UNIVERSITÄT BIELEFELD
Fakultät für Physik

CRC-TR 211

Study of quarkonium in QGP from unquenched lattice QCD

Sajid Ali
Faculty of Physics, Bielefeld University

L. Altenkort, D. Bala, O. Kaczmarek, H-T. Shu, T. Ueding
HOTQCD collaboration

Baryons 2022, 08.11.2022

Correlators and spectral functions

- Heavy $q\bar{q}$: a thermometer of QGP in heavy ion collisions
- The spectral functions $\rho_H(\omega)$ contains information about the in-medium hadron properties

$$\sum_{\vec{x}} \left\langle \bar{\psi}\Gamma_H \psi(\tau,\vec{x})(\bar{\psi}\Gamma_H \psi(0,\vec{0}))^\dagger \right\rangle \equiv G_H(\tau) = \int_0^\infty \frac{\omega}{\pi} \rho_H(\omega) \frac{\cosh(\omega(\tau - \frac{1}{2T}))}{\sinh(\frac{\omega}{2T})}$$

Correlators and spectral functions

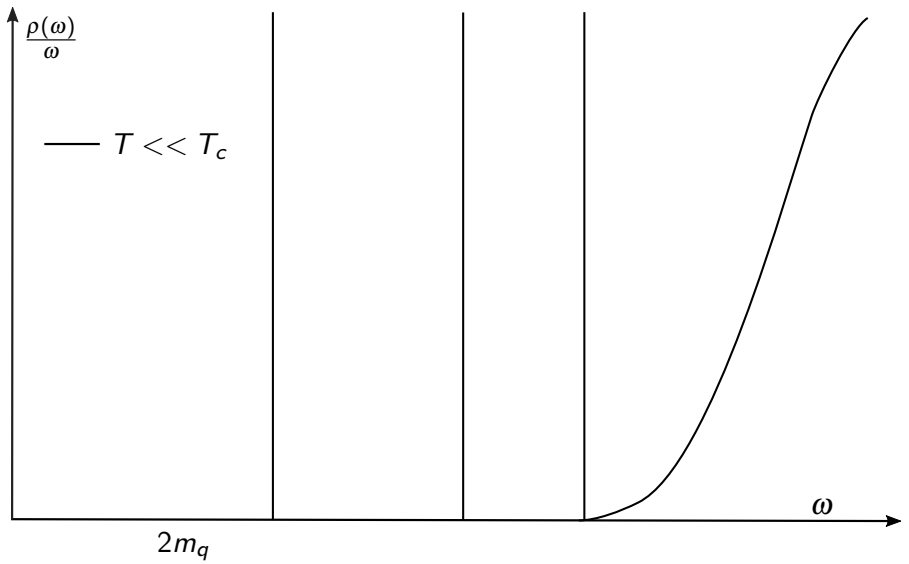
- Heavy $q\bar{q}$: a thermometer of QGP in heavy ion collisions
- The spectral functions $\rho_H(\omega)$ contains information about the in-medium hadron properties

$$\sum_{\vec{x}} \left\langle \bar{\psi}\Gamma_H \psi(\tau,\vec{x})(\bar{\psi}\Gamma_H \psi(0,\vec{0}))^\dagger \right\rangle \equiv G_H(\tau) = \int_0^\infty \frac{\omega}{\pi} \rho_H(\omega) \frac{\cosh(\omega(\tau - \frac{1}{2T}))}{\sinh(\frac{\omega}{2T})}$$

Strategy:

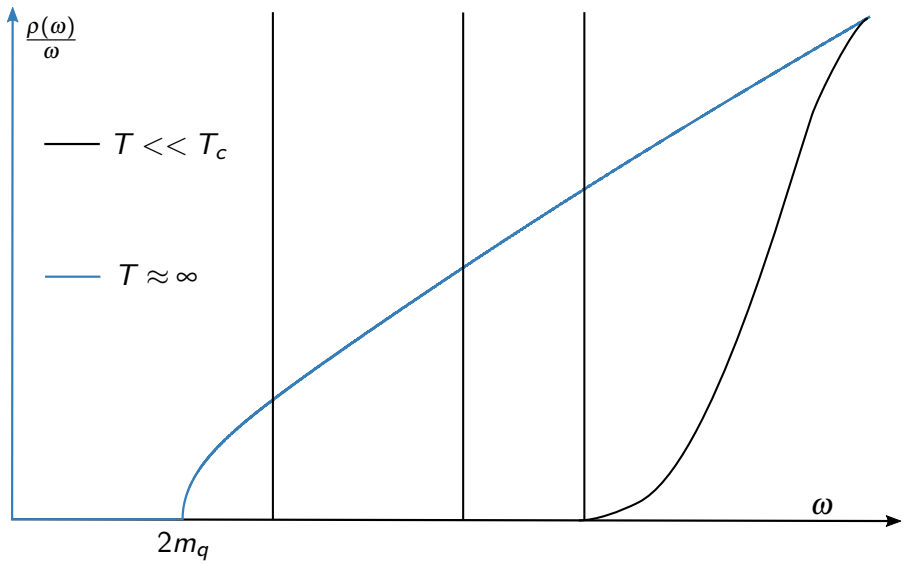
- $G_H(\tau)$ on the lattice
- Extract spectral function
- Estimate in-medium hadronic properties
- In addition transport coefficients, like heavy quark diffusion coefficients, are encoded in the vector meson spectral function

The spectral function



Ref. [H. Sandmeyer's thesis]

