Heavy quarks in the quark-gluon plasma from lattice QCD

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FASTSUM collaboration

Excited QCD, Schladming, 2 Feb 2019

Outline

Background

Simulation and analysis

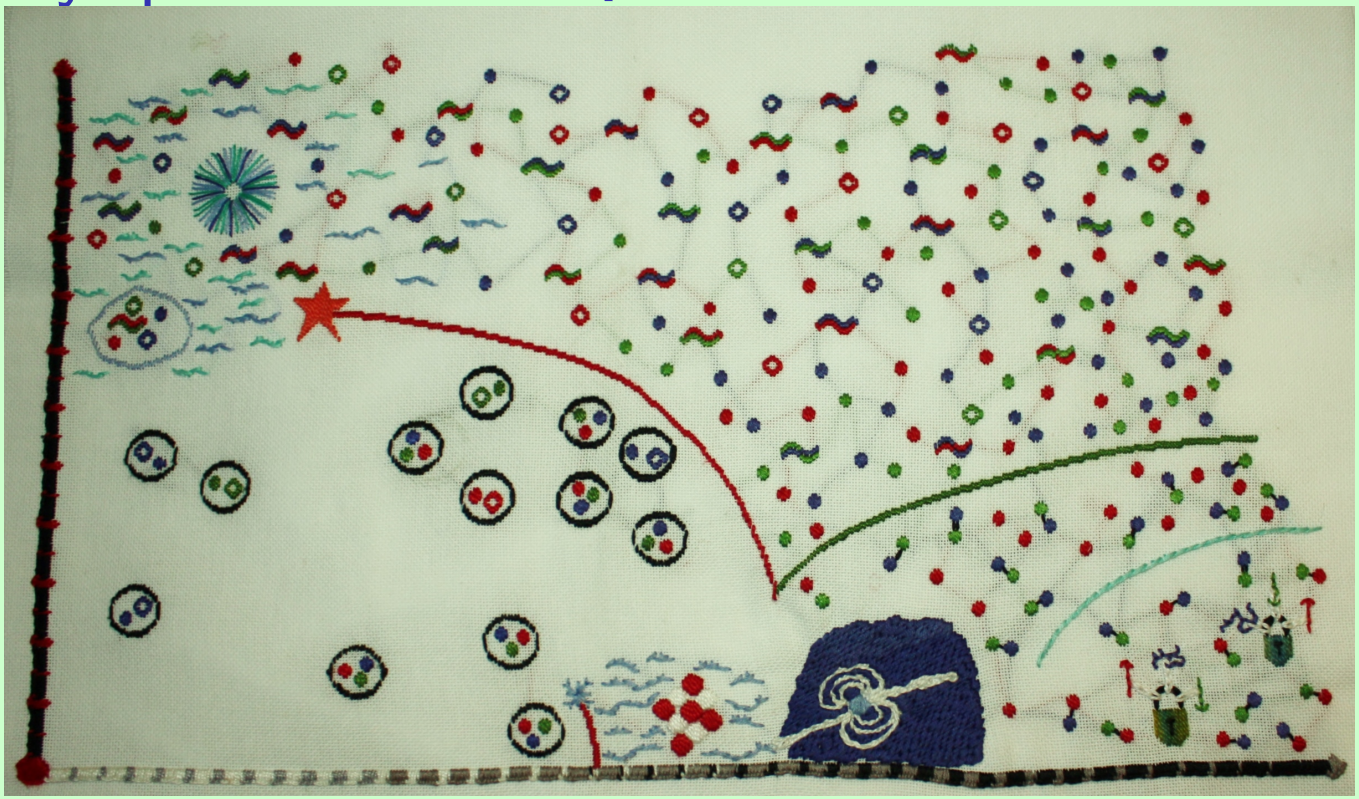
Charmonium

Open charm

Beauty

Summary and outlook

Heavy quarks in the QGP



- Heavy quarks are important probes of medium
- Long history of $c\bar{c}$ studies: experiment, pheno, lattice
- Sequential $b\bar{b}$ suppresion observed, numerous studies
- Open charm still in its infancy

Dynamical anisotropic lattices

- A large number of points in time direction required to extract spectral information
- For $T = 2T_c$, $\mathcal{O}(10)$ points $\Longrightarrow$ $a_t \sim 0.025$ fm
- Far too expensive with isotropic lattices $a_s = a_t$!
- Fixed-scale approach
  - vary T by varying N_τ (not a)
  - need only 1 $T = 0$ calculation for renormalisation
  - independent handle on temperature

- Introduces 2 additional parameters
- Non-trivial tuning problem
  [PRD **74** 014505 (2006); HadSpec Collab, PRD **79** 034502 (2009)]

Simulation parameters

FASTSUM Gen2 ensemble: $N_f = 2 + 1$ anisotropic clover
[HadSpec, PRD **79** 034502 (2009); FASTSUM, JHEP **1502** 186 (2015)]

ξ	3.5
a_s (fm)	0.123
a_τ^{-1} (GeV)	5.63
m_π (MeV)	380
m_π/m_ρ	0.45
N_s	24
L_s (fm)	2.94

N_τ	T (MeV)	T/T_c	N_{cfg}	n_{src}
128	44	0.24	500	16
48	117	0.63	125	16
40	141	0.76	500	16
36	156	0.84	500	16
32	176	0.95	1000	16
28	201	1.09	1000	16
24	235	1.27	1000	16
20	281	1.52	576	16
16	352	1.90	1000	16

Charm action params from Hadspec: JHEP **1207** 126 (2012)

Spectral functions

- contain information about the fate of hadrons in the medium
  - stable states $\rho(\omega) \sim \delta(\omega - m)$
  - resonances or thermal width $\rho(\omega) \sim$ lorentzian
  - continuum above threshold

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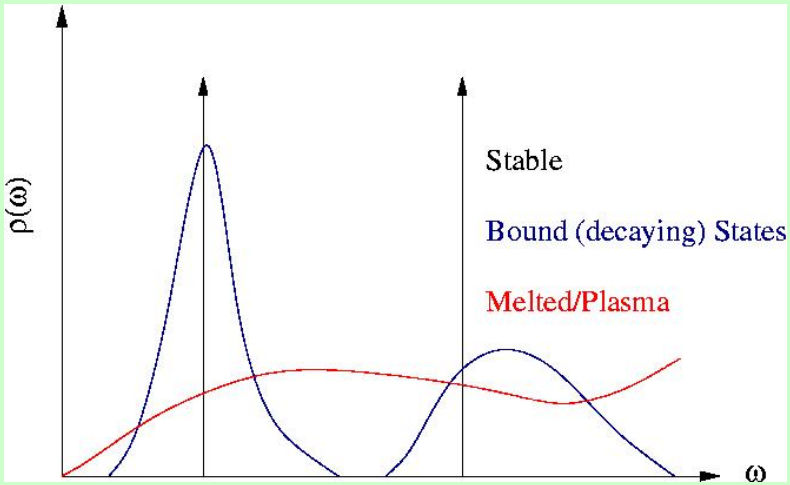

Spectral functions

- contain information about the fate of hadrons in the medium
  - stable states $\rho(\omega) \sim \delta(\omega - m)$
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  - continuum above threshold
- $\rho_\Gamma(\omega, \vec{p})$ related to euclidean correlator $G_\Gamma(\tau, \vec{p})$ according to

$$G_\Gamma(\tau, \vec{p}) = \int \rho_\Gamma(\omega, \vec{p}) K(\tau, \omega) d\omega\,, \quad K(\tau, \omega) = \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}$$

- an ill-posed problem — requires a large number of time slices
  - Fit to physically motivated Ansatz
  - Use Maximum Entropy Method or other Bayesian methods
  - Other inversion methods, eg Backus–Gilbert, Cuniberti

