Spatial correlators in lattice QCD

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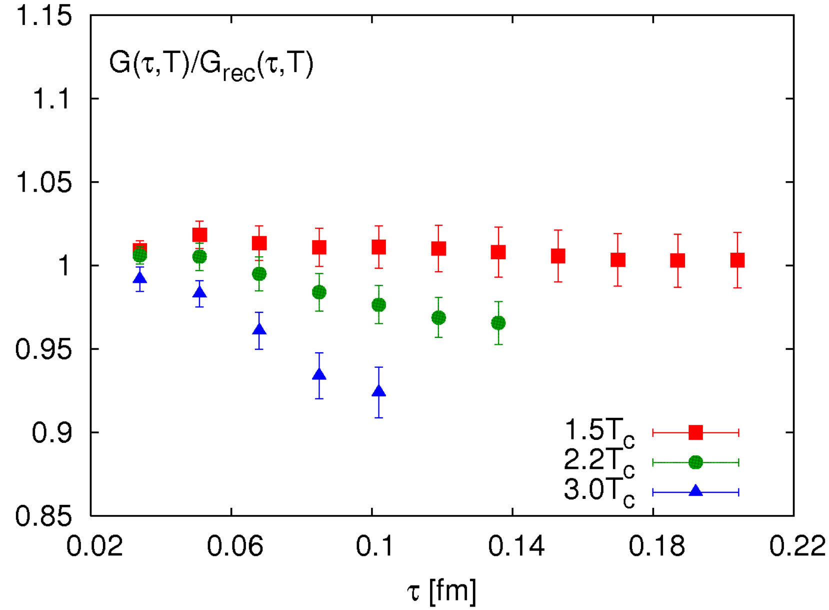
Why spatial correlators ?

In medium quarkonium properties are primarily encoded in the temporal correlators $G(\tau)$ but $\tau<1/T$ and therefore $G(\tau)$ has only mild T-dep.



Spatial meson correlation functions and charmonium melting
in collaboration with A. Bazavov, F. Karsch, Y, Maezawa and S. Mukherjee , arXiv:1411.3018

Static quark anti-quark free energy: lattice vs. perturbation theory
in collaboration with A. Bazavov, N. Brambilla, M. Berwein, A. Vairo, J. Weber

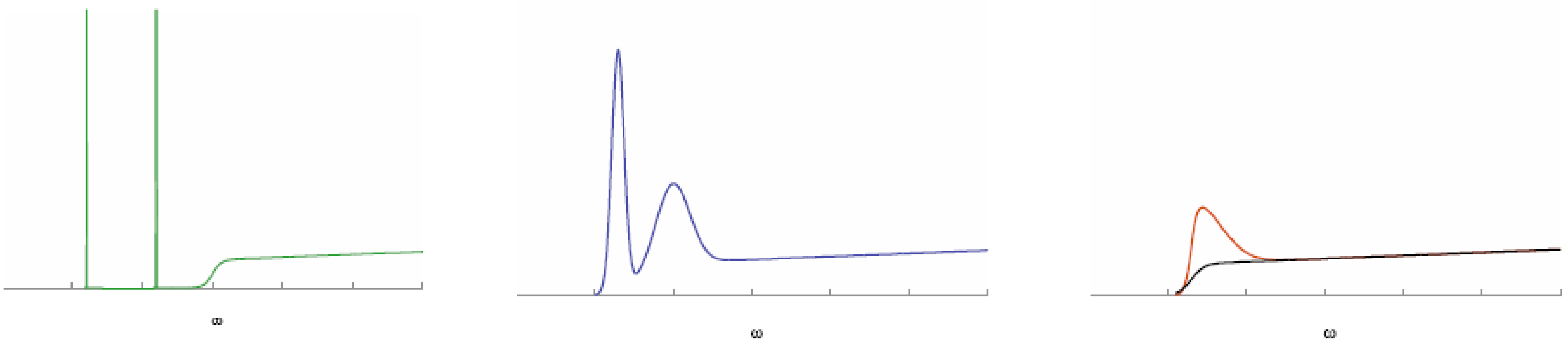
10th QWG workshop, CERN, Geneva, November 10-14, 2014

Meson spectral functions

In-medium properties and/or dissolution of quarkonium states are encoded in the spectral functions

$$\sigma(\omega, p, T) = \frac{1}{2\pi} \operatorname{Im} \int_{-\infty}^{\infty} dt e^{i\omega t} \int d^3x e^{ipx} \langle [J(x,t), J(x,0)] \rangle_T$$

Melting is see as progressive broadening and disappearance of the bound state peaks



Due to analytic continuation spectral functions are related to Euclidean time quarkonium correlators that can be calculated on the lattice

$$G(\tau, p, T) = \int d^3x e^{ipx} \langle J(x, -i\tau), J(x,0) \rangle_T$$

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

1S charmonium survives to $1.6T_c$??

Umeda et al, EPJ C39S1 (05) 9, Asakawa, Hatsuda, PRL 92 (2004) 01200, Datta, et al, PRD 69 (04) 094507, ...

Spatial vs. temporal meson correlators

Spatial correlation functions can be calculated for arbitrarily large separations $z \to \infty$

$$G(z,T) = \int_0^{1/T} d\tau \int dx dy \langle J(\mathbf{x},-i\tau), J(\mathbf{x},0)\rangle_T, \quad G(z \to \infty, T) \simeq A e^{-m_{scr}(T) z}$$

but related to the same spectral functions $\quad G(z,T) = \int_{-\infty}^{\infty} e^{ipz} \int_0^{\infty} d\omega \frac{\sigma(\omega,p,T)}{\omega}$

Low T limit :

$$\sigma(\omega,p,T) \simeq A_{mes}\delta(\omega^2 - p^2 - M_{mes}^2)$$

$$A_{mes} \sim |\psi(0)|^2 \to m_{scr}(T) = M_{mes}$$

$$G(z,T) \simeq |\psi(0)|^2 e^{-M_{mes}(T) z}$$

High T limit :