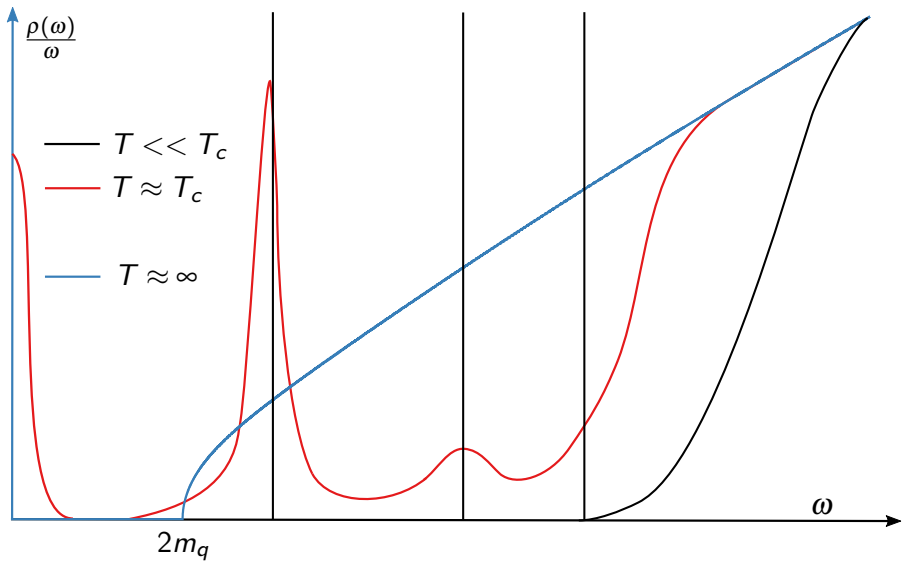
The spectral function



- At infinite temperature there cannot be bound states

Ref. [H. Sandmeyer's thesis]

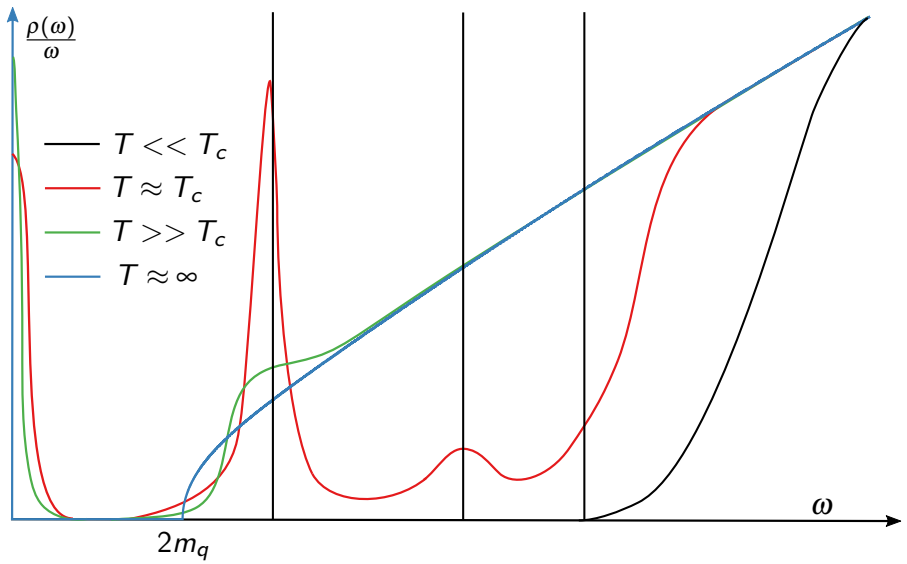
The spectral function



- At infinite temperature there cannot be bound states
- Melting of states visualizes in **shrinking and broadening of bound peaks**

Ref. [H. Sandmeyer's thesis]

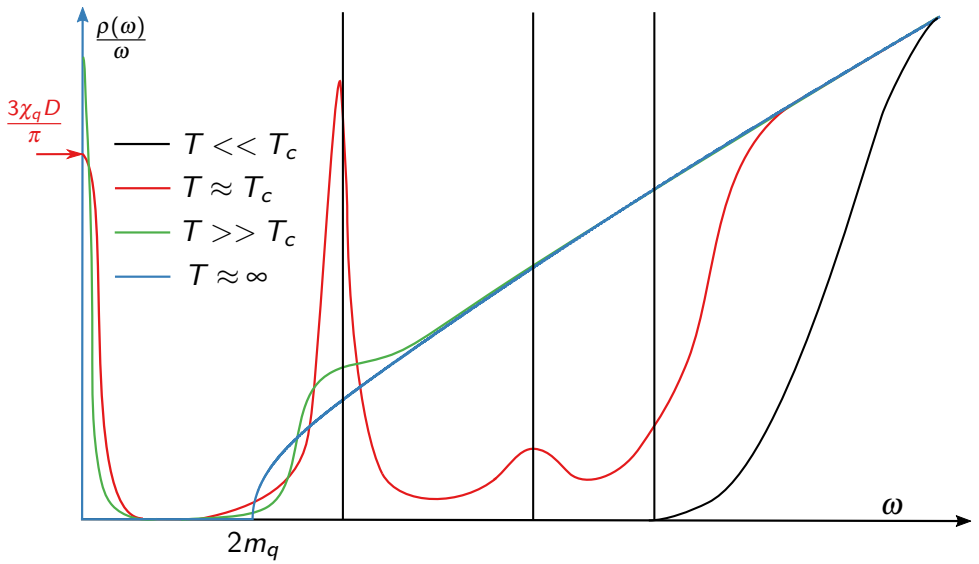
The spectral function



- At infinite temperature there cannot be bound states
- Melting of states visualizes in **shrinking and broadening of bound peaks**

Ref. [H. Sandmeyer's thesis]

The spectral function



- At infinite temperature there cannot be bound states
- Melting of states visualizes in **shrinking and broadening of bound peaks**
- **Heavy quark diffusion constant** can be read off in vector channel

$$D = \frac{\pi}{3\chi_q} \lim_{\omega \to 0} \sum_{i=1}^{3} \frac{\rho_V(\omega, T)}{\omega}$$

Extraction of spectral function is ill-posed problem $\rightarrow$ large lattices needed. Ref. [H. Sandmeyer's thesis]