Spectral function reconstruction

Spectral function $\rho(\omega)$ is expressed in terms of default model $m(\omega)$

$$\rho(\omega) = m(\omega) \exp[\sum_{k=1}^{N_b} b_k u_k(\omega)]$$

Singular value decomposition:

$$K(\omega, \tau) \to K(\omega_i, \tau_j) = K_{ij} = U \Xi V^T$$

Standard MEM (SVD basis): u_k are column vectors of U:
$N_b = N_s \leq N_{\text{data}}$
Fourier basis: use N_b Fourier modes as u_k
BR method: Alternative prior instead of Shannon–Jaynes entropy:

$$S = \alpha \int d\omega \left(1 - \frac{\rho}{\omega} + \ln \frac{\rho}{\omega}\right)$$

and use full search space for $\rho(\omega)$

Reconstructed correlators

The systematic uncertainty of the spectral function can be avoided by studying the reconstructed correlator, defined as

$$G_r(\tau; T, T_r) = \int_0^\infty \rho(\omega; T_r) K(\tau, \omega, T) d\omega$$

where K is the kernel

$$K(\tau, \omega, T) = \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}$$

If $\rho(\omega; T) = \rho(\omega; T_r)$ then $G_r(\tau; T, T_r) = G(\tau; T)$

Small changes in correlators is compatible with large changes in spectral function [Mocsy&Petreczky (2007)]

Direct correlator reconstruction

[Ding et al (2012)]

With

$$T = \frac{1}{a_\tau N}, \; T_r = \frac{1}{a_\tau N_r}, \quad \frac{N_r}{N} = m \in \mathbb{N}$$

and using

$$\frac{\cosh\left[\omega(\tau - N/2)\right]}{\sinh(\omega N/2)} = \sum_{n=0}^{m-1} \frac{\cosh\left[\omega(\tau + nN + mN/2)\right]}{\sinh(\omega mN/2)}$$

we have

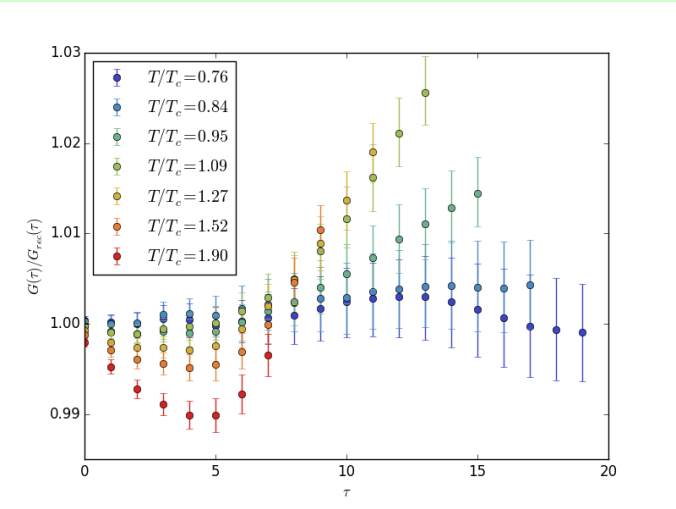
$$G_r(\tau; T, T_r) = \sum_{n=0}^{m-1} G(\tau + nN, T_r)$$

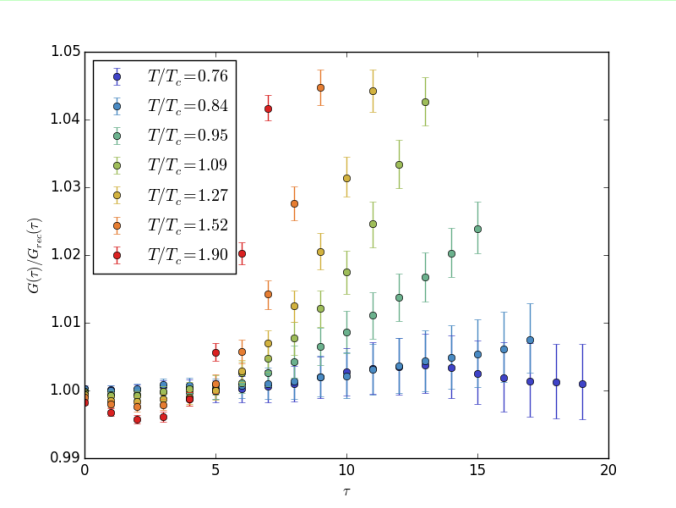
Charm

[Results from PRD **97** (2018) 114509, PoS **(Confinement2018)** 272]

- J/ψ suppression — a probe of the quark–gluon plasma? [Matsui & Satz 1986]
- c quarks created in primordial collisions, hard probes?
- To what extent do c quarks thermalise?
- How reliable are quenched lattice simulations?
- Are potential models valid?

Charmonium: reconstructed correlators

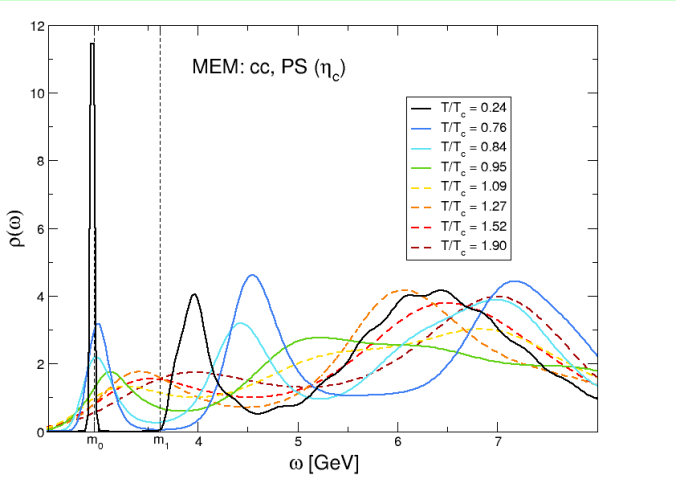


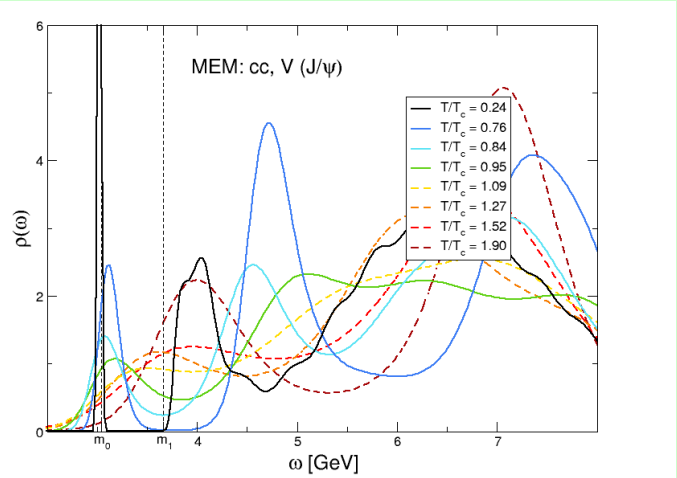


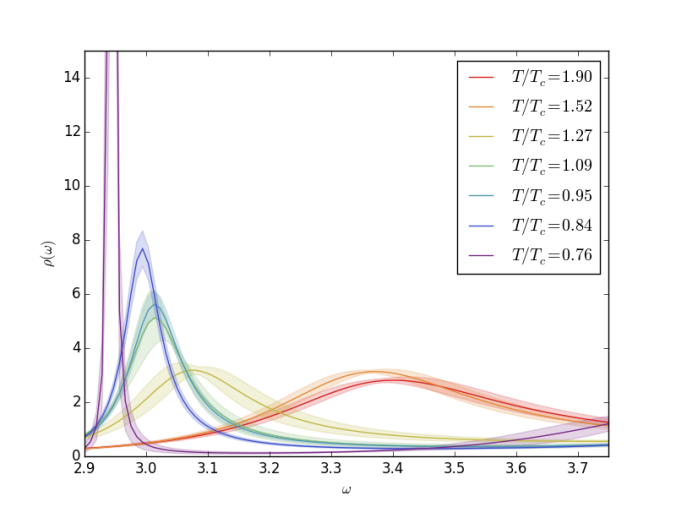
Top: pseudoscalar (η_c)
Bottom: vector (J/ψ)

