Thermal modifications of quarkonia and heavy quark diffusion from a comparison of continuum-extrapolated lattice results to perturbative QCD

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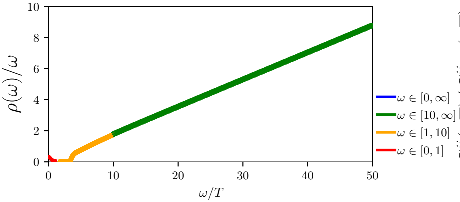
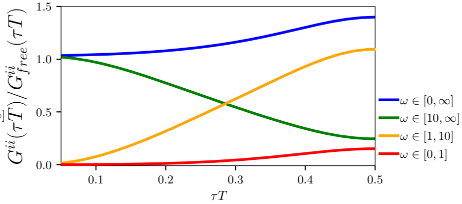
Strong-interaction matter under extreme conditions

Introduction

- Information about in-medium properties of quarkonia encoded in spectral function
- Extraction of spectral functions from correlators difficult

$$G_{ii}(\tau) = \int_0^\infty \frac{\mathrm{d}\omega}{2\pi} \rho_{ii}(\omega) K(\omega,\tau), \quad K(\omega,\tau) = \frac{\cosh(\omega(\tau - \frac{1}{2T}))}{\sinh(\frac{\omega}{2T})}$$





- Many reconstruction methods available [see also plenary talk by H. Ohno]
- Here: Fit of perturbative spectral function and MEM

Perturbative Spectral Function

Combination of different energy regimes, matched to connect at ω^{match} [Burnier et al., JHEP11(2017)206]

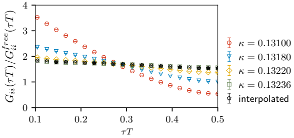
- High energy: Vacuum asymptotics [Burnier, Laine, Eur.Phys.J.C 72 (2012) 1902]
- Threshold region: pNRQCD [Laine, JHEP 0705:028,2007]
- Suppressed at low ω

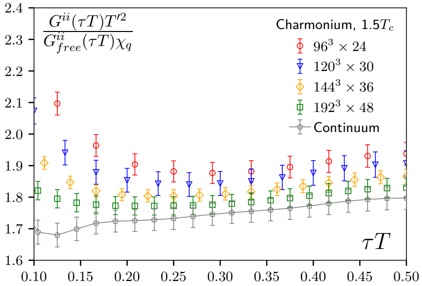
$$\rho^{pert}(\omega) = \underbrace{\rho^{vac}(\omega)}_{\text{Vacuum asymptotics}}\theta(\omega - \omega^{match}) + A^{match}\underbrace{\rho^{NRQCD}(\omega)}_{\text{pNRQCD}}\theta(\omega^{match} - \omega)\underbrace{\Phi(\omega)}_{\text{Suppression}}$$

Lattice Setup

- Large and fine lattices needed
  $\Rightarrow$ Quenched approximation
- Continuum extrapolated with a modified version of [Ding et al., EPJ WoC 175 (2018) 07010]

- Normalization with χ_q/T^2
- Mass interpolation to physical charmonium and bottomonium masses
- Continuum extrapolation with splines