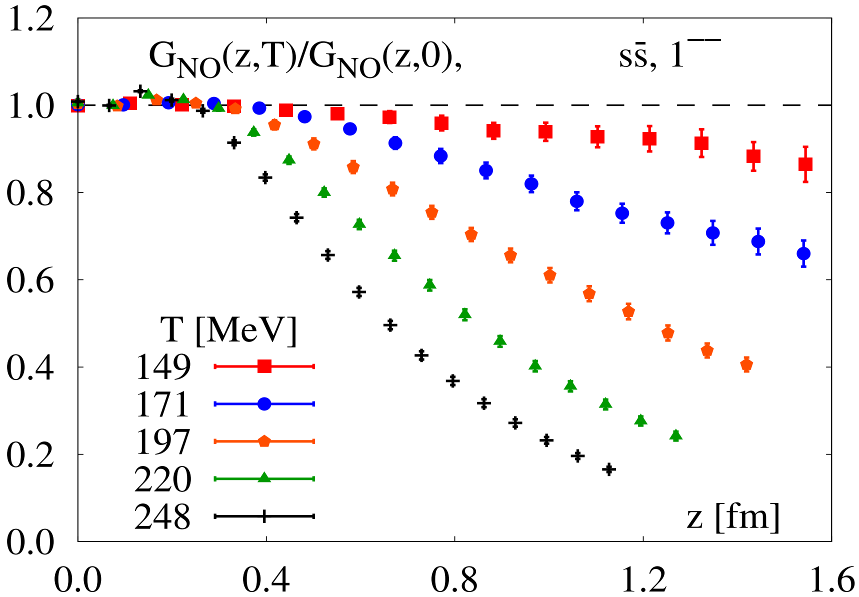
$$m_{scr}(T) \simeq 2\sqrt{m_c^2 + (\pi T)^2}$$

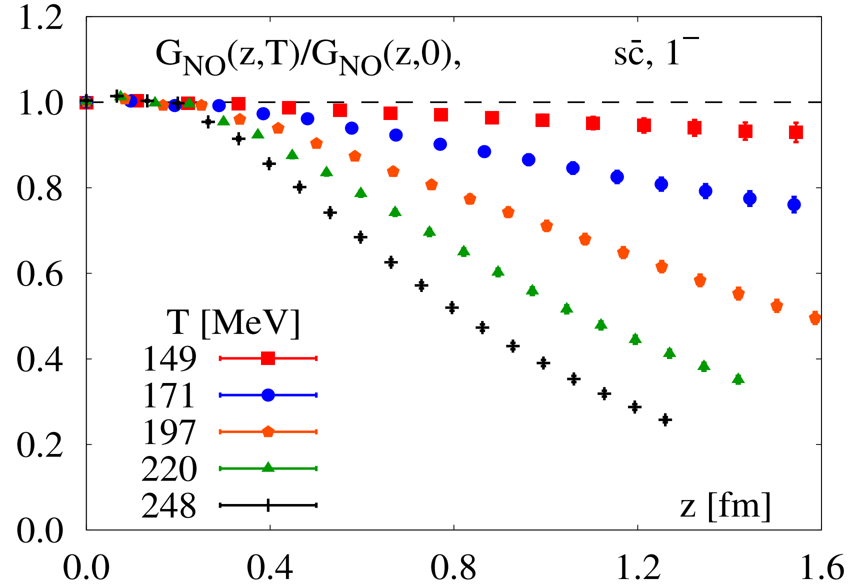
Temporal meson correlator only avalaible for $\tau T < ½$ and thus may not be very sensitive to In-medium modifications of the spectral functions; also require large N_τ (difficult in full QCD)

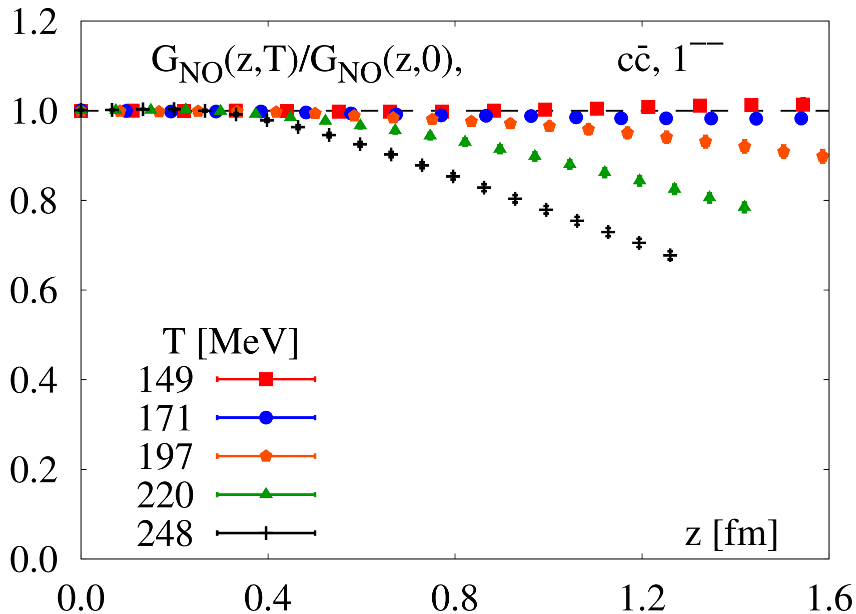
Spatial correlators can be studied for arbitrarily large separations and thus are more sensitive to the changes in the meson spectral functions; do not require large N_τ (easy in full QCD).

Lattice calculations: spatial meson correlators in 2+1 flavor QCD for ssbar, scbar and ccbar sectors using 48^3x12 lattices and highly improved staggered quark (HISQ) action (also suitable for charm quarks) , physical m_s and $m_\pi=160$ MeV.