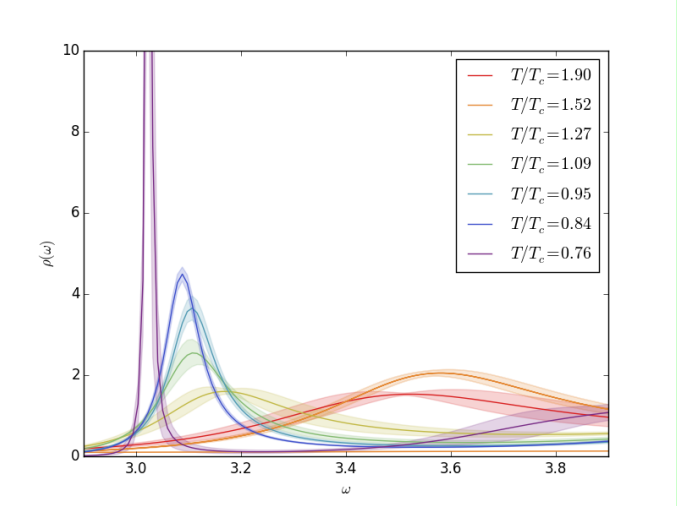
- $T \lesssim T_c$ consistent with no change
- Small but significant modifications above T_c
- P-wave analysis in progress

Charmonium spectral functions: S-waves

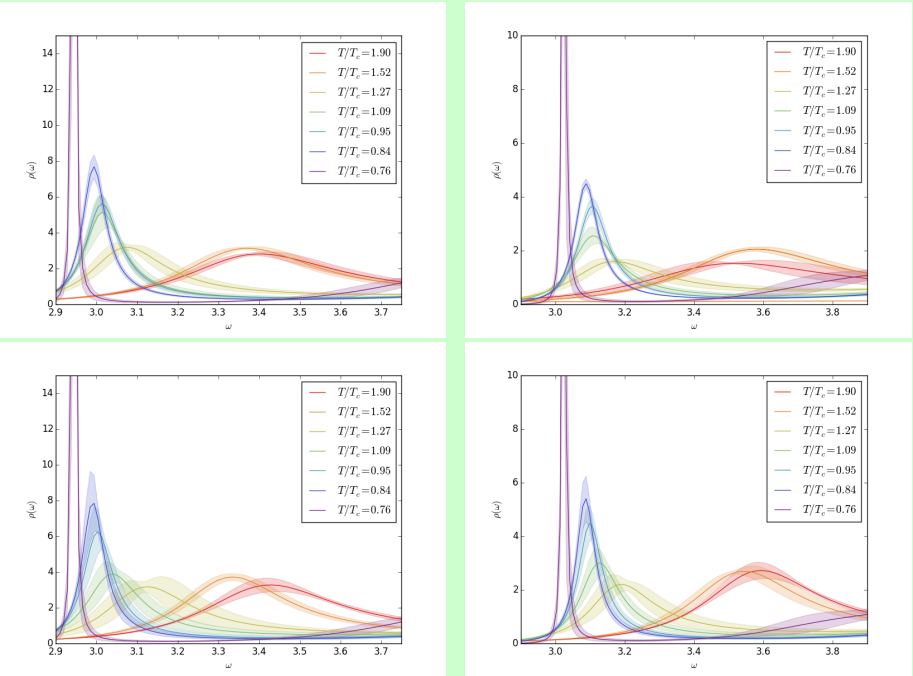








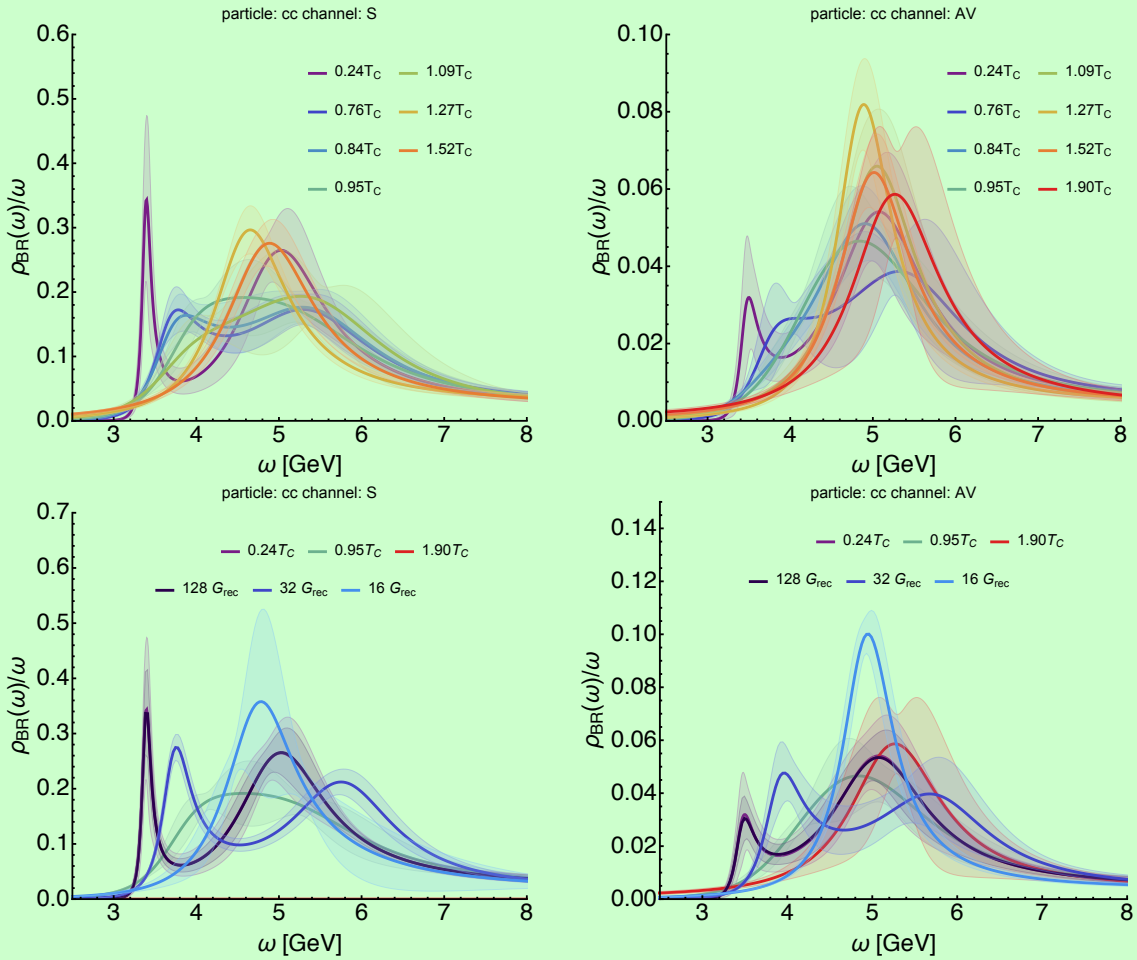
Comparison with reconstructed correlators