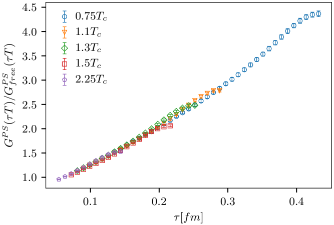




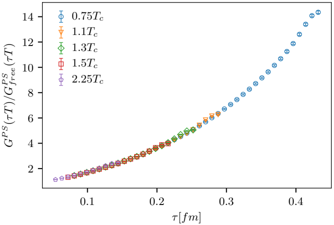
Continuum Correlators

Pseudoscalar

Charmonium

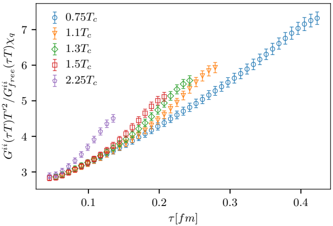


Bottomonium

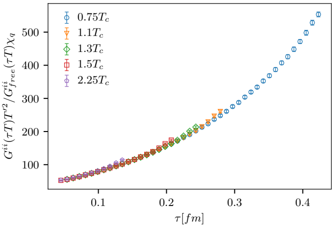


Vector

Charmonium



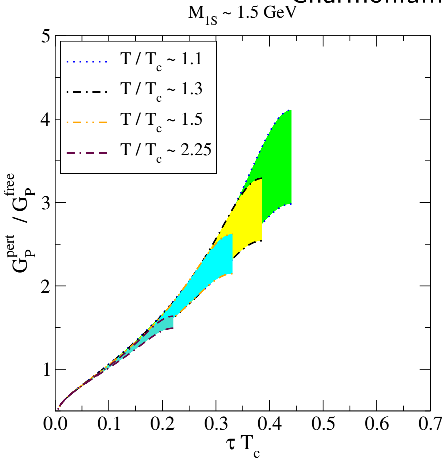
Bottomonium

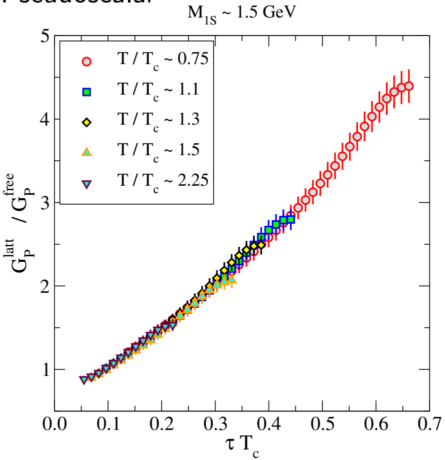


Compare Lattice and Perturbative Correlators

$$G(\tau) = \int_0^\infty d\omega K(\omega,\tau)\rho(\omega)$$

Charmonium - Pseudoscalar





Compare Lattice and Perturbative Correlators

A first look reveals qualitative agreement!
Systematic uncertainties may arise from

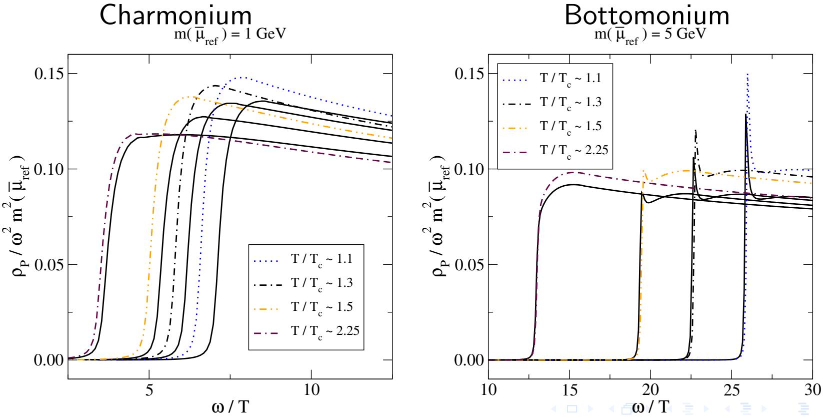
- a slightly incorrect renormalization on the lattice side
  $\Rightarrow$ Overall normalization A
- the not exactly known relation between the pole mass and the $\overline{MS}$ mass on the perturbative side
  $\Rightarrow$ Mass shift B

Resulting model spectral function

$$\rho^{\textbf{mod}}(\omega) = \mathbf{A}\rho^{\textbf{pert}}(\omega - \mathbf{B})$$

Pseudoscalar Channel

- No transport peak → easier
- Perturbative spectral function describes lattice data perfectly
- Only slight modifications needed ($A \approx 1$, B small) [Burnier et al., JHEP11(2017)206]



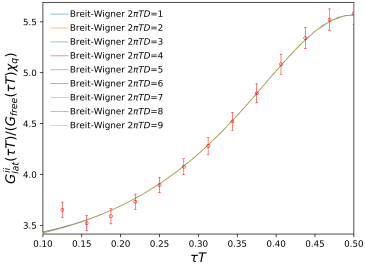
Vector Channel

- Here: Additional transport peak
  $\rho^{ii}(\omega) = A\rho^{pert}(\omega - B) + \rho^{trans}(\omega)$
- No perturbative description of transport peak
- Assume Breit-Wigner ansatz
  $\rho^{trans}(\omega) = 3D\chi_q \frac{\omega {\eta_D}^2}{\omega^2 + {\eta_D}^2} \frac{1}{\cosh\left(\frac{\omega}{2\pi T}\right)}$
- In total 4 parameters: A, B, D, η_D $\Rightarrow$ too many
- Try to fix some of the parameters

