Bottomonium at finite temperature

Signals for the quark-gluon plasma from lattice QCD

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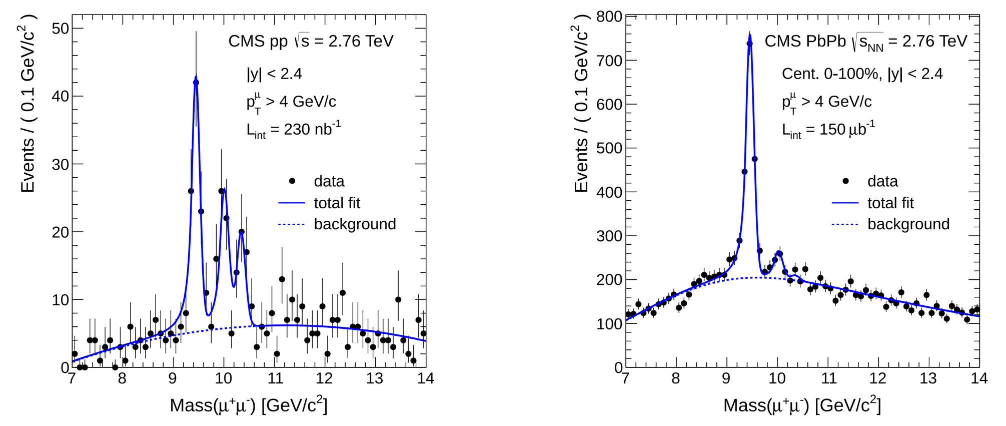
Numerical lattice QCD offers access to key observables at finite temperature in a straightforward way. Despite being the subject of much theoretical investigation, the in-medium modification of heavy-quarkonium states is not yet fully understood. We hope that calculations of the bottomonium spectral functions from the lattice, along with other approaches from potential models and effective field theories, may contribute to determine the fate of these states in a deconfined medium. This is particularly important to understand the yield suppression mechanisms in heavy-ion collisions and therefore to find a signal for the formation of the quark-gluon plasma. Earlier work [FASTSUM:1109.4496] observed the melting of the 1P states and the survival of the 1S states above the crossover temperature T_c. Those conclusions are supported from calculations using a new generation of ensembles including the dynamical strange quark, with finer lattice spacings and lighter light quarks.



Heavy quarks on the lattice

N_f	N_s	N_τ	a_s	$1/a_\tau$	$\xi = a_s/a_\tau$	m_π/m_ρ	$m_\pi L$
2+1	16	128	0.12 fm	5.67 GeV	3.5	0.448	3.9

- Anisotropic Symanzik-improved gauge and clover light-quark action allows high temporal resolution of correlation functions essential for reconstruction of spectral functions.
- At attainable lattice spacings, b-quark has $m_b a_s \gtrsim 1$ so cannot be simulated without large discretization effects, so resort to the discretization of a non-relativistic effective theory, NRQCD.
- NRQCD uses power counting in $v^2 \approx 0.1$ for b-quark in bottomonium.
- Lattice provides momentum cutoff $a^{-1} \sim m_b \approx 5\,\mathrm{GeV}$, which cannot be removed $\Rightarrow$ no continuum limit!
- $O(v^4)$ effective action is matched to QCD at tree-level:

$$S_\psi = a_s^3 \sum_{n\in\Lambda} \psi^\dagger(n)\left[\psi(n) - K_\tau \psi(n - a_\tau \boldsymbol{e}_\tau)\right]$$

$$K_{\tau+1} = \left[1 - \frac{a_\tau H_0|_{\tau+1}}{2}\right] U^\dagger_{\tau,n} \left[1 - \frac{a_\tau H_0|_\tau}{2}\right] [1 - a_\tau \delta H], \quad H_0 = -\frac{\Delta^{(2)}}{2m_b}, \quad \Delta^{(2n)} = \sum_i (\nabla_i^+ \nabla_i^-)^n,$$

$$\delta H = -\frac{(\Delta^{(2)})^2}{8m_b^3} + \frac{ig_0}{8m_b^2}(\boldsymbol{\nabla}^\pm \cdot \boldsymbol{E} - \boldsymbol{E}\cdot\boldsymbol{\nabla}^\pm) - \frac{g_0}{8m_b^2}\boldsymbol{\sigma}\cdot(\boldsymbol{\nabla}^\pm \times \boldsymbol{E} - \boldsymbol{E}\times\boldsymbol{\nabla}^\pm) - \frac{g_0}{2m_b}\boldsymbol{\sigma}\cdot\boldsymbol{B} + \frac{a_s^2 \Delta^{(4)}}{24 m_b} - \frac{a_\tau (\Delta^{(2)})^2}{16 m_b^2}.$$