Left: pseudoscalar
Right: vector
Bottom: Reconstructed corrs

- Consistent with no change below T_c
- Possible weakening or melting at $1.9\,T_c$

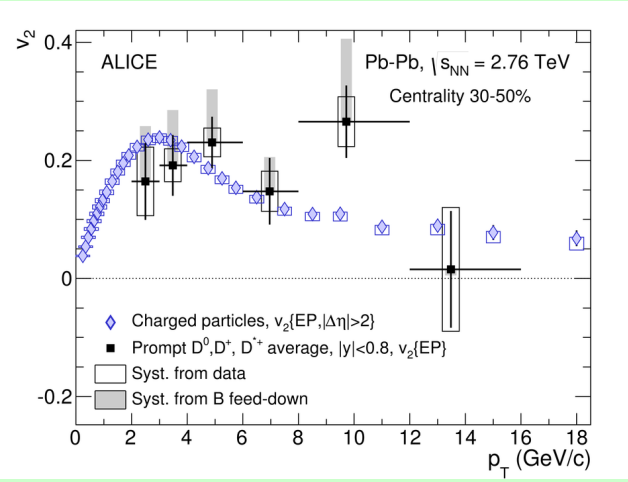
Charmonium spectral functions: P-waves

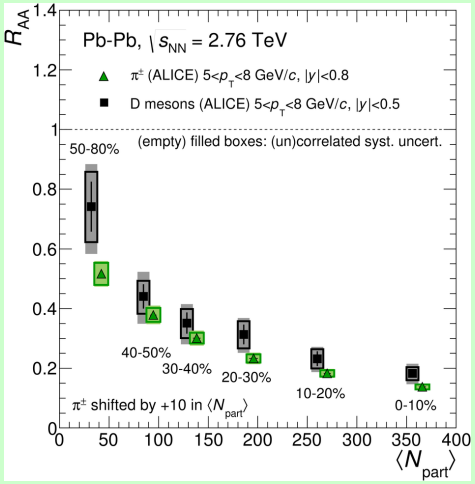


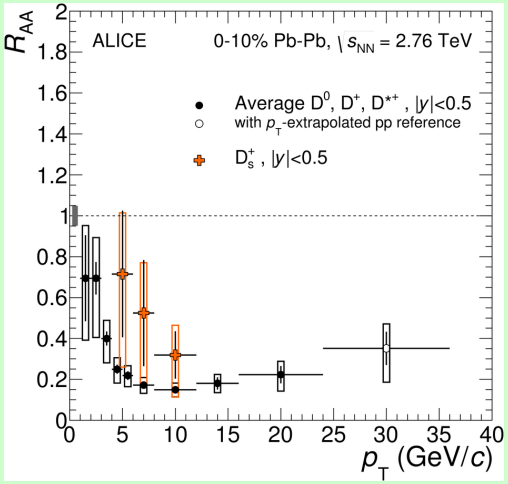
Data suggest that P-waves dissociate at $T \lesssim T_c$

Why D mesons?

Experimental interest in open heavy flavour in A–A collisions:







Why D mesons?

Open and hidden charm

Cannot study $c\bar{c}$ in isolation from open charm

- Recombination at freeze-out
- Increased yield of D mesons relative to J/ψ?
- Double ratio better measure than R_{AA}?
- Thermal modifications of D mesons may be important
- Charm quark diffusion $\leftrightarrow$ D meson flow

Open charm — issues

Open charm

- Increased experimental interest in open charm
- Suggestions of D meson survival in QGP?
- Modifications of yields of open charm states?
- Increased D_s/D ratio (strangeness enhancement)?

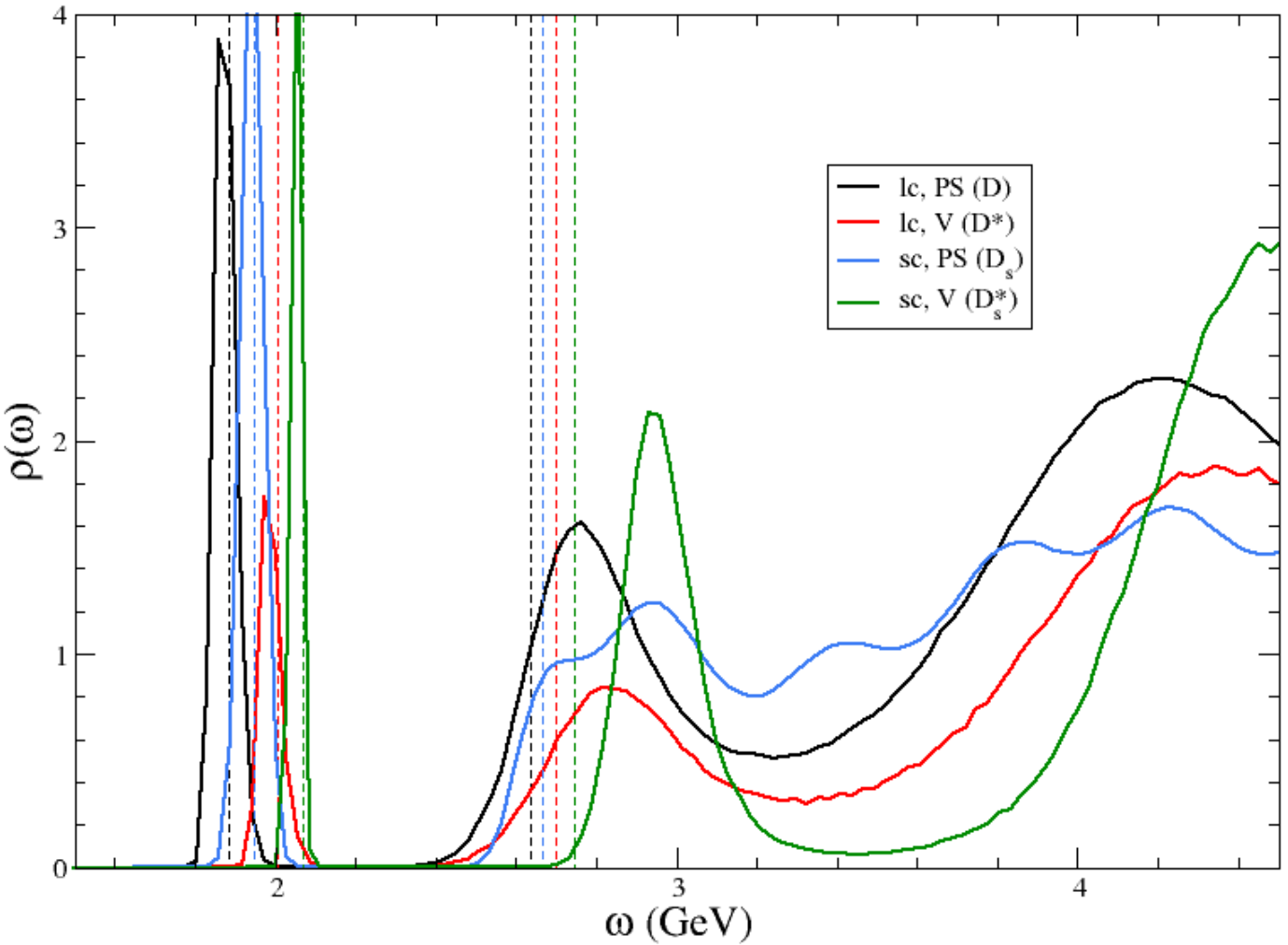
Open charm from the lattice

Very few studies so far:

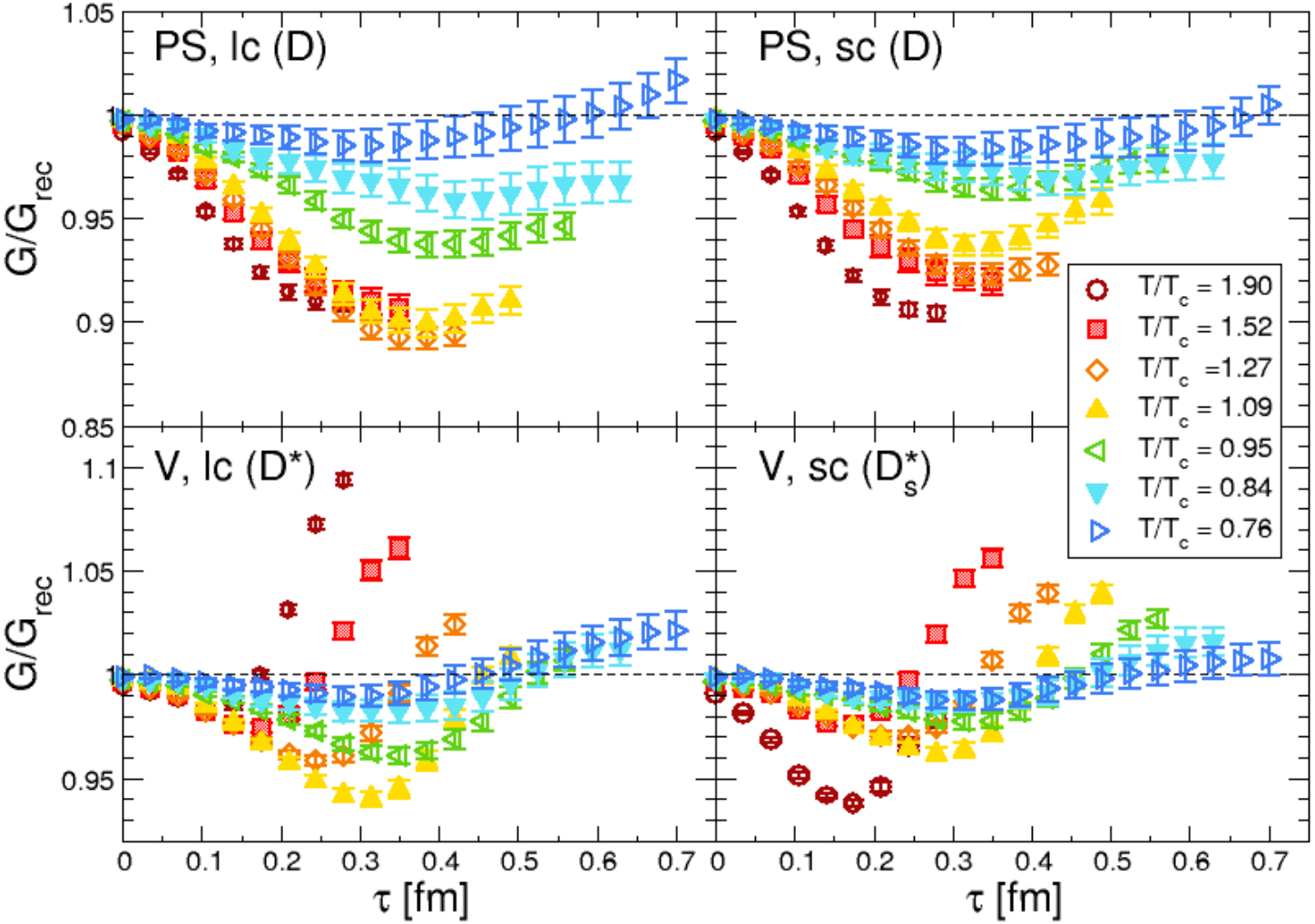
- Cumulants [Bazavov et al, Mukherjee et al (2015)]
- Screening correlators [Bazavov et al (2014)]

May contribute up to $1.2\,T_c$?

Zero temperature spectral functions



Reconstructed correlators



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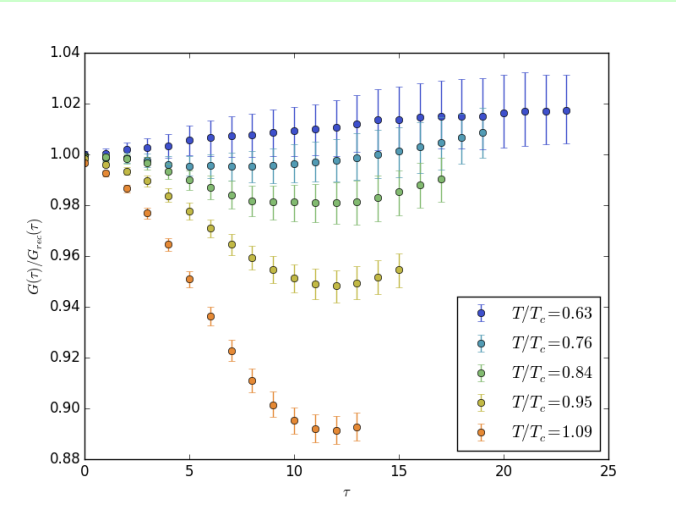
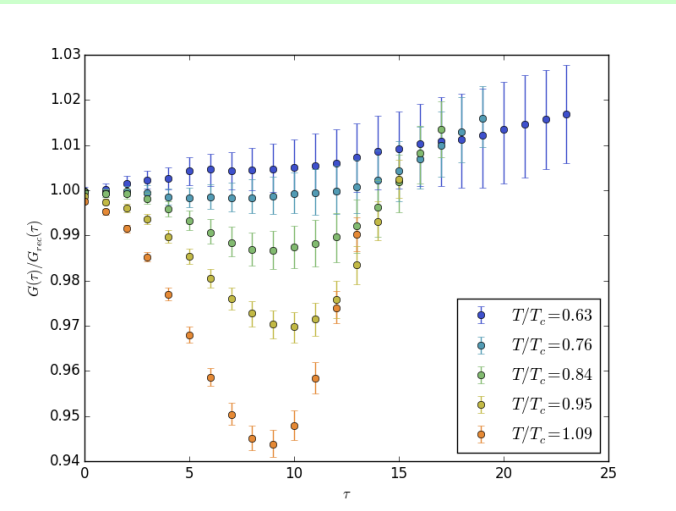
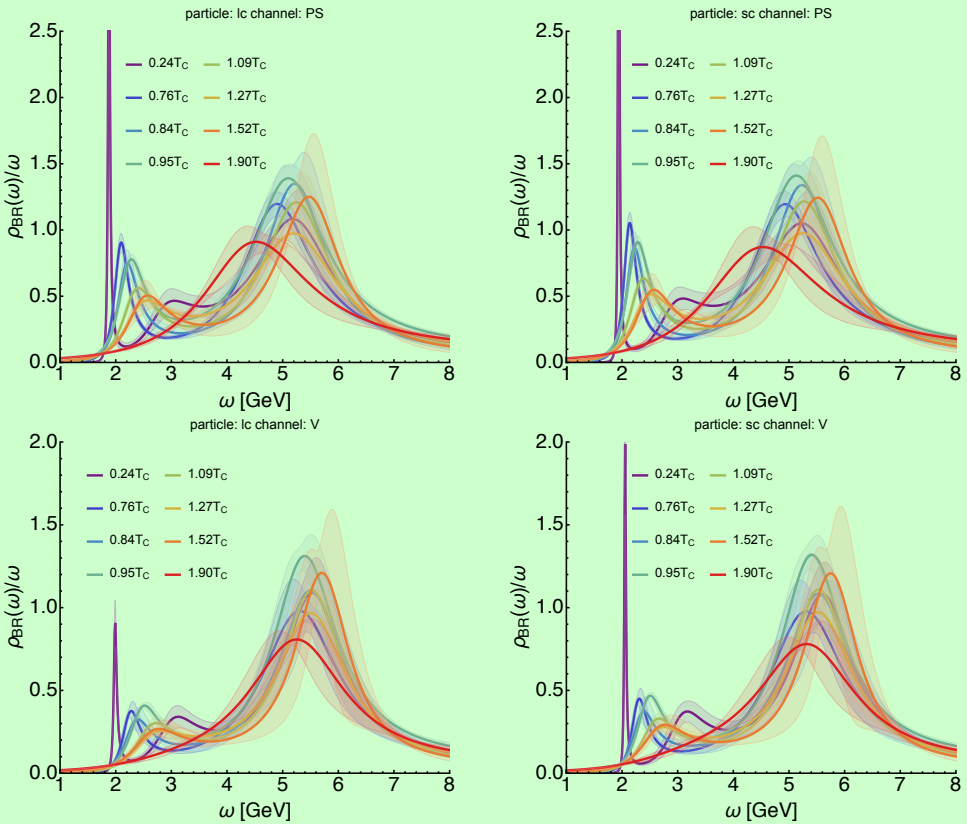