Temperature dependence of spatial meson correlators





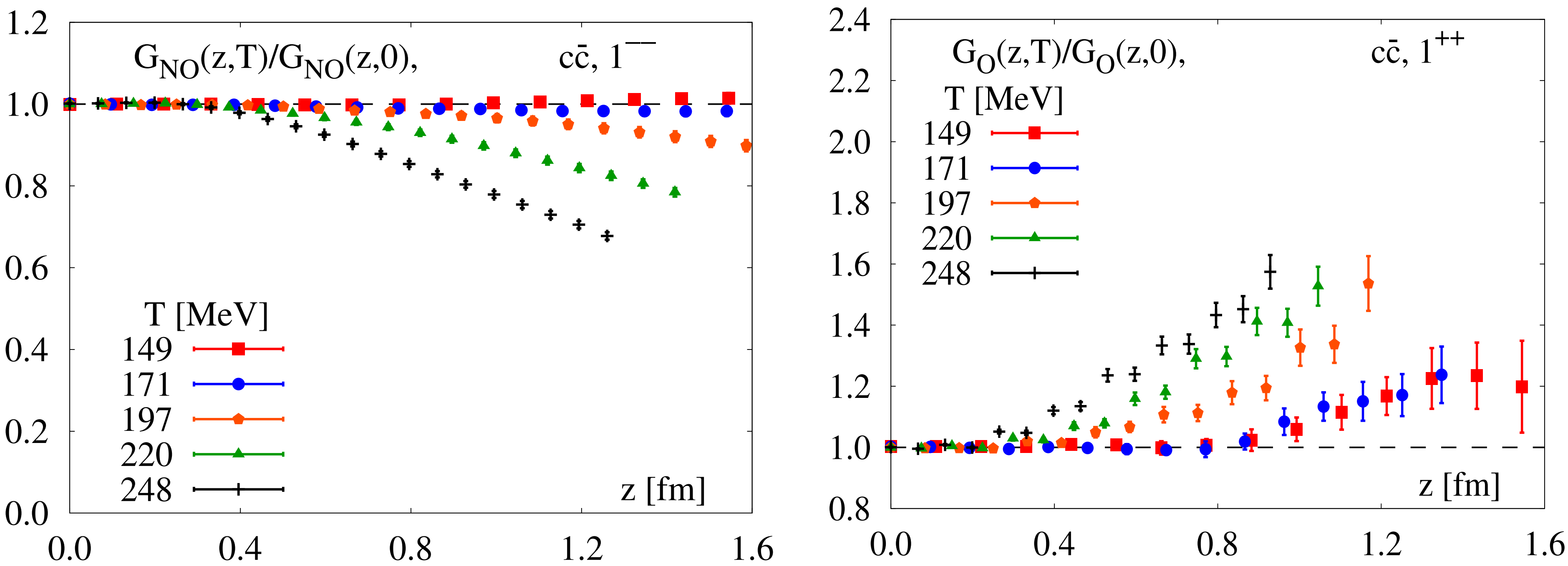


Medium modifications of meson correlators increase with T, but decrease with heavy quark content

Significant modifications for $T>T_c$=154 MeV

For $z< 1/(2\ T)$ the T-dependence of the vector charmonium correlators is very small

Temperature dependence of spatial charmonium correlators

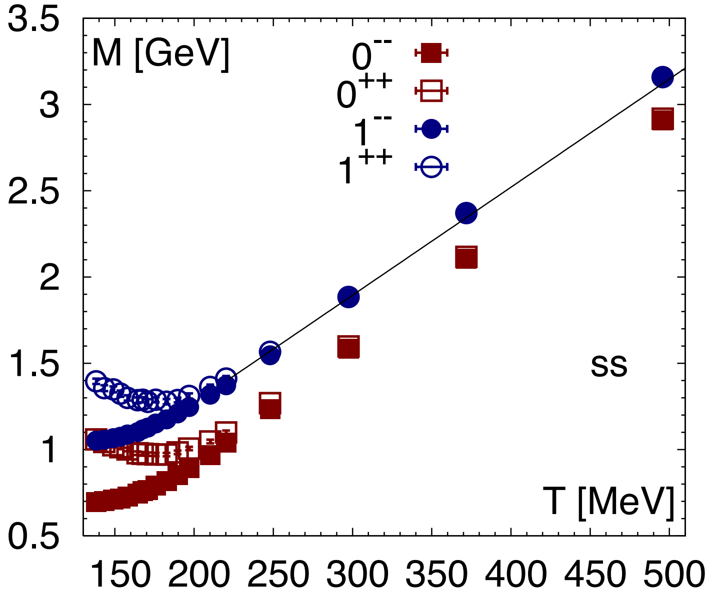


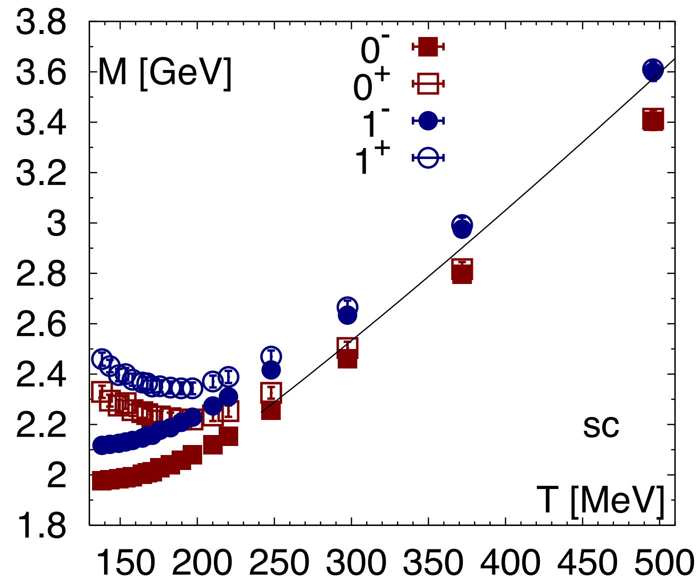
Almost no medium modification of S-wave charmonium correlators across $T_c \approx 154$ MeV,
Medium modification of the correlators start to be visible for $T > 197$ MeV