SPF's contribution to correlators

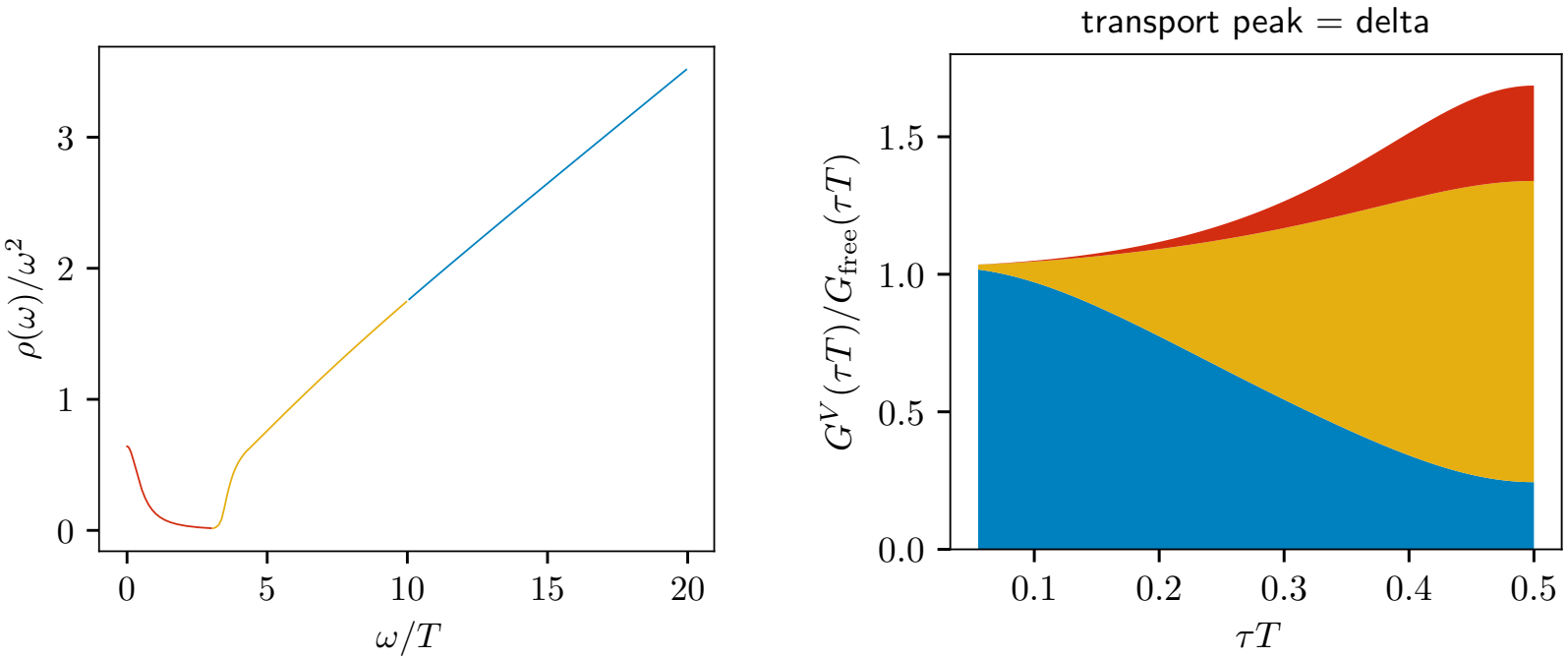
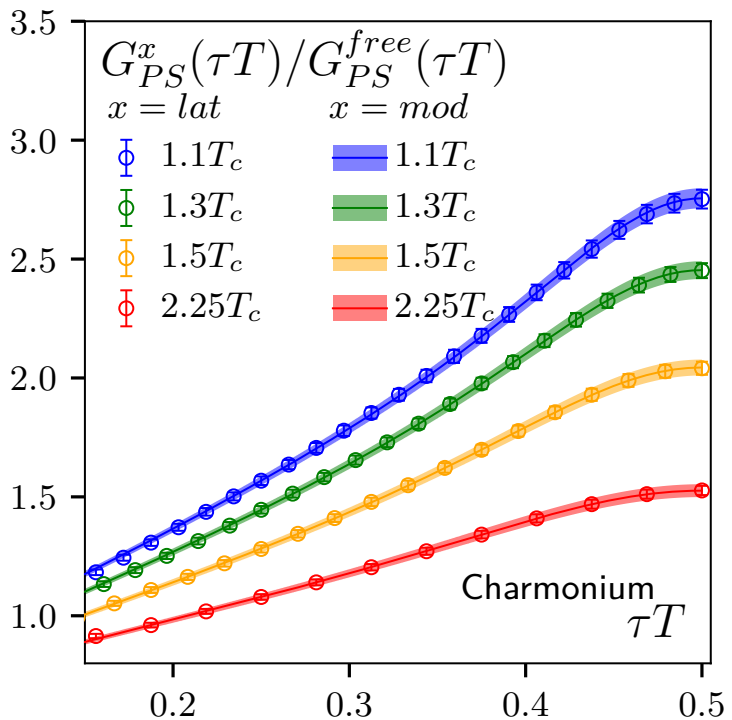


Figure: Visualization of which parts of the spectral function contribute to the correlator at different τT. Ref. [H. Sandmeyer's thesis]

Spectral reconstruction (Quenched)

$$\rho_{PS}^{pert}(\omega) = \rho_{PS}^{VAC}(\omega) + A^{match}\rho_{PS}^{THERM}(\omega)$$