- Heavy-quark propagators, $S(n)$, satisfy evolution equation $S(n + a_\tau \boldsymbol{e}_\tau) = K_{\tau+1} S(n)$.
- Tune heavy quark mass via kinetic mass, $M_{\rm kin}(\overline{1S})$, from quarkonium dispersion relation.
- Heavy quark rest mass plays no role and term is omitted in action, leading to an undetermined energy shift in spectrum.

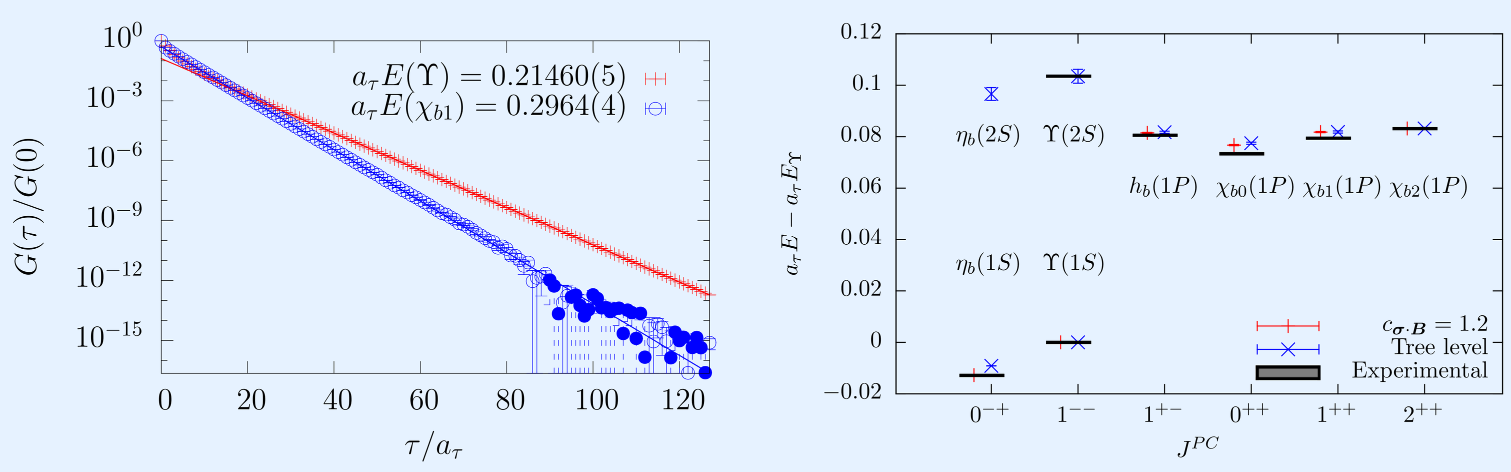


Figure : Correlation functions and zero-temperature spectrum

Maximum entropy method

$$G(\tau) = \int_0^\infty \frac{\mathrm{d}\omega}{2\pi} \frac{\cosh(\omega\tau - \omega/2T)}{\sinh(\omega/2T)}\rho(\omega) \longrightarrow \int_{\omega_{\rm min}}^{\omega_{\rm max}} \frac{\mathrm{d}\omega}{2\pi} e^{-\omega\tau}\rho(\omega)$$

- Kernel is T-independent reflecting heavy-quark not in thermal equilibrium with medium.
- Resort to Bayesian inference of most plausible spectral function given finite noisy correlator data, $G(\tau)$.
- Solution is unique but hypothesis must be provided and dependence on this input thoroughly tested.