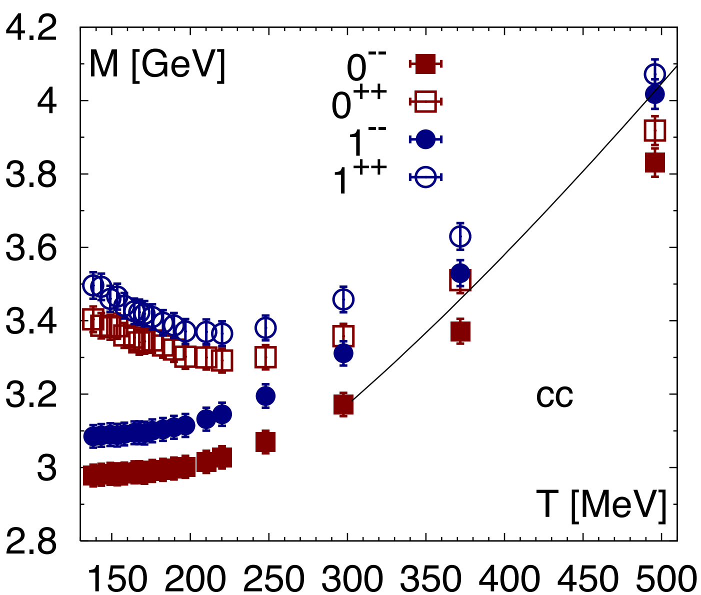
Significant medium modification of P-wave charmonium correlators already at T_c
and larger T-dependence than for 1S correlator for

Fits into the picture of sequential charmonium melting:
χ_c melts at smaller temperature than the more tightly bound J/ψ

Temperature dependence of meson screening masses





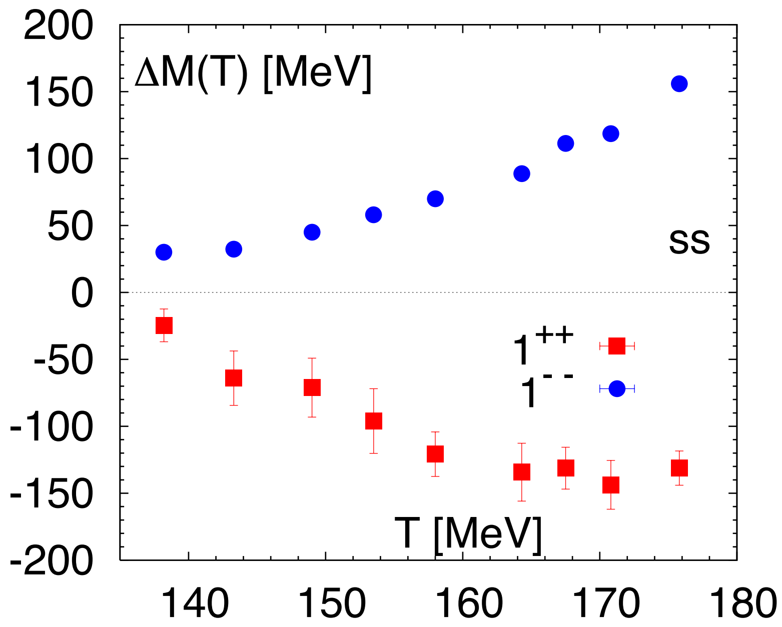


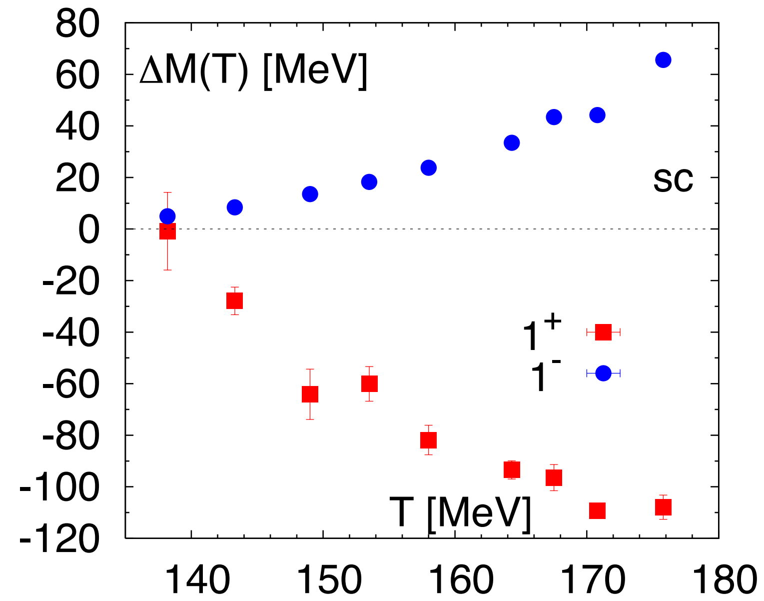
Qualitatively similar behavior of the screening masses for ssbar, scbar and ccbar sectors

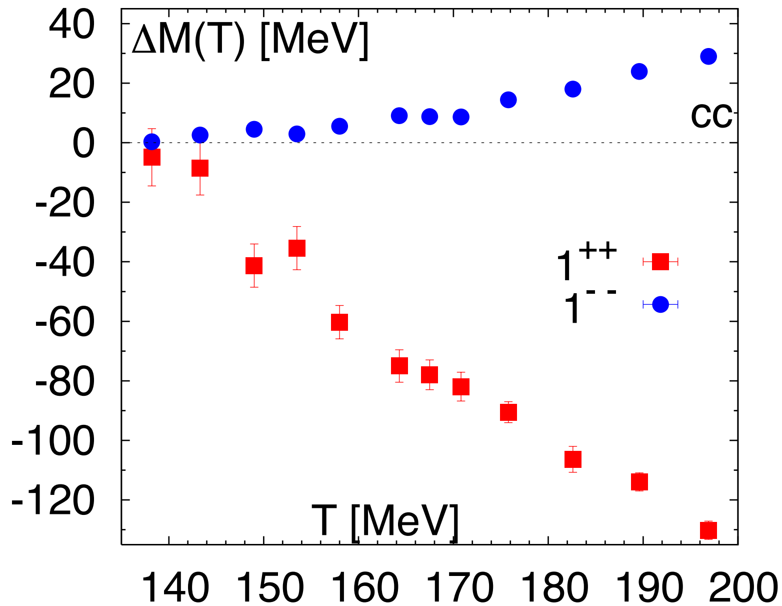
Screening Masses of opposite parity mesons become degenerate at high T (restoration of chiral and axial symmetry)

Screening masses are close to the free limit $2\,(m_q^2+(\pi T)^2)^{1/2}$ at $T>200$ MeV, $T>250$ MeV, $T>300$ MeV for ssbar, scbar and ccbar sectors, respectively.

