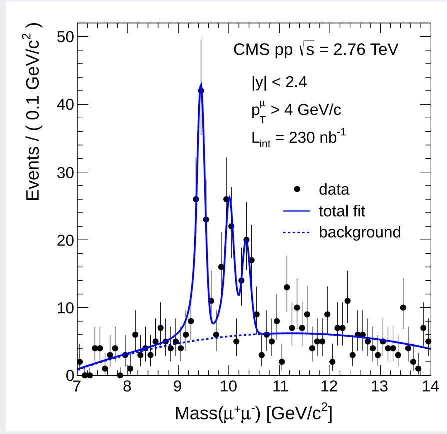
# Bottomonium at finite temperature

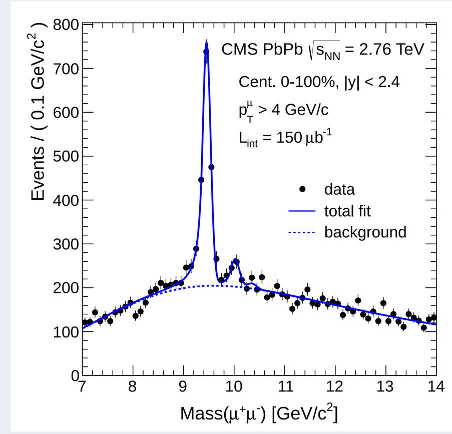
## Signals for the quark-gluon plasma from lattice QCD

TRINITY COLLEGE DUBLIN
COLÁISTE NA TRÍONÓIDE, BAILE ÁTHA CLIATH
THE UNIVERSITY OF DUBLIN

Tim Harris for the FASTSUM collaboration • XQCD 2013 • tharris@maths.tcd.ie

Numerical lattice QCD offers access to key observables at finite temperature in a straightforward way. Despite being the subject of many theoretical investigations, 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 may contribute, along with other approaches from potential models and effective field theories, to determining the fate of these states in a deconfined medium. This is particularly important to understand the yield suppression mechanisms in heavy-ion collisions and thus 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 $T_c$. These conclusions are supported from calculations using a new generation of ensembles including the dynamical strange quark, with finer lattice spacings and lighter quarks.




## Heavy quarks on the lattice

| $N_s$ | $N_\tau$ | $a_s$ | $1/a_\tau$ | $\xi$ | $m_\rho/m_\pi$ | $m_\pi L$ |
|---|---|---|---|---|---|---|
| 16 | 128 | 0.12 fm | 5.67 GeV | 3.5 | 0.448 | 3.9 |

- Anisotropic, Symanzik gauge/$2+1$ clover.
- Temporally fine lattice allows high resolution needed when the temporal extent is small.
- At attainable lattice spacings, $b$-quark has $\hat{m}_b = m_b a_s \gtrsim 1$ so cannot be simulated without large discretization effects.
- NRQCD uses power counting in $v^2 \approx 0.1$ for $b$-quark in bottomonium.
- Lattice provides momentum cutoff $a^{-1} \gtrsim m_b \approx 5\,\mathrm{GeV}$, which cannot be removed in NRQCD $\Rightarrow$ no continuum limit!
- Operator coefficients in action are matched at tree level with QCD.

$$S_\psi = a_s^3 \sum_{n\in\Lambda} \psi^\dagger(n)\left[\psi(n) - K(n_\tau)\psi(n - a_\tau e_\tau)\right],$$

$$H_0 = -\frac{\Delta^{(2)}}{2m_b}, \qquad \Delta^{(2)} = \sum_i \nabla_i^+ \nabla_i^-,$$

$$\delta H_{v^2} = -\frac{(\Delta^{(2)})^2}{8m_b^3} + \frac{ig_0}{8m_b^2}(\boldsymbol{\nabla}^\pm \cdot \boldsymbol{E} - \boldsymbol{E}\cdot\boldsymbol{\nabla}^\pm),$$

$$\delta H_{\boldsymbol{\sigma}} = -\frac{g_0}{8m_b^2}\boldsymbol{\sigma}\cdot(\boldsymbol{\nabla}^\pm \times \boldsymbol{E} - \boldsymbol{E}\times\boldsymbol{\nabla}^\pm) - \frac{g_0}{2m_b}\boldsymbol{\sigma}\cdot\boldsymbol{B},$$

$$\delta H_{\mathrm{imp}} = \frac{a_s^2\Delta^{(4)}}{24m_b} - \frac{a_\tau(\Delta^{(2)})^2}{16m_b^2}, \qquad \Delta^{(4)} = \sum_i(\nabla_i^+\nabla_i^-)^2.$$