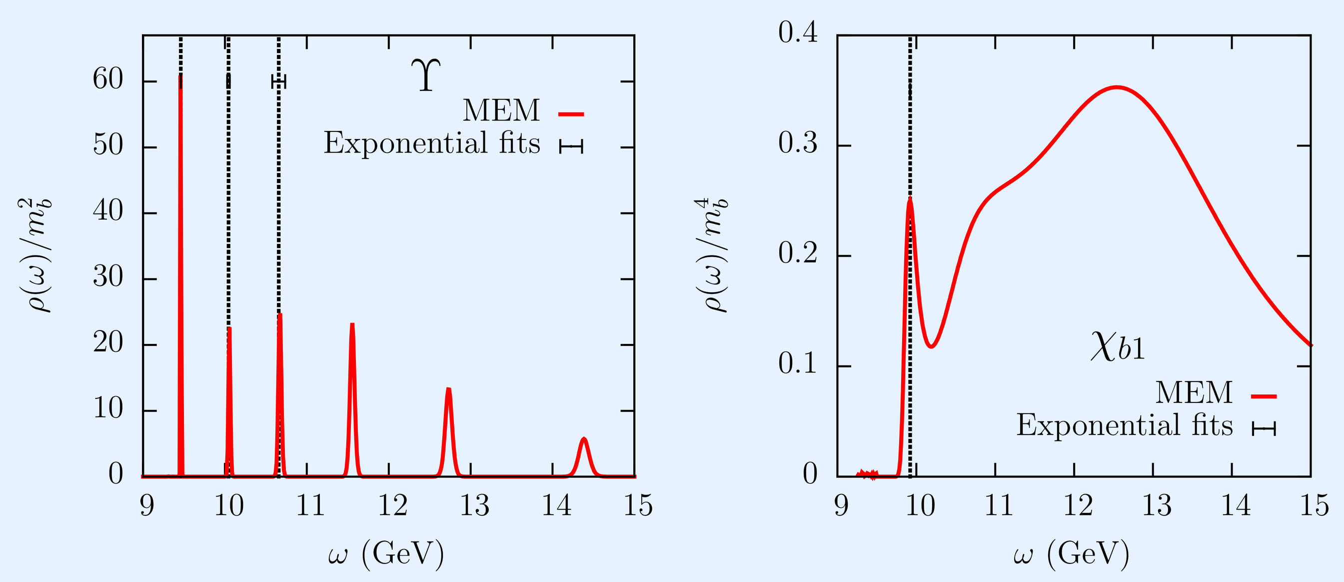


Figure : Zero-temperature spectral functions extracted with MEM

- Good agreement between low-lying S-waves extracted from multi-exponential fits and peaks from MEM.

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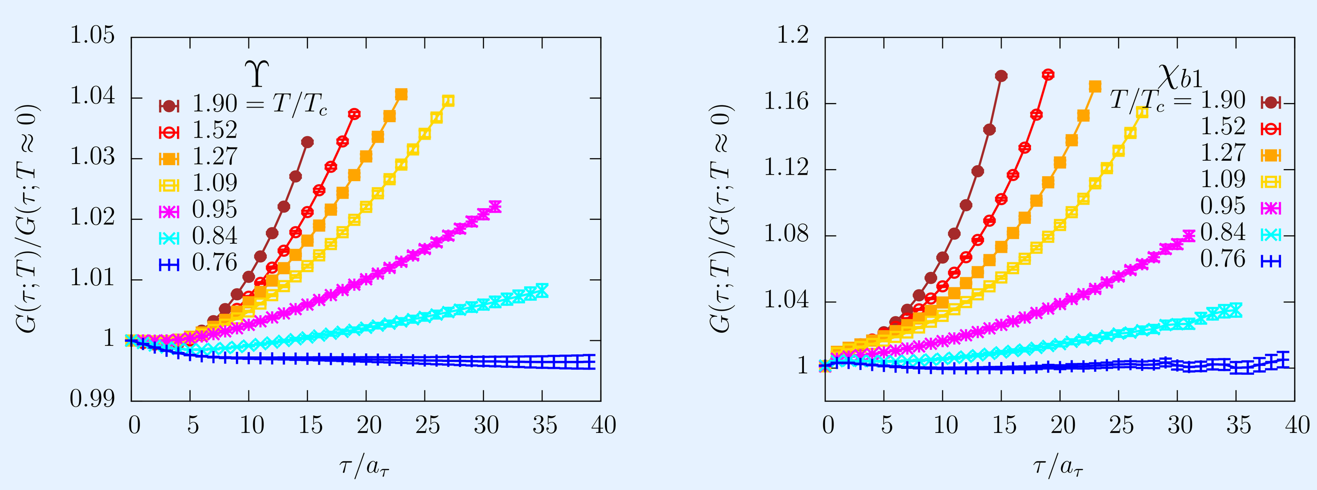


Figure : T-dependence of correlators relative to zero-temperature

- P-wave (right) shows stronger temperature dependence than S-wave (left).