Temperature dependence of meson screening masses (cont'd)

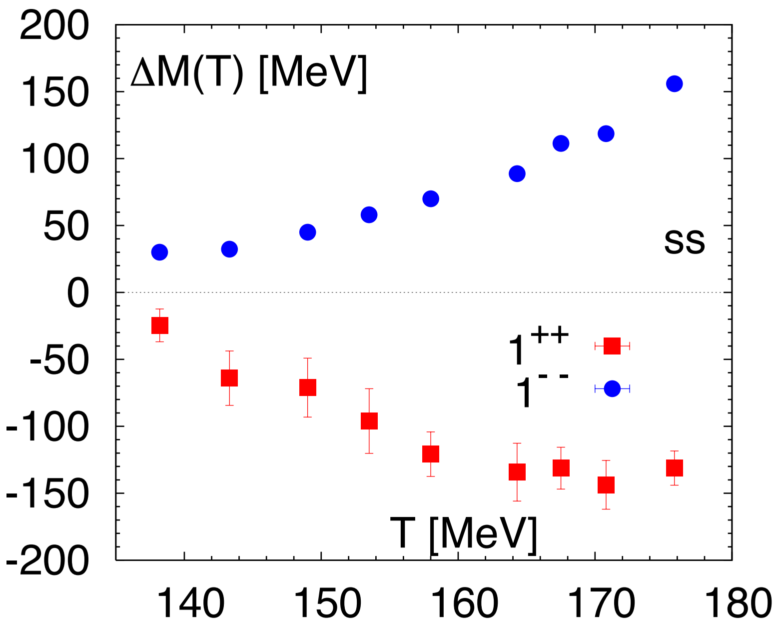


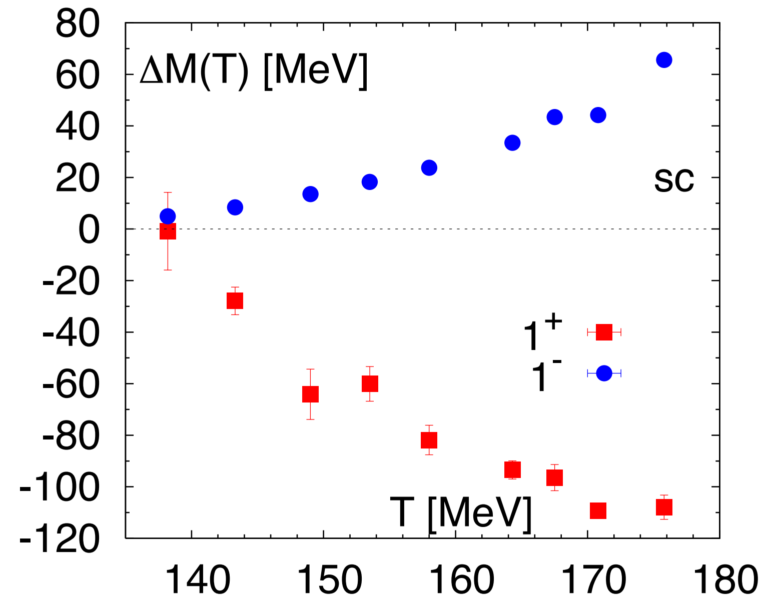


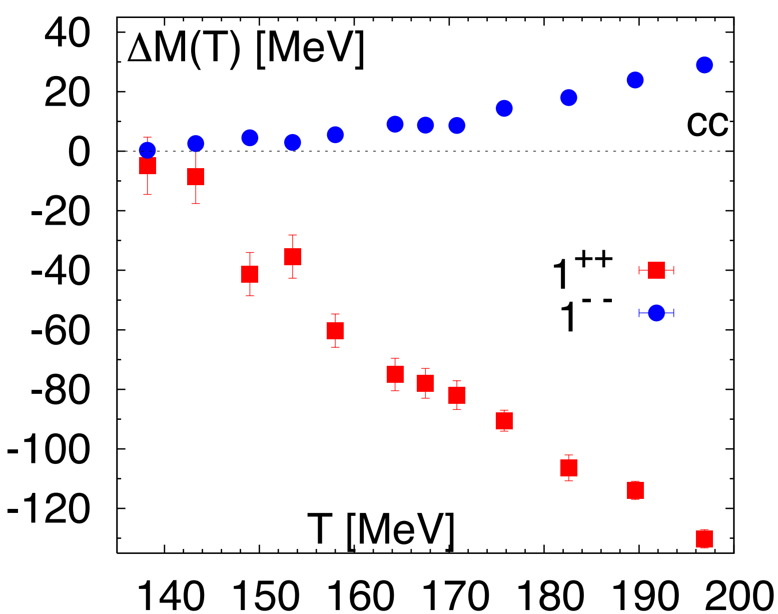


- At low T changes in the meson screening Masses $\Delta M=M_{scr}(T)-M_{T=0}$ are indicative of the changes in meson binding energies
- ΔM is significant already below $T_c=154$ MeV
- Above the transition temperature the changes in ΔM are comparable to the meson binding energy and are consistent with melting of meson states except for $1S$ charmonium

Temperature dependence of meson screening masses (cont'd)





