau,T)$ is governed by heavy quark diffusion

No diffusion ($D=\infty \leftrightarrow \eta = 0$): $G_i^{\text{low}} = const = T\chi_i(T)$

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

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

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