m_b-dependence

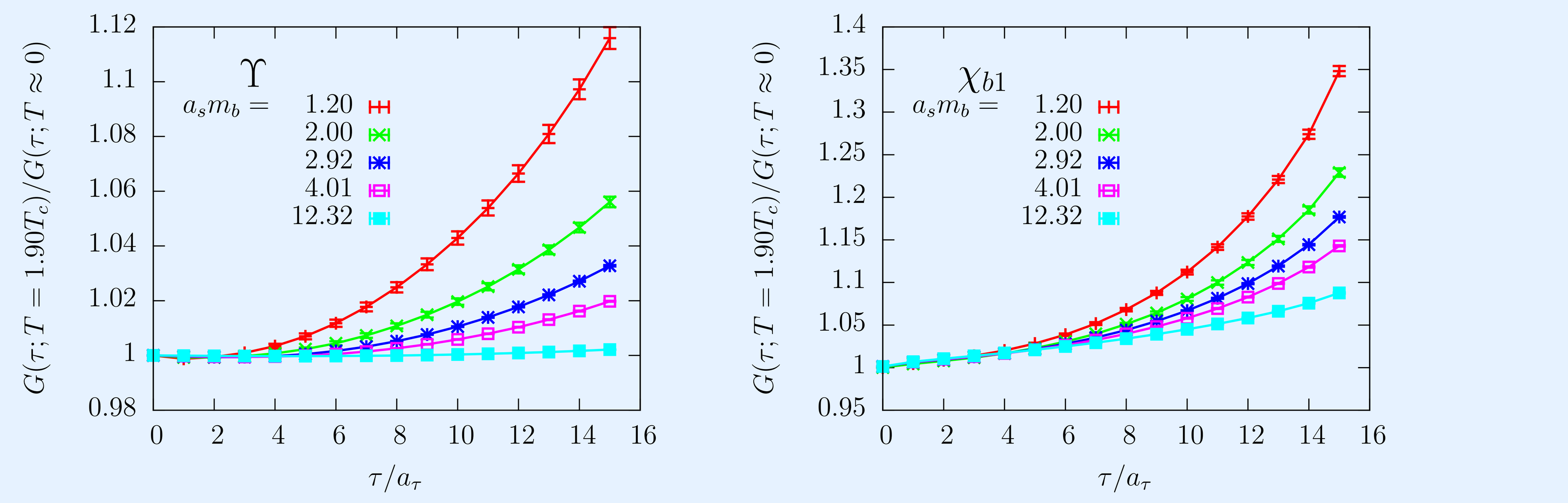
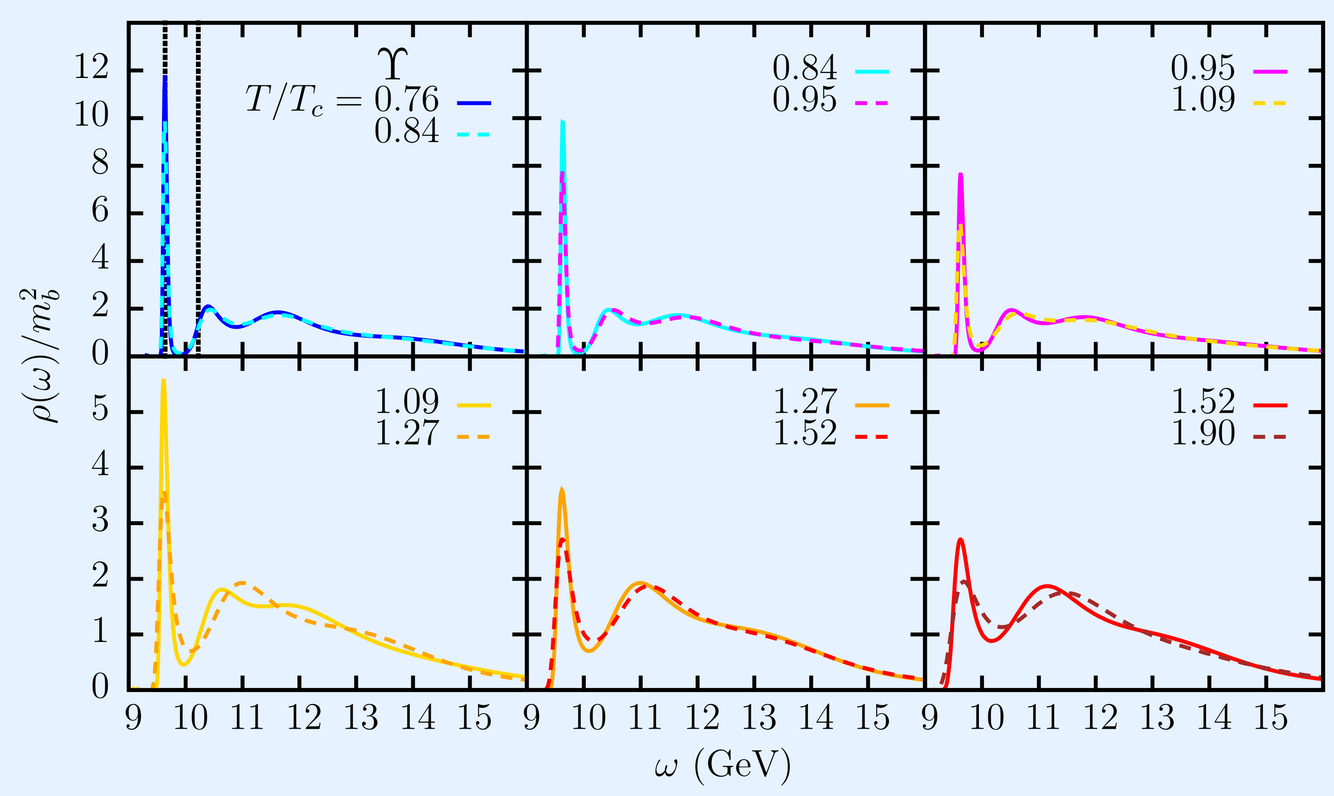