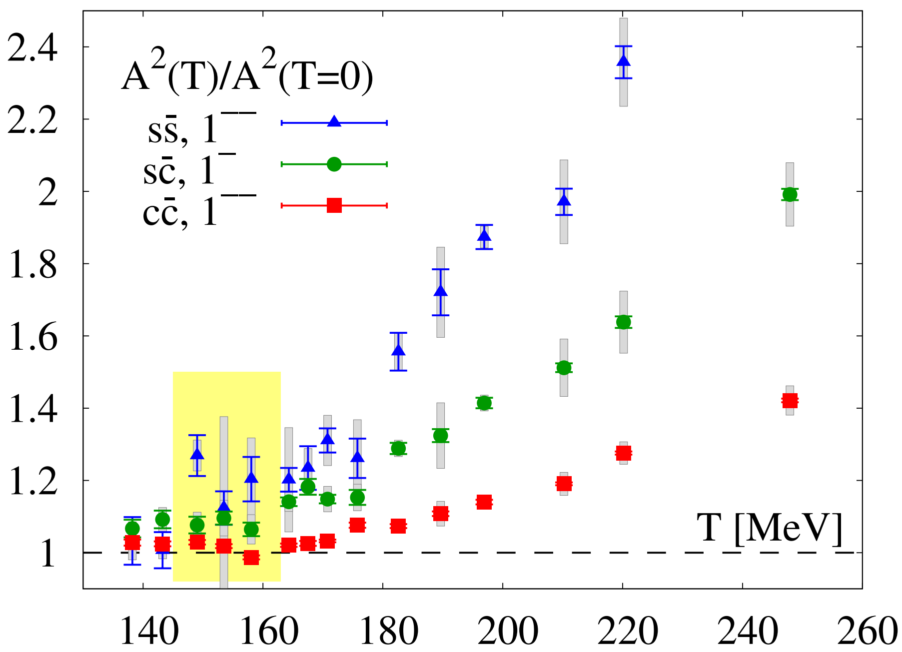


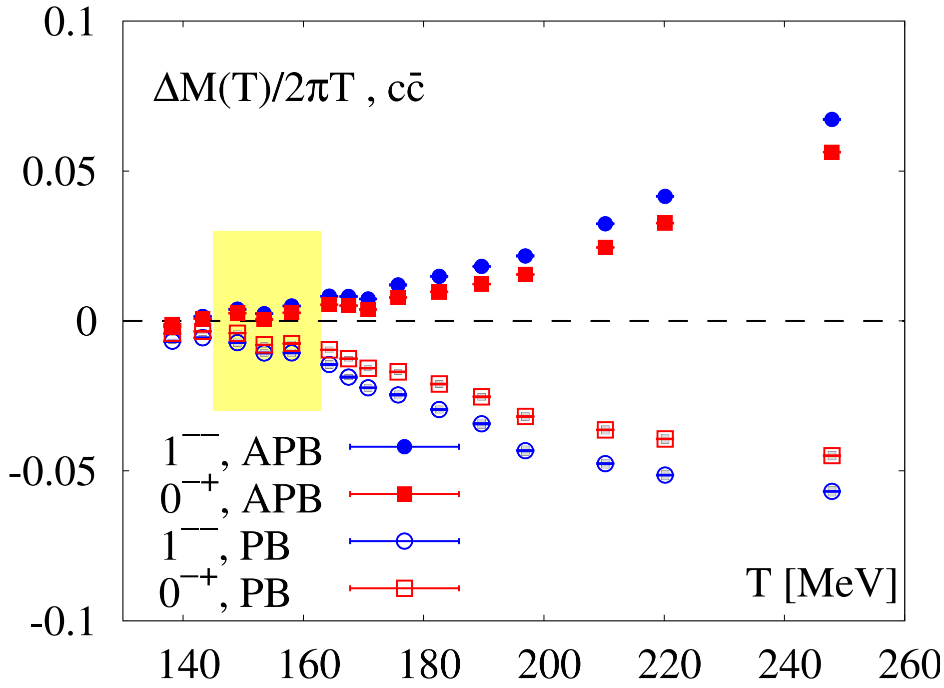
- At low T changes in the meson screening Masses $\Delta M = M_{scr}(T) - M_{T=0}$ are indicative of the changes in meson binding energies

- ΔM is significant already below T_c

- Above the transition temperature the changes in ΔM are comparable to the meson binding energy and are consistent with melting of meson states except for $1S$ charmonium

Temperature dependence of meson screening masses (cont'd)





$s\bar{s}$ and $s\bar{c}$ mesons : Significant modifications of the squared amplitudes around T_c

$c\bar{c}$ mesons : Similar medium modifications of the amplitudes only for $T>210$ MeV

If D_s and ϕ melt just above T_c them J/ψ will melt around $T>210$ MeV

For small bound state like J/ψ the screening mass should not boundary condition
Large dependence on the temporal boundary conditions of *S*-wave charmonium correlator for $T>200$ MeV

Potential model for charmonium

Take the upper limit for the real part of the potential allowed by lattice calculations