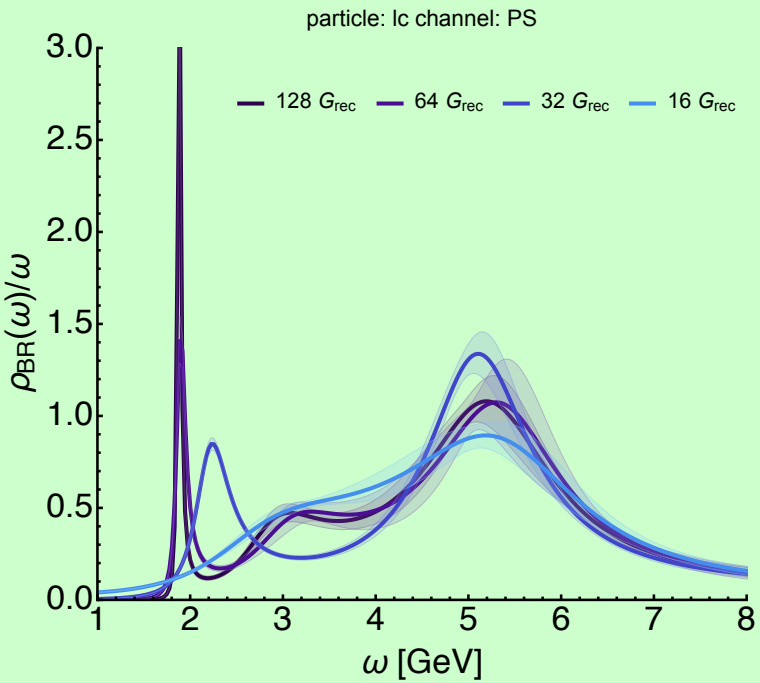
- Significant changes for $T \gtrsim T_c$
- Modifications below T_c?
- Smaller for D_s
- Transport contribution in V channel?

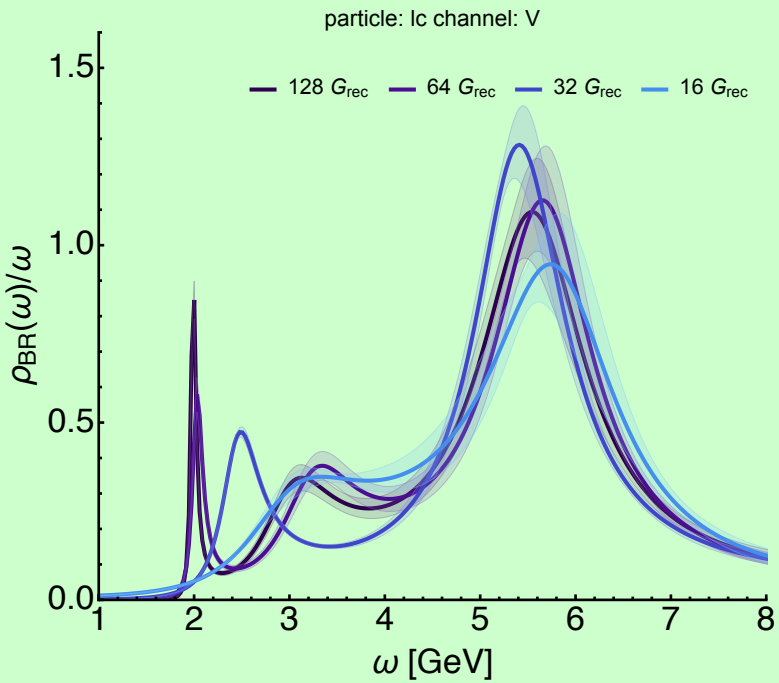
Open charm: spectral functions from BR



- Systematic peak shift and weakening
- No sign of non-monotonic mass shift
- No qualitative change at T_c?

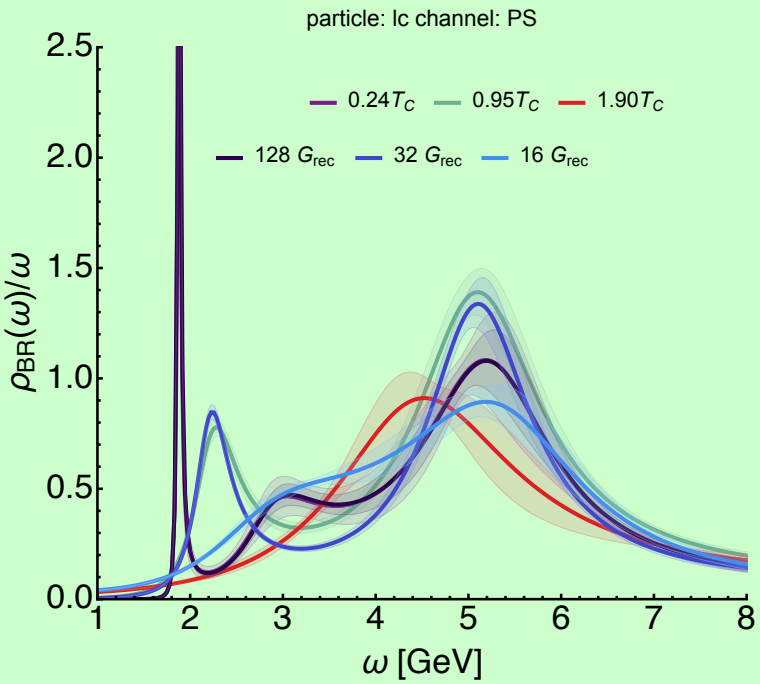
Spectral functions from reconstructed correlators

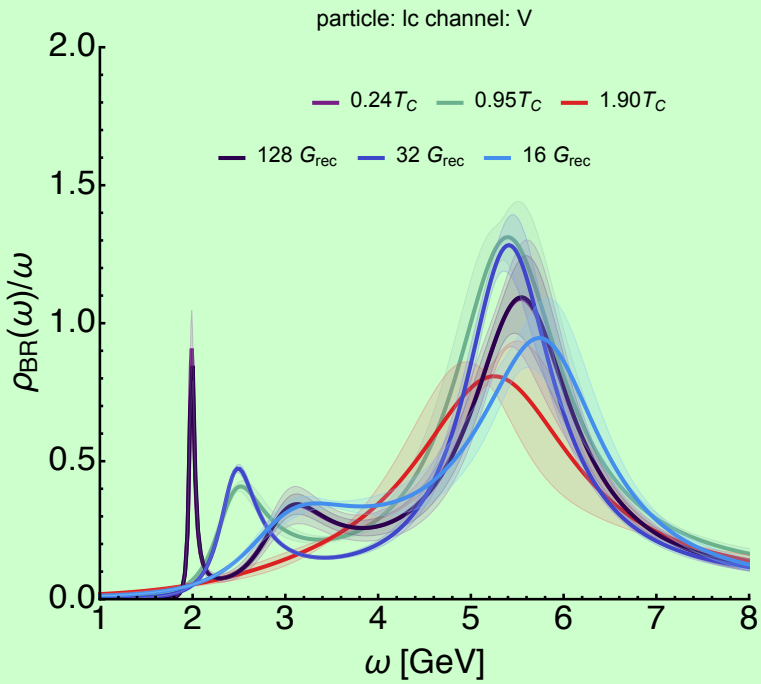




Systematic shift and weakening is an effect of the reduced temporal extent!