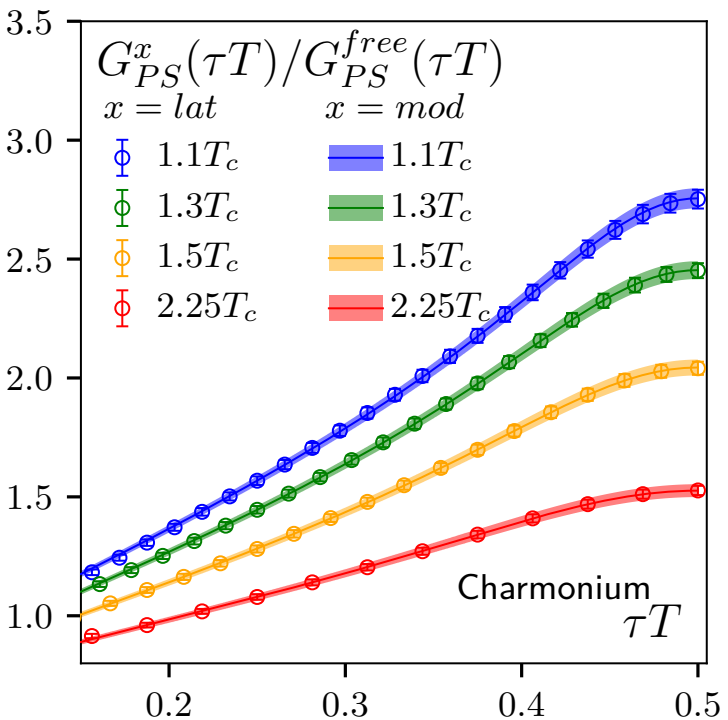
$$\rho_{PS}^{mod}(\omega) = A\rho_{PS}^{pert}(\omega - B)$$

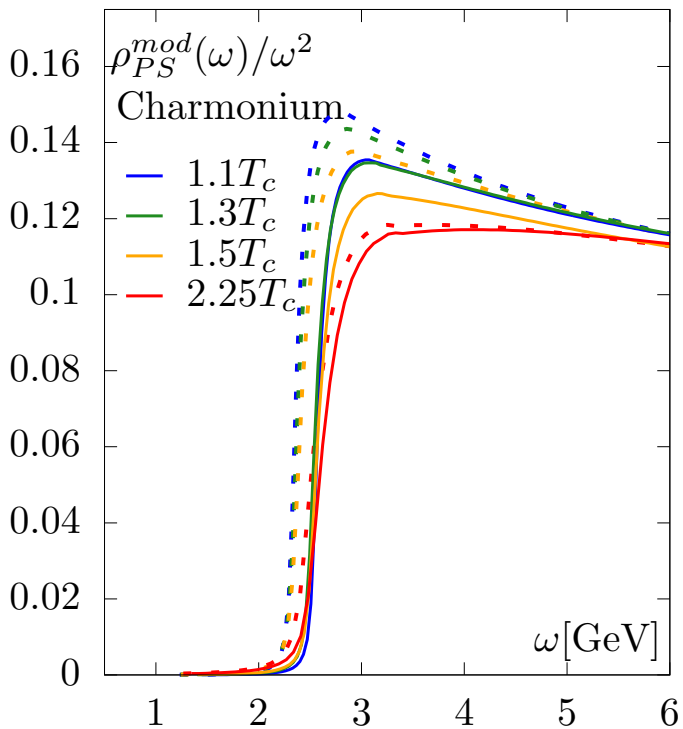


Spectral reconstruction (Quenched)

$$\rho_{PS}^{pert}(\omega) = \rho_{PS}^{VAC}(\omega) + A^{match}\rho_{PS}^{THERM}(\omega)$$

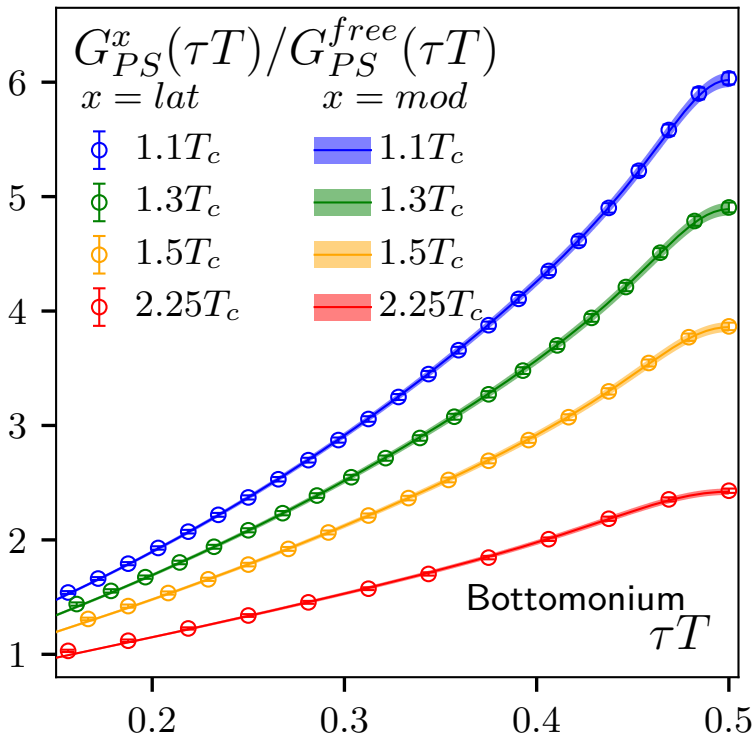
$$\rho_{PS}^{mod}(\omega) = A\rho_{PS}^{pert}(\omega - B)$$

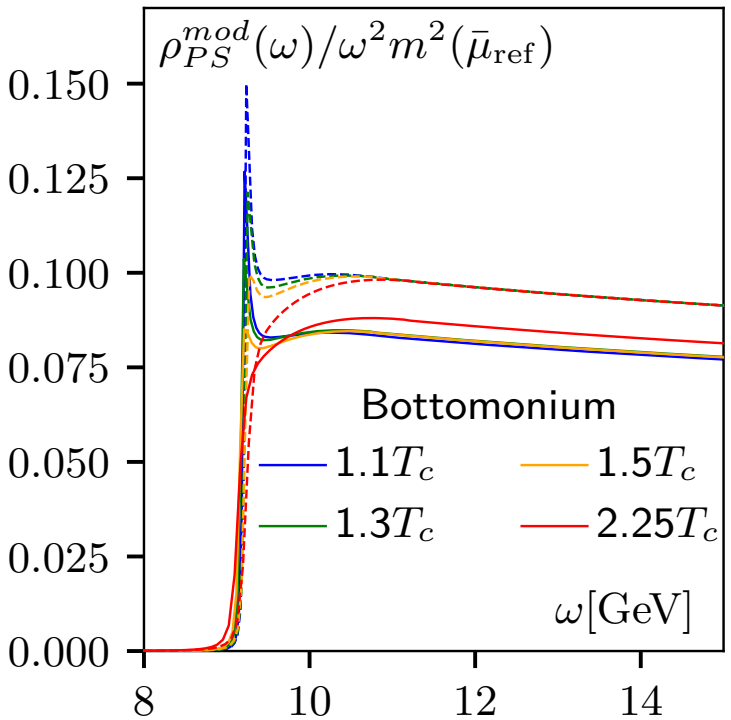




Ref. [JHEP 11 (2017) 206, A. Lorenz's thesis]