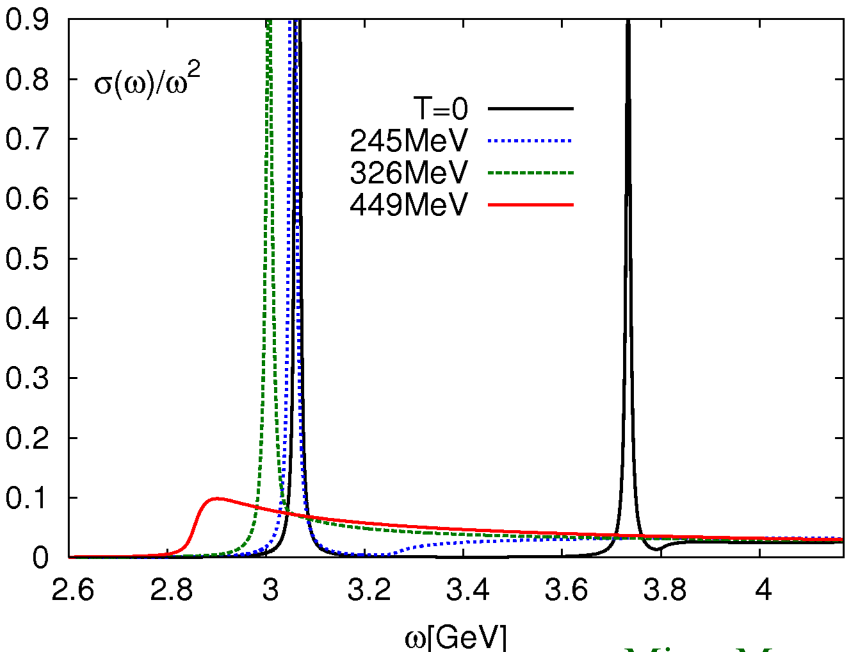
Mócsy, P.P., PRL 99 (07) 211602

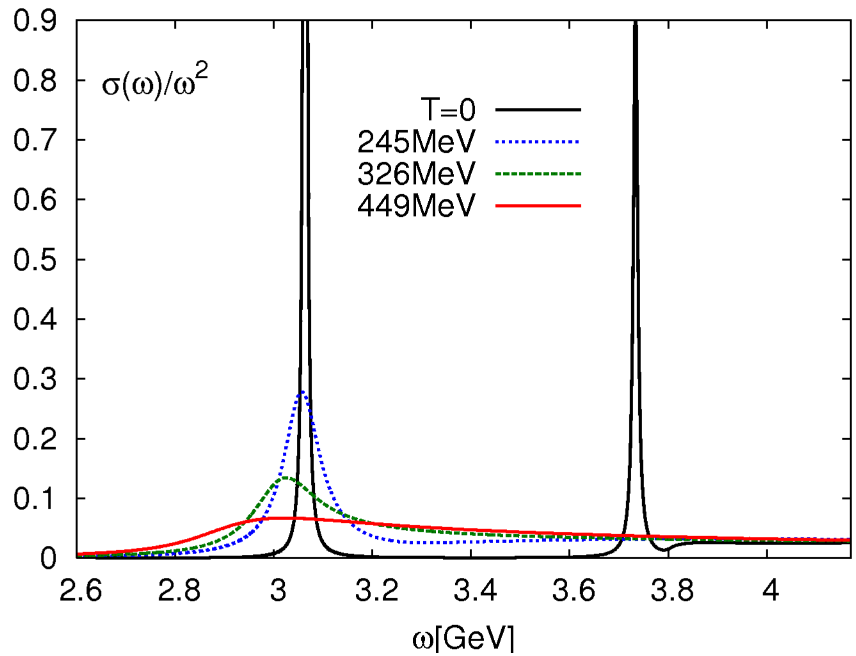
Take the perturbative imaginary part

Burnier, Laine, Vepsalainen JHEP 0801 (08) 043

Im $V_s(r) = 0$:
1S state survives for $T = 330$ MeV

imaginary part of $V_s(r)$ is included :
all states dissolves for $T > 240$ MeV





Miao, Mocsy, P.P., NPA855 (2011) 125

no charmonium state could survive for $T > 245$ MeV

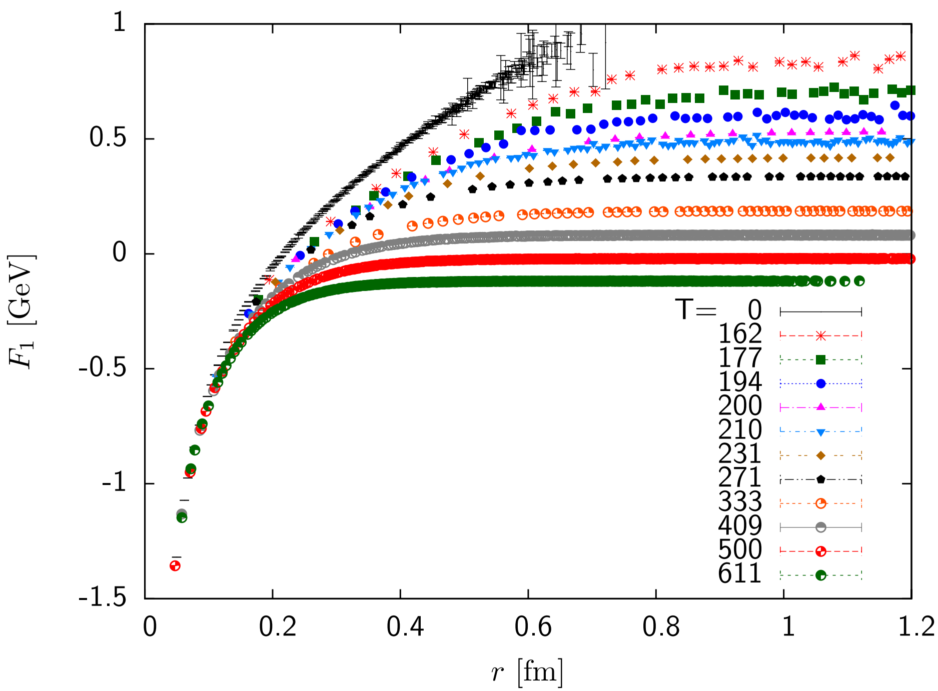
this is consistent with earlier analysis of Móczy, P.P., PRL 99 (07) 211602 ($T_{dec} \sim 204 MeV$)

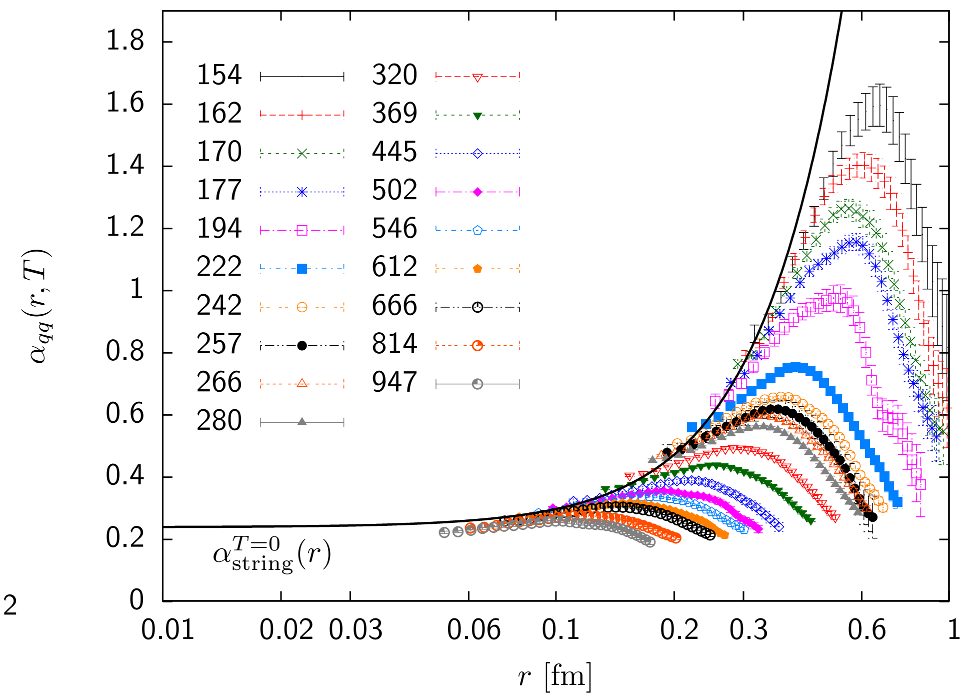
as well as with Riek and Rapp, New J. Phys. 13 (2011) 045007