- Heavy quark rest mass plays no role and term is omitted in action, leading to an undetermined energy shift in spectrum.

$$P(n + a_\tau e_\tau) = K(n_\tau + a_\tau)P(n) = \left(1 - \frac{a_\tau H_0|_{n_\tau+a_\tau}}{2}\right) U_\tau^\dagger(n) \left(1 - \frac{a_\tau H_0|_{n_\tau}}{2}\right)(1 - a_\tau \delta H)\,P(n).$$

- Tune heavy quark mass via kinetic mass, $M_{\mathrm{kin}}$, from meson dispersion relation:
- Use spin-averaged $1S$ mass, $\overline{M} = (3M_\Upsilon + M_{\eta_b})/4$, to remove tuning dependence on spin terms.

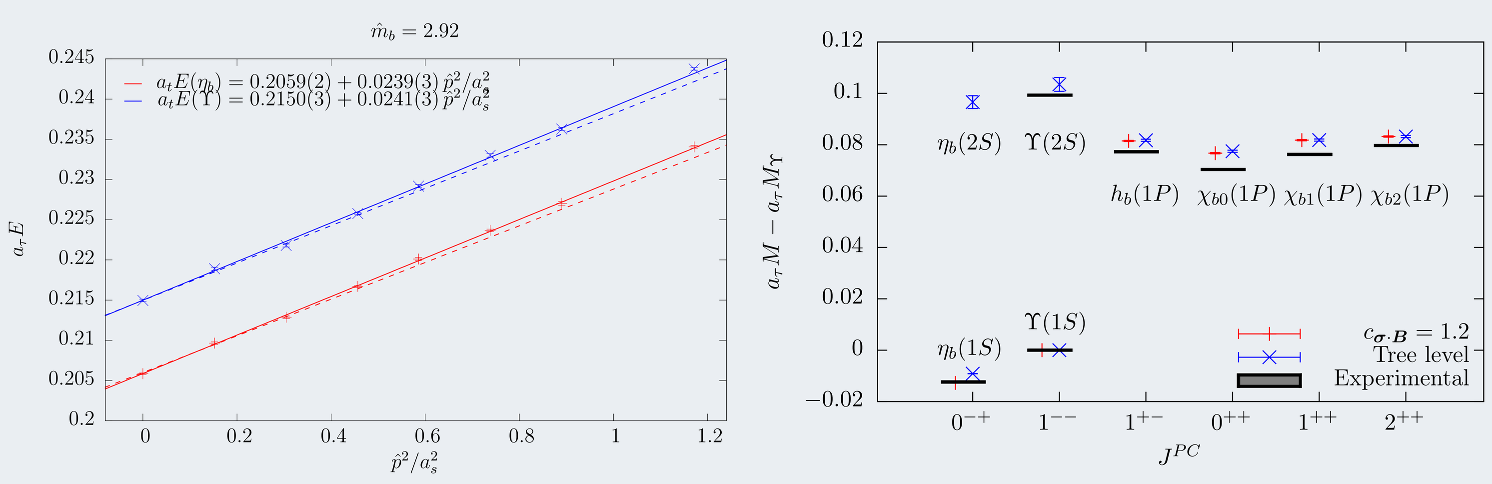



Figure: Dispersion relation and zero-temperature spectrum

## Maximum entropy method

$$G(\tau) = \int_0^\infty \frac{\mathrm{d}\omega}{2\pi}\frac{\cosh(\omega\tau - \omega/2T)}{\sinh(\omega/2T)}\rho(\omega) \longrightarrow \int_{-\omega_0}^\infty \frac{\mathrm{d}\omega}{2\pi} e^{-\omega\tau}\rho(\omega+\omega_0)$$

- 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.