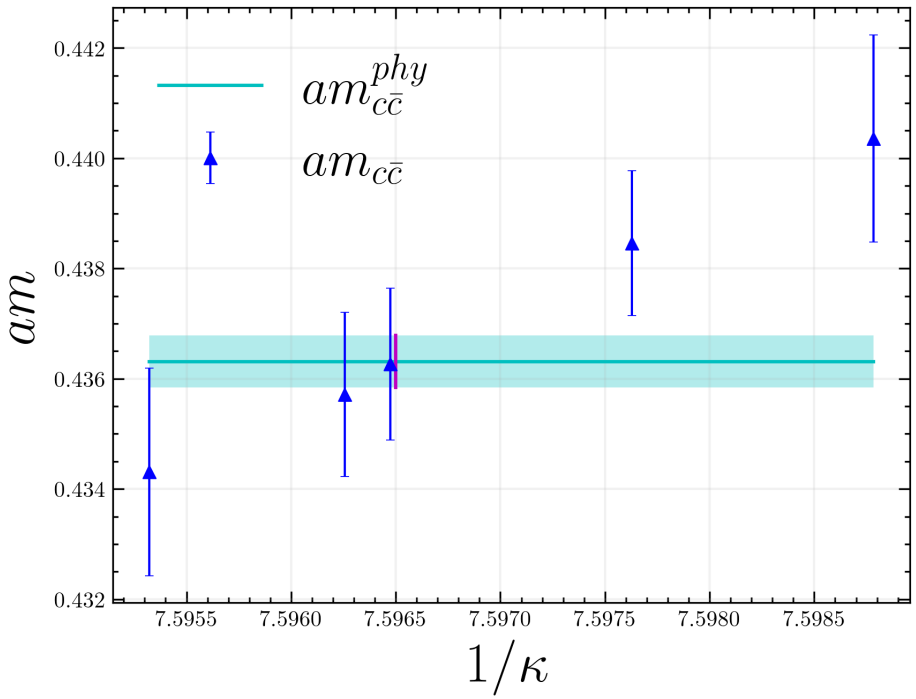
Spectral reconstruction (Quenched)





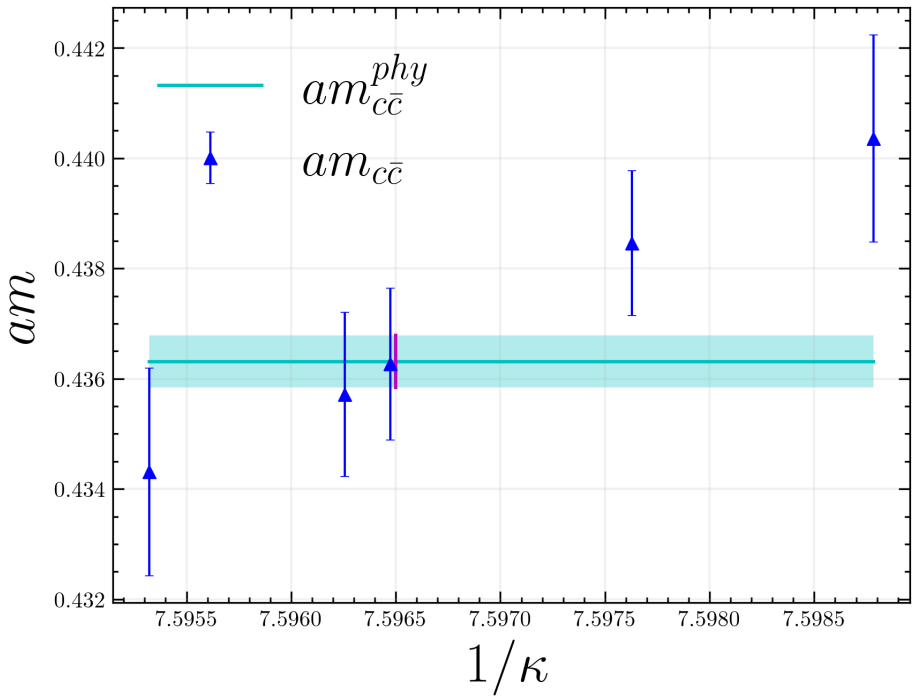
Ref. [JHEP 11 (2017) 206, A. Lorenz's thesis]

Mass tuning on mixed action (Full QCD)



- Mixed action approach (Wilson Clover fermions on HISQ configurations)
- Tadpole improved tree-level, $c_{SW} = \frac{1}{u_0{}^3}$, $u_0 = (tr[U_{\mu\nu}])^{\frac{1}{4}}$
- Quark mass tuning
- Tune spectrum to experimental values

Mass tuning on mixed action (Full QCD)