Singlet free energy of static QQbar pair

Singlet free energy in Coulom gauge:

$$e^{-F_1(r,T)/T} = \mathrm{Tr}\langle L(r)L^\dagger(0)\rangle,\ \ L(x) = \prod_{x_0=1}^{N_\tau-1} U_0(x_0,x) \qquad \alpha_{qq}(r,T) = r^2\frac{dF_1(r,T)}{dr}$$

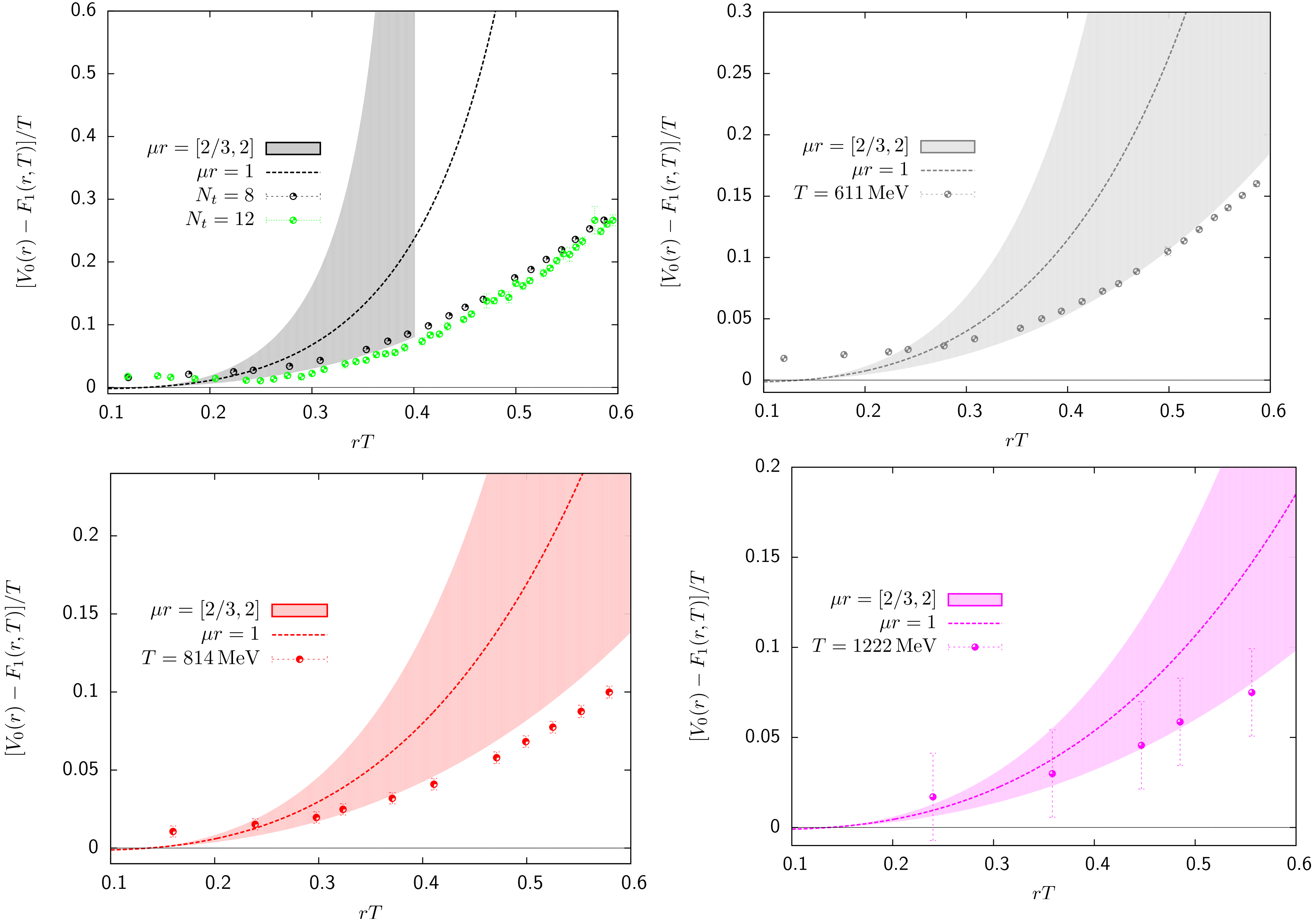




$\alpha_{qq}(r_{max},T) > 0.5$ for $T < 300$MeV → Strongly interacting QGP

Perturbation theory may be applicable for *T>300* MeV; use perturbative results from Burnier et al, JHEP 1001 (2010) 054

Singlet free energy: comparison with perturbation theory



Summary

Spatial meson correlators show strong temperature dependence across the deconfinement transition implying significant change in the meson spectral functions except for 1S charmonium

The size of medium effects in the meson correlators depends on the heavy quark content and binding energy, i.e. meson correlators corresponding to lighter and more loosely bound states experience larger modications

The observed medium modifications are consistent with melting of all meson states in the vicinity of the transition temperature with the exception of 1S charmonium (J/ψ and η_c) states that melt at 210 MeV $< T < 300$ MeV
First direct lattice QCD indication of sequential melting

Spatial correlation function of static quarks are useful to test in-medium interaction of heavy quarks and to what extent it is perturbative; perturbation theory can describe the singlet free energy for $T > 300$ MeV and $rT < 0.6$