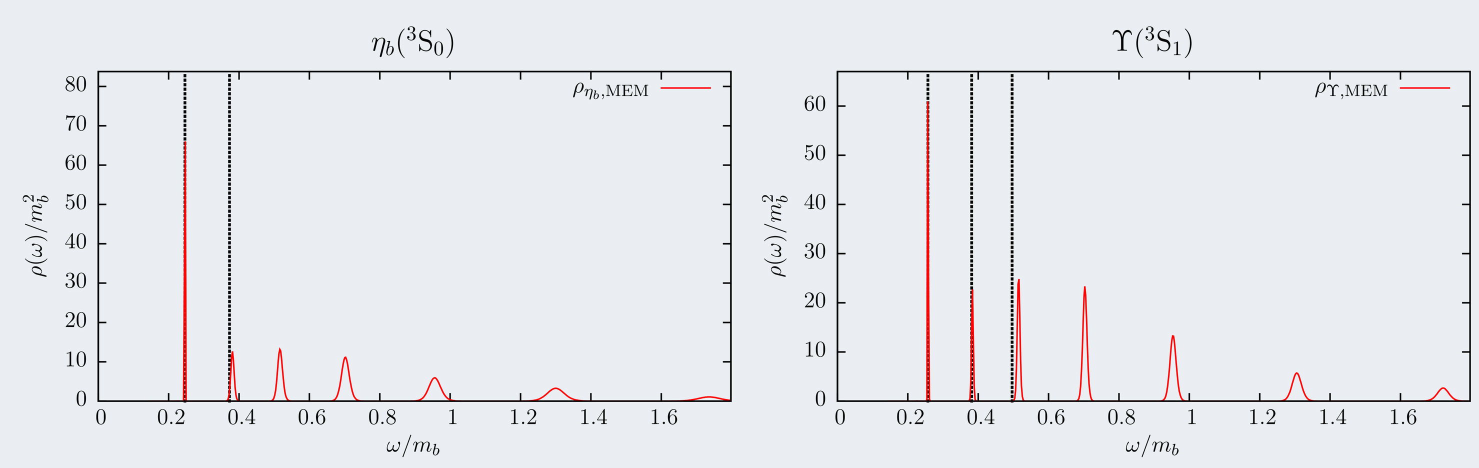



Figure: Zero-temperature spectral functions extracted with MEM

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

## Bottomonium at finite temperature

- Transition temperature, $T_c$, determined through the renormalized Polyakov loop.

| $N_s$ | $N_\tau$ | $T/T_c$ | $N_{\mathrm{cfg}}$ |
|---|---|---|---|
| 24 | {16,...,40} | {1.89,...,0.76} | ≥500 |

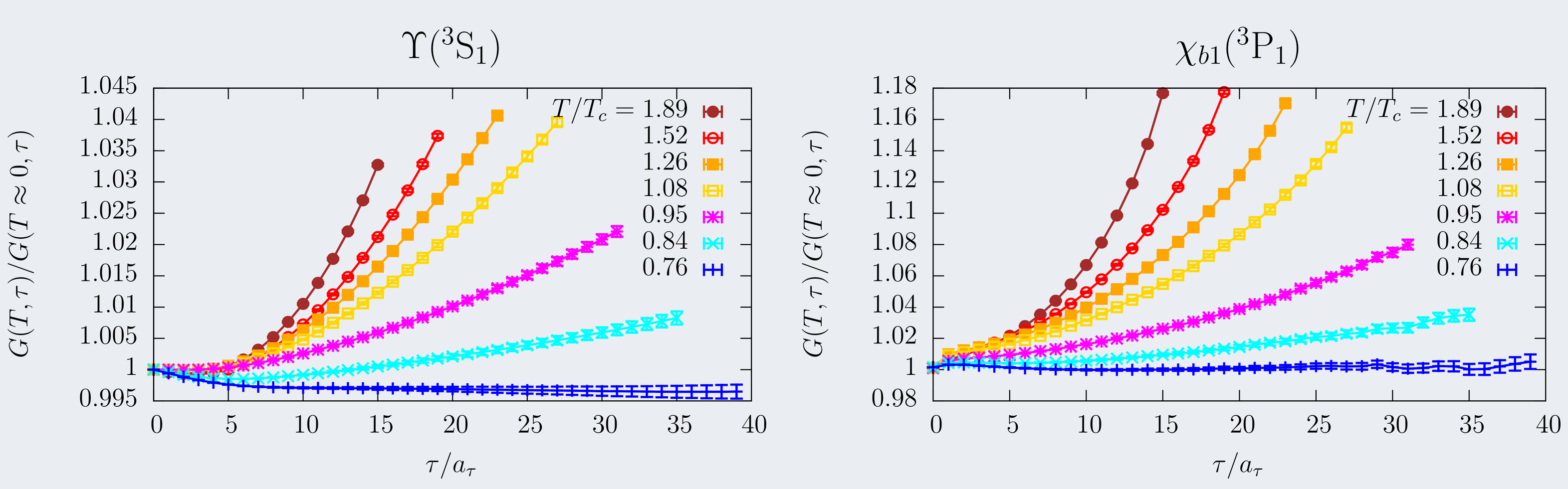



Figure: $T$-dependence of correlators relative to zero-temperature

- $P$-wave shows stronger temperature dependence than $S$-wave.