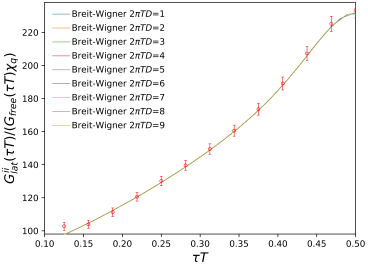
Model 1 - Three Parameter Fits

Model 1: Fix $2\pi TD$ to values between 1 and 9, determine A, B, η_D via fit

Charmonium $2.25\,T_c$

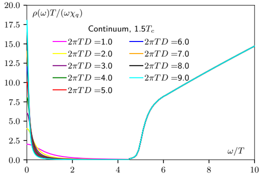


Bottomonium $2.25\,T_c$

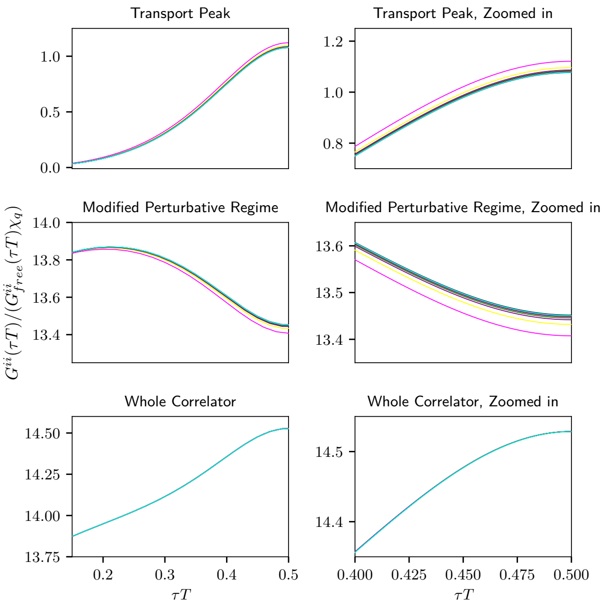


- Transport contribution can be described with Breit-Wigner
- All choices for $2\pi TD$ reproduce the data equally well

Model 1 - A closer look

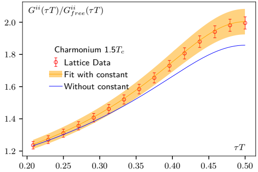


- Small changes in *A* and *B*
- Changes in different parts cancel each other



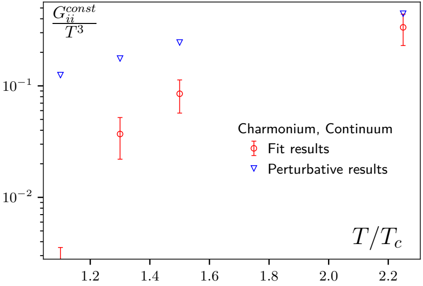
Model 2: Separating the Fit

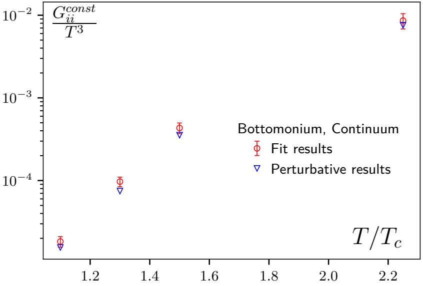
- Reminder: $\rho^{ii}(\omega) = A\rho^{pert}(\omega - B) + \rho^{trans}(\omega, D, \eta_D)$
  In total 4 parameters: A, B, D, η_D
- Fitting transport and bound state region simultaneously does not lead to results
  $\Rightarrow$ Separate the fit into transport and bound state region
- Investigation of bound state region: Assume constant contribution for transport peak (=δ-peak in ρ)
  $$\Rightarrow G^{ii}(\tau T) = G^{pert.mod}(\tau T) + c$$
- Analyze constant contribution to gain information on transport peak