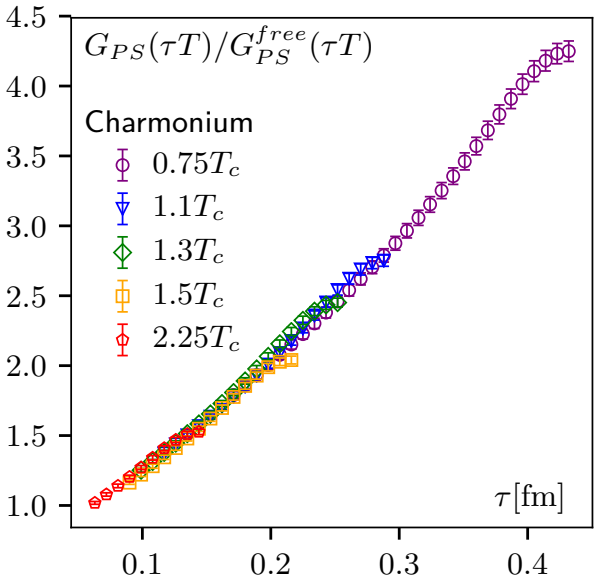


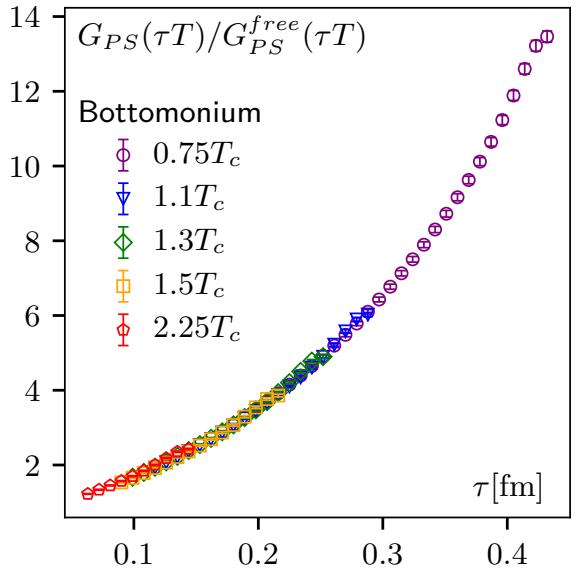
- Mixed action approach (Wilson Clover fermions on HISQ configurations)
- Tadpole improved tree-level, $c_{SW} = \frac{1}{u_0{}^3}$, $u_0 = (tr[U_{\mu\nu}])^{\frac{1}{4}}$
- Quark mass tuning
- Tune spectrum to experimental values

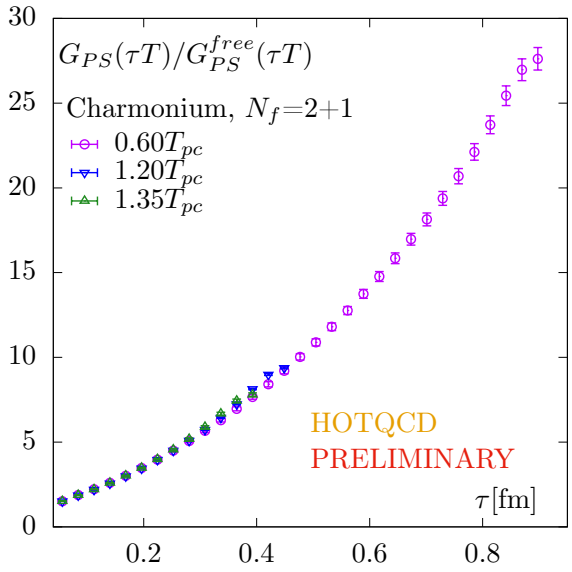
- HISQ lattices from HotQCD (arXiv:2110.11659) ($m_l = m_s/5$); 64^3x64, 96^3x32, new temperatures at 96^3x56 and 96^3x28

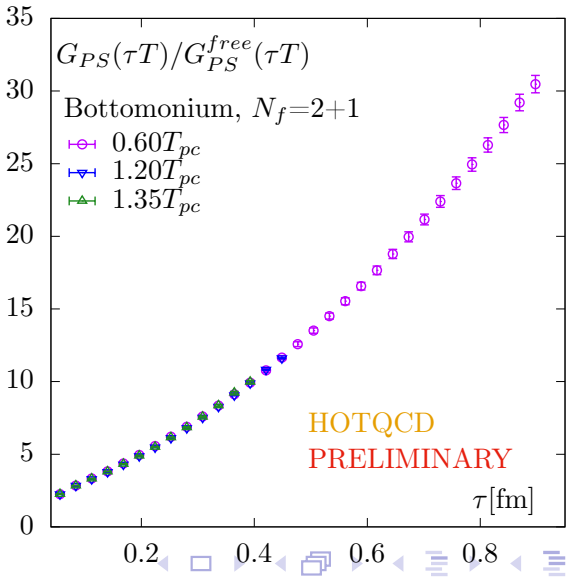
- Gradient flow (renormalizes the operators, removes cut-off and mixed action effects and improves signal-to-noise ratio)

Correlators: Quenched VS Unquenched









Perturbative SPF (Full QCD)

$$\frac{\rho_{PS}^{VAC}(\omega)}{\omega^2 m^2(\bar{\mu})} \equiv \frac{N_c}{8\pi} \tilde{R}_c^p(\omega, \bar{\mu})$$

Perturbative SPF (Full QCD)

$$\frac{\rho_{PS}^{VAC}(\omega)}{\omega^2 m^2(\bar{\mu})} \equiv \frac{N_c}{8\pi}\tilde{R}_c^p(\omega,\bar{\mu})$$

$$\rho_V^{NRQCD}(\omega) = \frac{1}{2}\left(1-e^{-\frac{\omega}{T}}\right)\int_{-\infty}^{\infty} \mathrm{d}t\, e^{i\omega t}\, C_>$$

$$\rho_{PS}^{THERM} = \frac{M^2}{3}\rho_V^{NRQCD}\,, \quad \omega \approx 2M$$

Perturbative SPF (Full QCD)

$$\frac{\rho_{PS}^{VAC}(\omega)}{\omega^2 m^2(\bar{\mu})} \equiv \frac{N_c}{8\pi}\tilde{R}_c^p(\omega,\bar{\mu})$$