## $m_b$-dependence

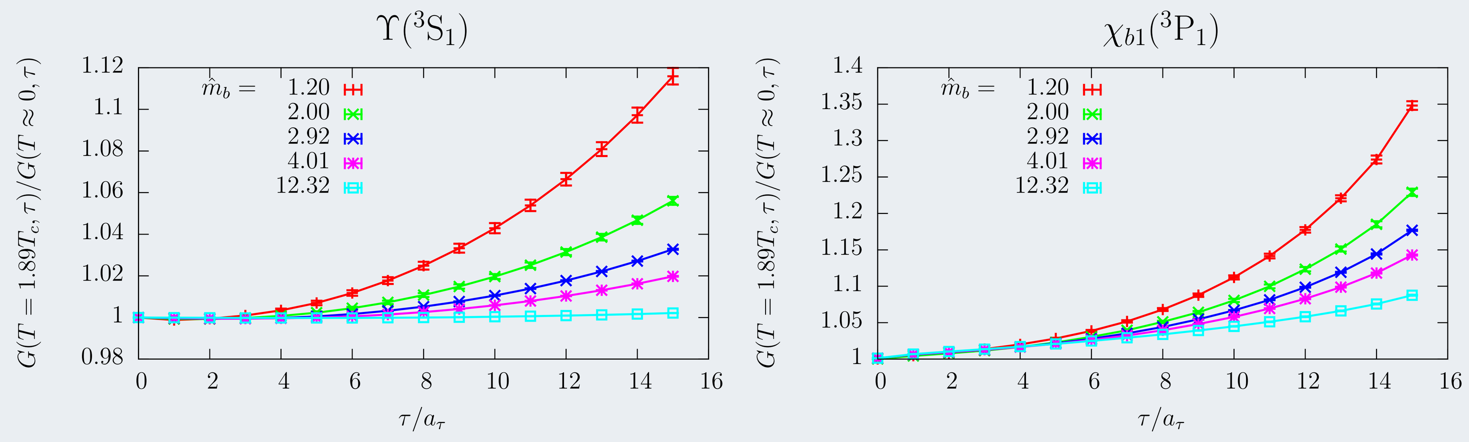
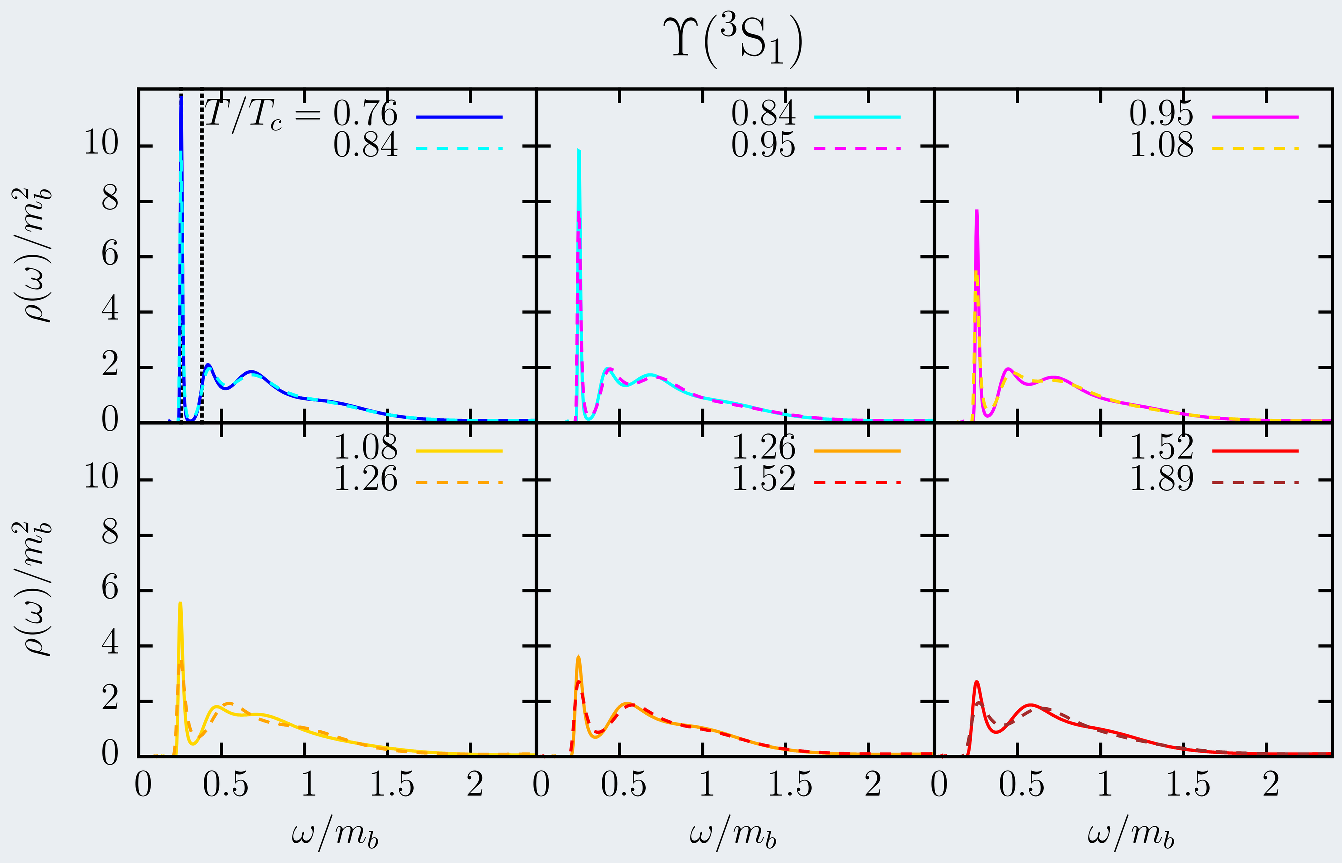