Comparison of reconstructed and thermal correlators





- No significant modification below T_c
- Clear difference at $T \approx 1.9\,T_c$

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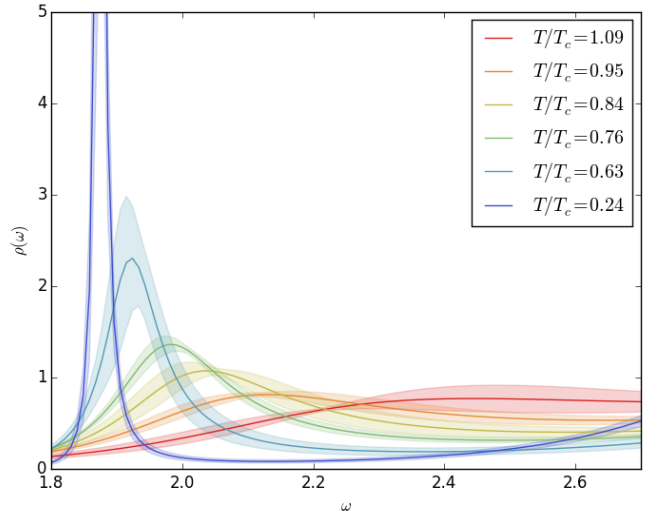
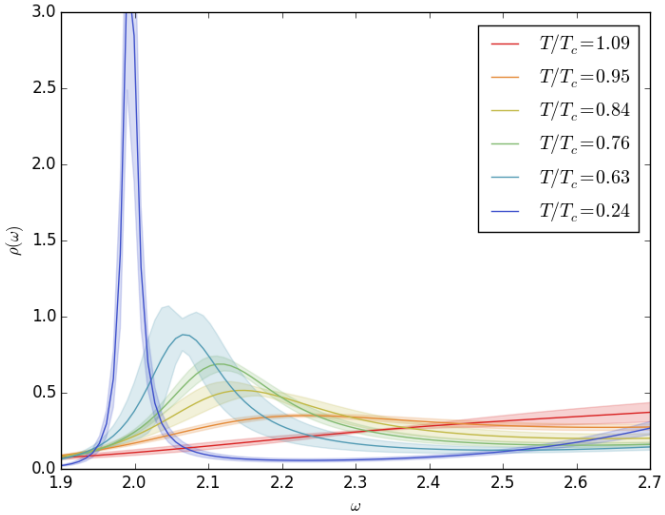
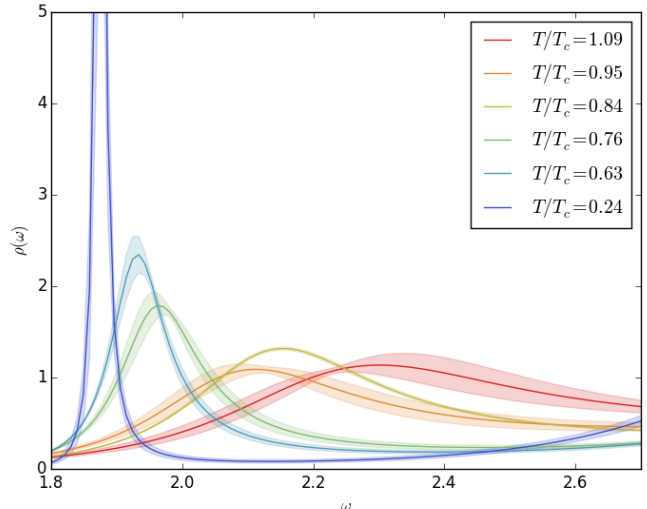
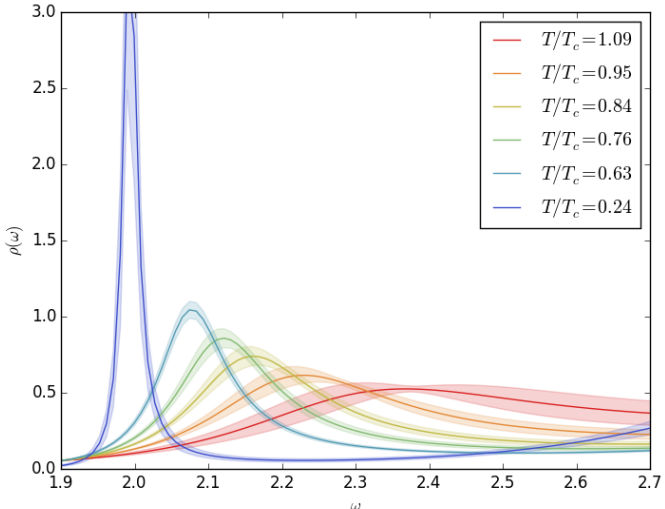




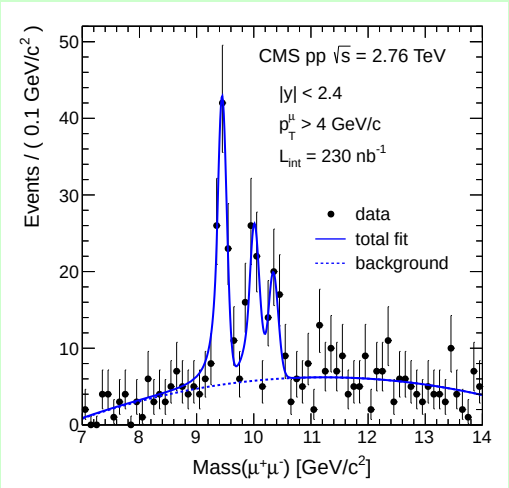


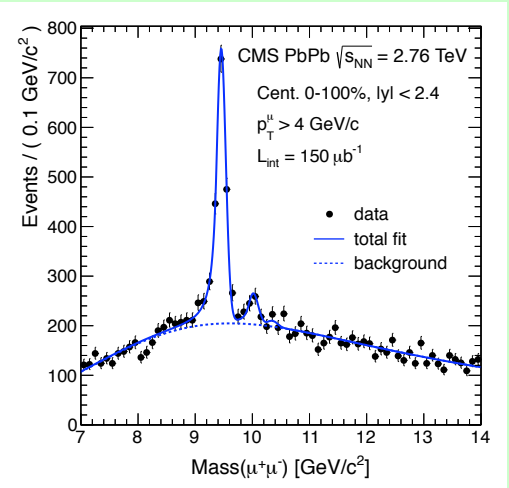


Beauty (and the beast?)

[JHEP **1407** (2014)097]

- Many b quarks are produced at LHC
- Cold nuclear matter effects, recombination less important
  $\rightarrow$ cleaner probes?
- $T_d^{\Upsilon} \sim 3 - 5\,T_c$ — hard to do on the lattice
- $\chi_b, \Upsilon(2S)$ melt at $T_d' \lesssim 1.2\,T_c$?
- Sequential suppression observed at CMS (+ ATLAS, STAR)?