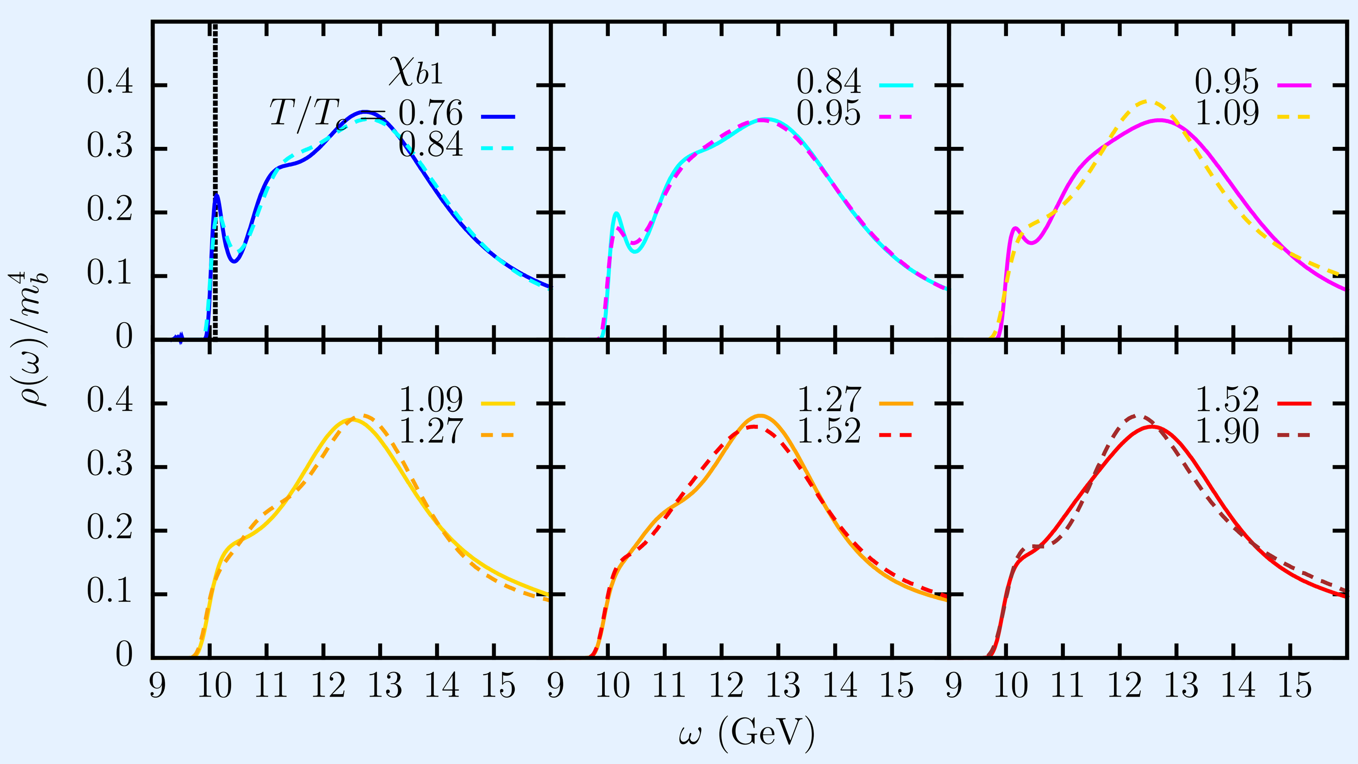
Figure : m_b-dependence of modification of correlators at $T/T_c = 1.89$