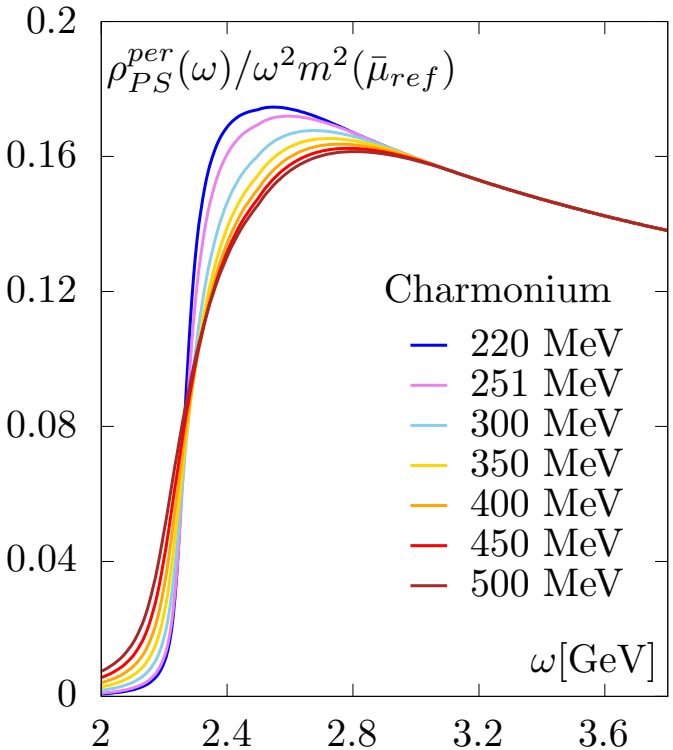
$$\rho_V^{NRQCD}(\omega) = \frac{1}{2}\left(1-e^{-\frac{\omega}{T}}\right)\int_{-\infty}^{\infty} \mathrm{d}t\, e^{i\omega t}\; C_>$$

$$\rho_{PS}^{THERM} = \frac{M^2}{3}\rho_V^{NRQCD}\,, \quad \omega \approx 2M$$

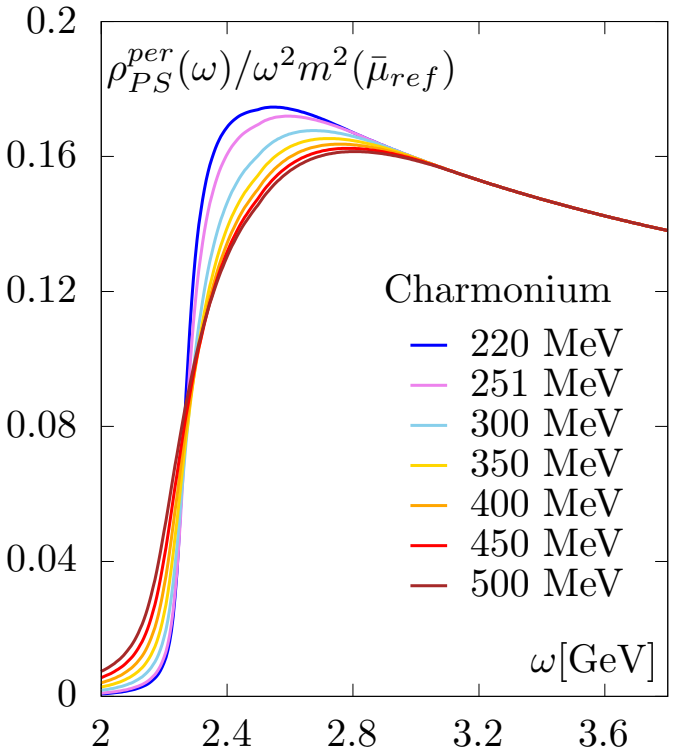
$$\rho_{PS}^{pert}(\omega) = \rho_{PS}^{VAC}(\omega) + A^{match}\rho_{PS}^{THERM}(\omega)$$

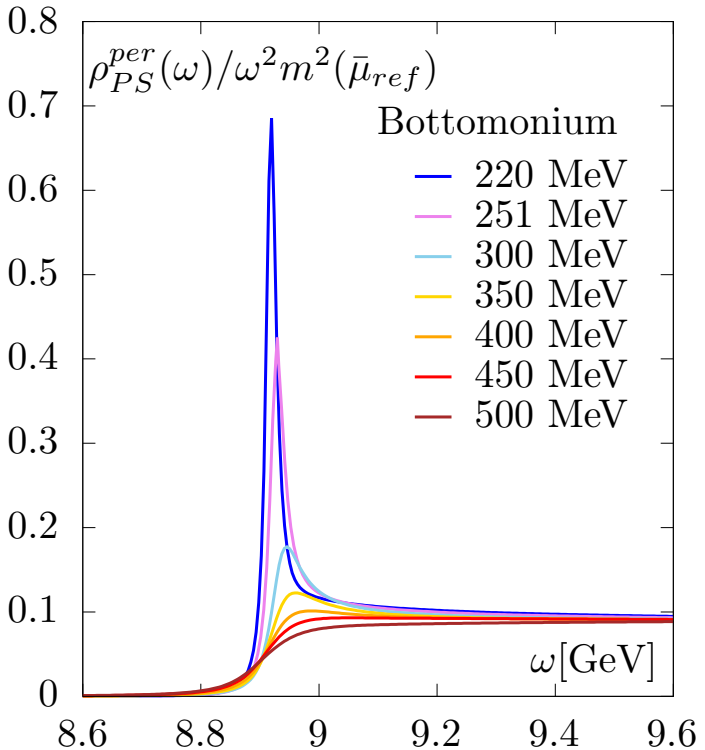
Ref. [JHEP 11 (2017) 206]

Perturbative SPF (Full QCD)