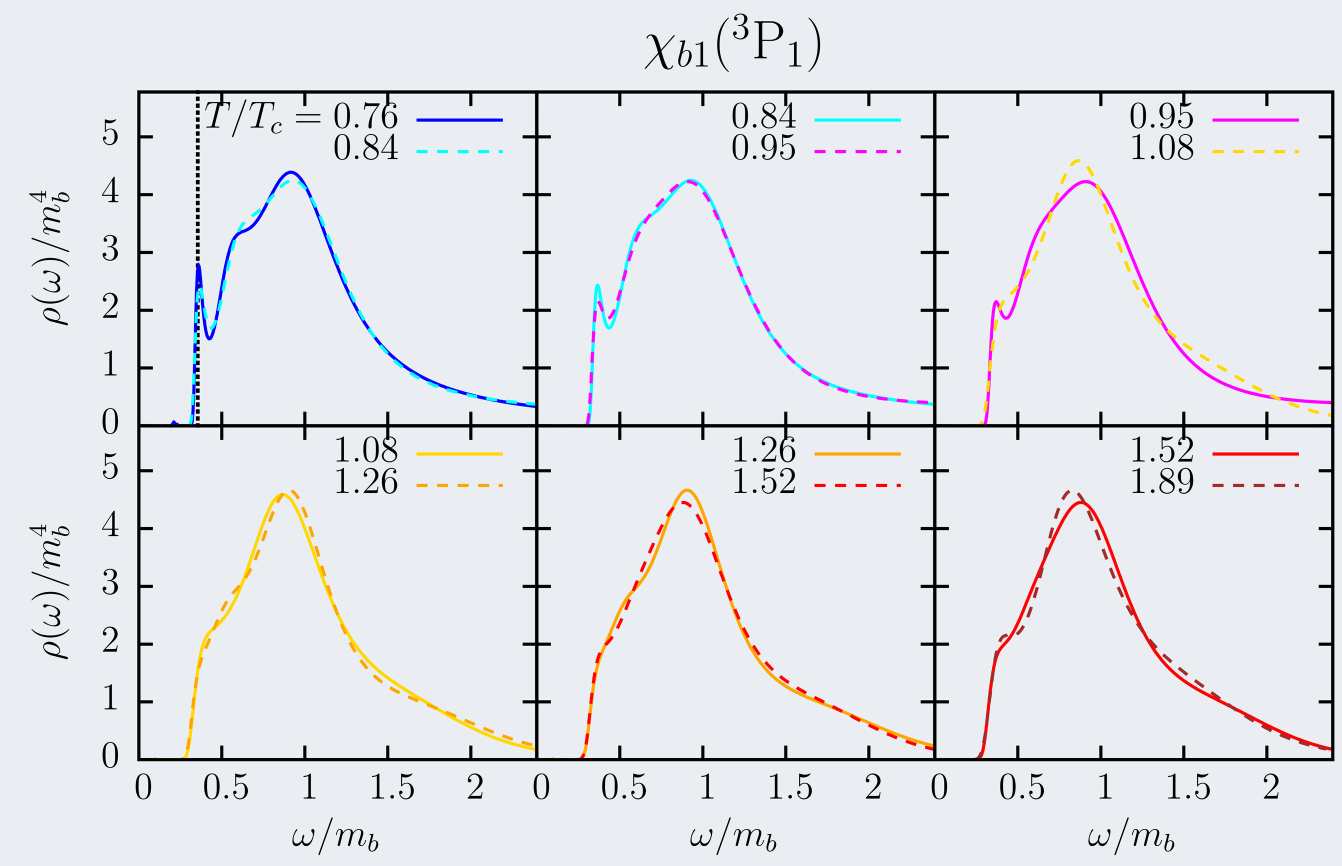

Figure: $\hat{m}_b$-dependence of modification of correlators at $T/T_c = 1.75$

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

## Melting bottomonia




- Ground state $S$-wave survives above $T_c$, while $2S$-wave peak broadens and becomes suppressed.




- Ground state $P$-wave peak disappears directly above $T_c$, supported by direct analysis of the correlators.
- For free quarks, the effective exponent observable has a non-zero constant term.

$$\rho_{\mathrm{free}}(\omega) \propto \omega^{5/2}\Theta(\omega) \;\Rightarrow\; G_{\mathrm{free}}(\tau) \propto \frac{e^{-\omega_0\tau}}{\tau^{5/2}} \qquad \gamma_{\mathrm{eff}}(\tau) \equiv -\tau\frac{G'(\tau)}{G(\tau)} \overset{G=G_{\mathrm{free}}}{=} \omega_0\tau + 5/2$$

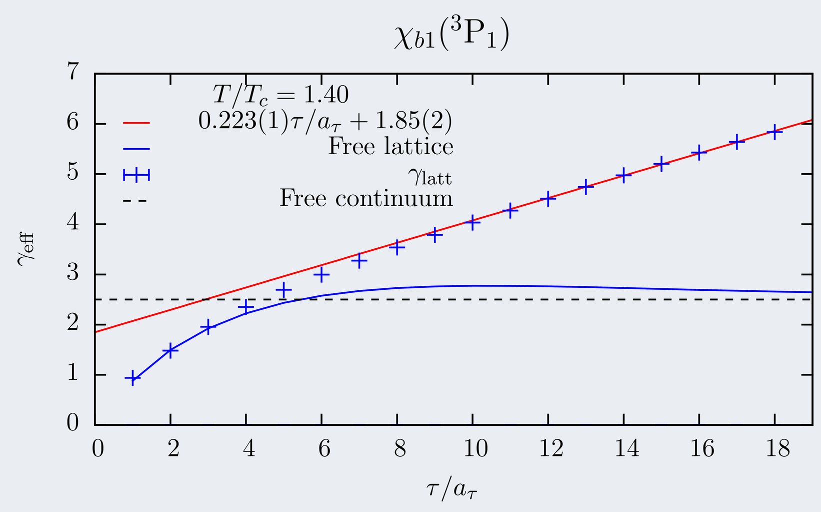



Figure: Linear fit to $\gamma_{\mathrm{eff}}$ observable

| | Single exponential | Effective exponent |
|---|---|---|
| $T/T_c$ | $\chi^2/\mathrm{dof}$ | $\alpha$ |
| 0.76 | 0.82 | -0.1(1) |
| 0.84 | 0.80 | 0.35(9) |
| 0.95 | 5.36 | 0.42(11) |
| 1.08 | 20.2 | 0.52(3) |
| 1.26 | 122 | 0.52(3) |
| 1.52 | $\mathcal{O}(10^5)$ | 0.85(2) |

Table: $P$-wave direct correlator analysis

- Data at high $T$ are unlikely to come from a single exponential decay model.
- Broad trend of fitted exponent is toward value predicted by free quark dynamics.

## Future work

- Results consistent with earlier analyses of correlators and spectral functions.
- Must investigate $T$-dependence on widths extracted from MEM.
- Must test default model dependence and other systematics of MEM thoroughly.
- Tuning of new ensemble with $\xi = 7$ and increased temporal resolution and larger spatial volumes.