- Modification is greatly enhanced for a lighter heavy quark, consistent with our expectations of more effective screening for lighter larger states.

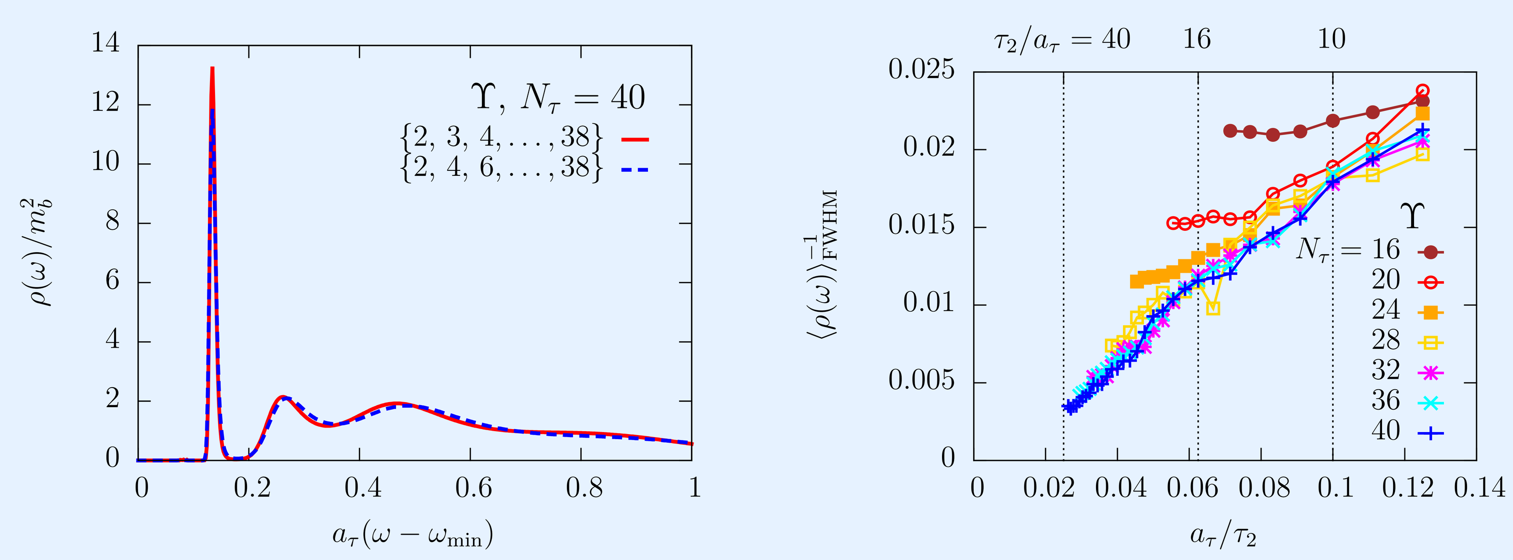
Melting bottomonium?



- Ground state S-wave survives above T_c, while excited state peak broadens significantly above T_c.



- Ground state P-wave peak disappears directly above T_c, supported by direct analysis of the correlators.



Preliminary : Stability of reconstructed spectral function

- The reconstruction is stable when omitting half of the available correlator data (left).
- Peak height depends on the subinterval, $[\tau_1/a_\tau,\ \tau_2/a_\tau]$, of correlator data used in the reconstruction but at high temperatures illustrates the suppression is not an artefact of MEM.

Future work

- Investigation of temperature dependence of width and analysis of D-wave states.
- Comparison with other Bayesian reconstructions of the spectral function [Burnier, Rothkopf: 1310.0645].
- Tuning of new ensembles with $\xi = 7$, increased temporal resolution and larger spatial volumes.
- See [FASTSUM:1402.6210] for more!