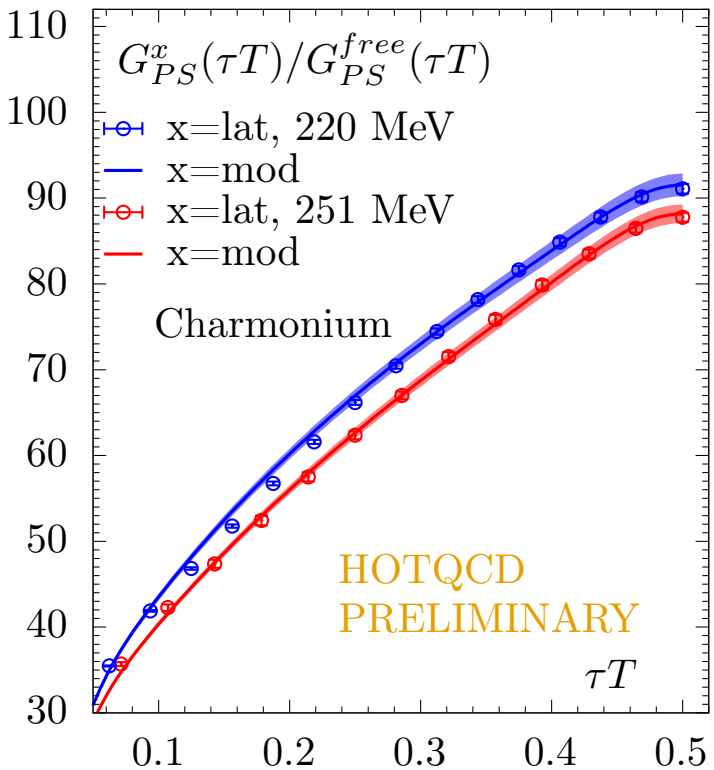
Perturbative SPF (Full QCD)





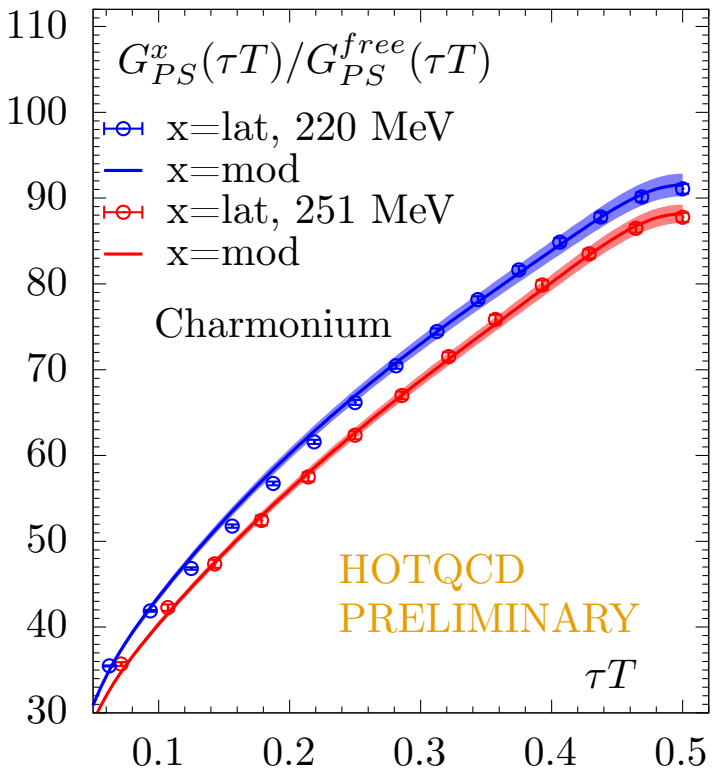
Spectral reconstruction (Full QCD)

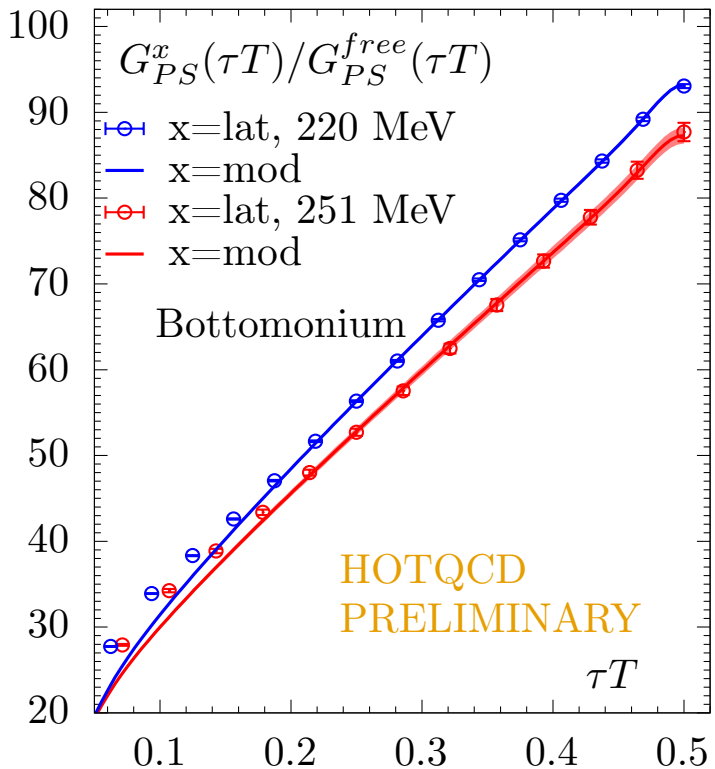
$$\rho_{PS}^{mod}(\omega) = A\,\rho_{PS}^{pert}(\omega - B)$$



Spectral reconstruction (Full QCD)

$$\rho_{PS}^{mod}(\omega) = A\,\rho_{PS}^{pert}(\omega - B)$$





Outlook

- Extend the studies on spectral and transport properties from quenched to dynamical QCD
- Study light quark mass effects by comparing $m_l = m_s/5$ and $m_l = m_s/27$
- Study cut-off effects and perform continuum extrapolation
- Improve on perturbative and non-perturbative spectral function models
- Spectral reconstruction based on spectral function model fits and other reconstruction methods
- Estimate in-medium hadronic and transport properties (Kubo relation)

Thank you for your attension !