Constant contribution

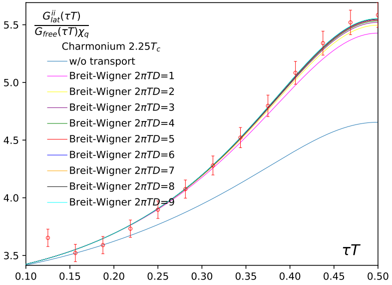
- Constant contribution can be estimated perturbatively
- High agreement for bottomonium
- Decreasing agreement for decreasing temperature for charmonium





Modelling the Transport Peak

- A, B fixed by fit for high ω, Transport so far described by constant
- Replace constant by Breit-Wigner
- $2\pi TD$ varied from 1 to 9
- η_D solved to obtain the constant contribution from previous fit

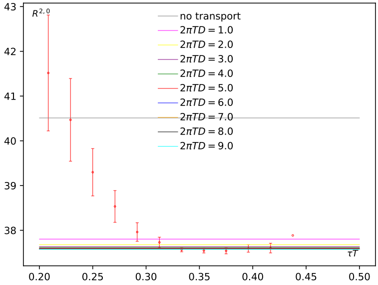


Modelling the Transport Peak

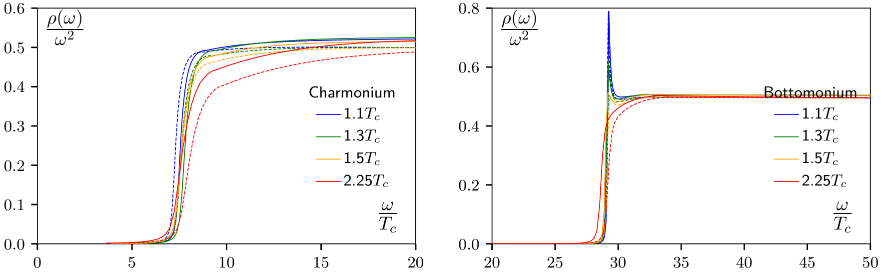
- Possible lower bound at $2\pi TD = 2$
- Compare to thermal moments:

$$G^{(n)} = \frac{1}{n!} \left. \frac{\mathrm{d}\omega^n G(\tau T)}{\mathrm{d}\omega(\tau T)^n} \right|_{\tau T = \frac{1}{2}}, \qquad R^{(n+2,n)} = \frac{G^{(n+2)}}{G^{(n)}}$$

- Thermal moments = Taylor coefficients of the correlator around the midpoint $\tau T = 0.5 \to$ High influence of transport peak



Result for high ω

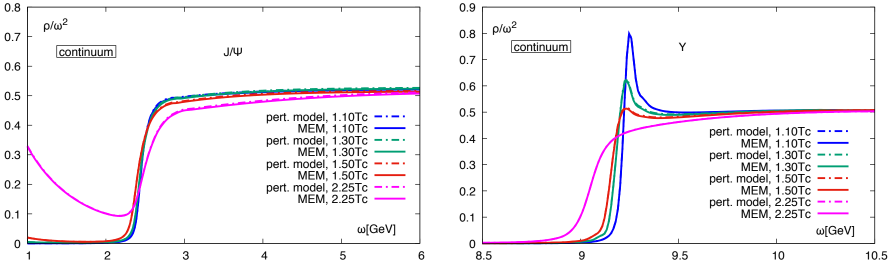


Dashed: Perturbative spectral function, Solid: Model spectral function

Like in pseudoscalar, the perturbative spectral function describes the data well with only slight modifications!

Crosscheck by MEM

- Use Maximum Entropy Method to crosscheck spectral functions
- Use the results from fits as default model
- Default model remains almost unchanged
  $\Rightarrow$ MEM confirms the fit results



Conclusion & Outlook

- Transport peak can be described with Breit-Wigner ansatz
- Solving for η_D hints to a lower bound of $2\pi TD = 2$
- Correlators in pseudoscalar channel perfectly described by modified perturbative spectral function
- Bound state region in vector channel also perfectly matched by modified perturbative spectral function

In the future: Go to full QCD

- Transition temperature around 2 times smaller, no longer 1st order
- Effective couplings become larger

$\Rightarrow$ The physics may change, but the method remains the same!