NRQCD

Scale separation $M_Q \gg T, M_Q v$

Integrate out hard scales $\longrightarrow$ Effective theory

Expand in orders of heavy quark velocity $\mathbf{v}$; we use $\mathcal{O}(\mathbf{v}^4)$ action

Advantages

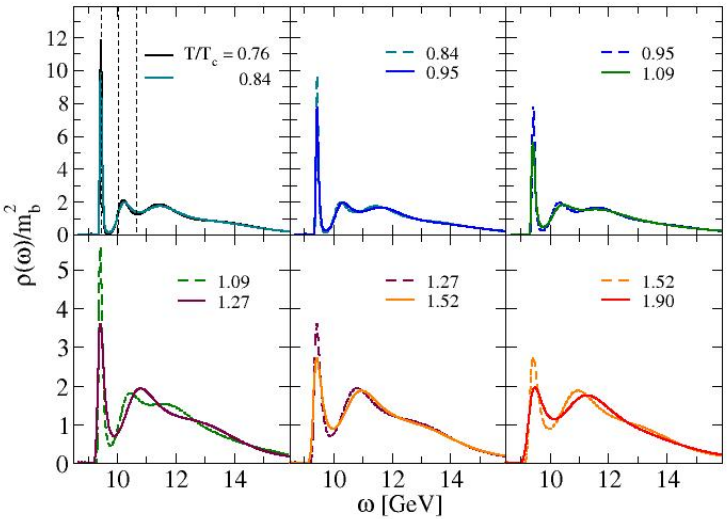
- No temperature-dependent kernel, $G(\tau) = \int \rho(\omega) e^{-\omega\tau} \frac{d\omega}{2\pi}$
- No zero-modes
- Longer euclidean time range
- Appropriate for probes not in thermal equilibrium

Disadvantages

- Not renormalisable, requires $Ma_s \gtrsim 1$
- Does not incorporate transport properties

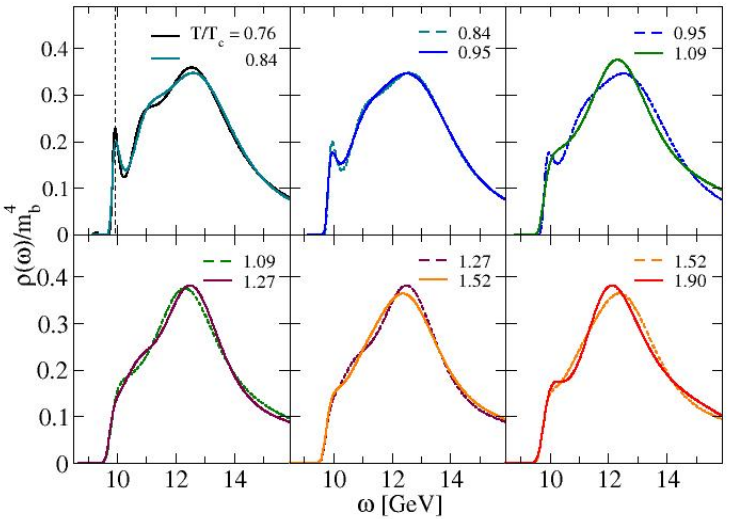
Spectral functions — MEM analysis

S-waves



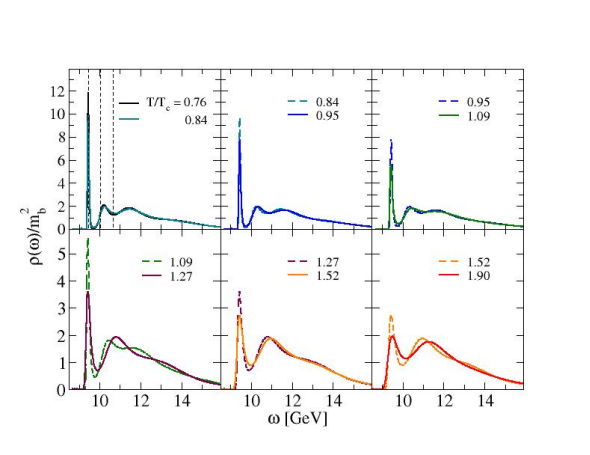
Υ (2S) melts, but ground state remains robust

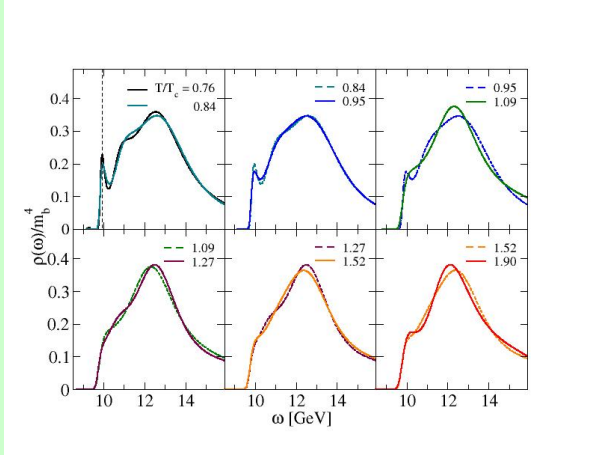
P-waves

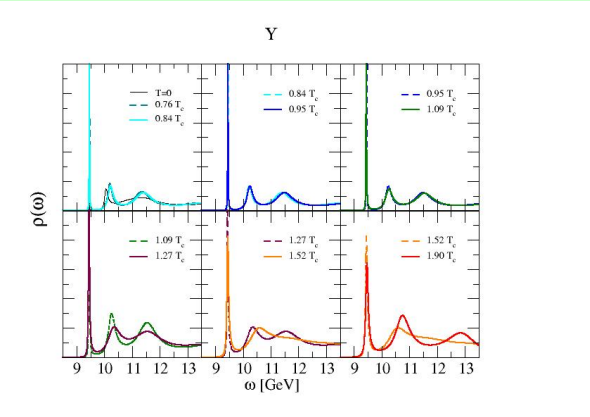


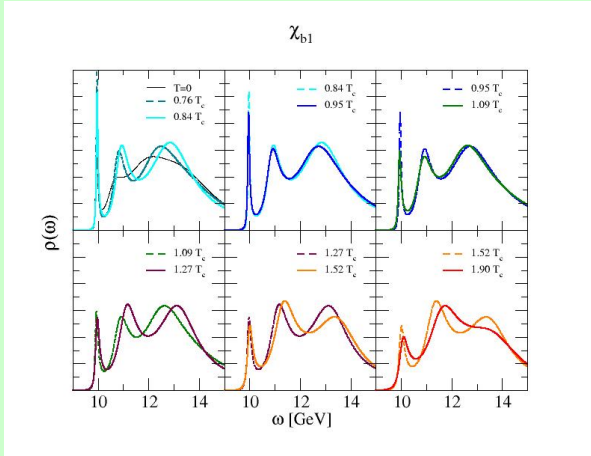
P-waves dissociate close to T_c

MEM vs BR method









Known discrepancy: BR produces more peak structures
Smoothed BR [1808.08781] or other methods may resolve this

Summary and outlook

Summary

- Charmonium correlators show thermal modifications near T_c
- Spectral functions consistent with vacuum until $\sim 1.3 T_c$

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- First lattice study of open charm temporal correlators and spectral functions
- Thermal modifications already below T_c
- No sign of surviving bound states above T_c?

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Outlook

- Simulations with lighter u, d quarks underway
- Open beauty in progress
- Repeat with smaller a_τ