Thermal D mesons from lattice QCD

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FASTSUM collaboration

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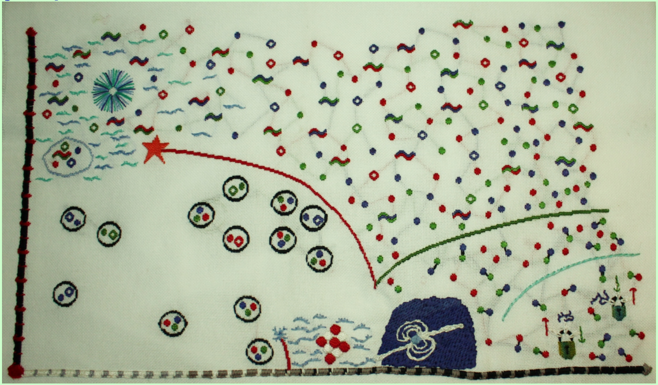
Outline

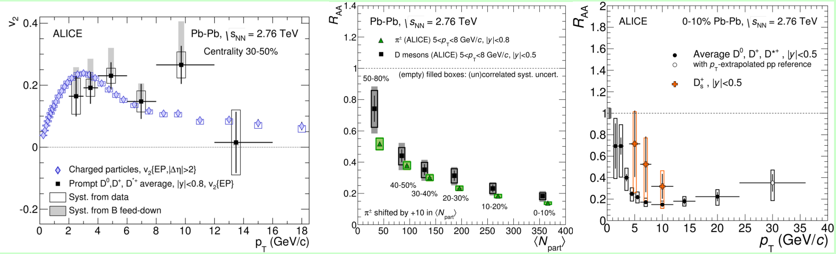
Why open charm?



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

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 $1.2T_c$?

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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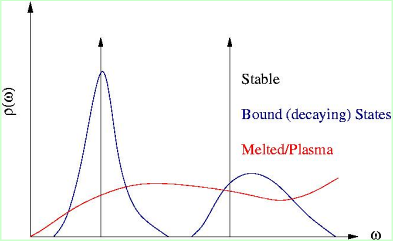


Spectral functions

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

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}
128	44	0.24	500
40	141	0.76	500
36	156	0.84	500
32	176	0.95	1000
28	201	1.09	1000
24	235	1.27	1000
20	281	1.52	576
16	352	1.90	1000

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

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:

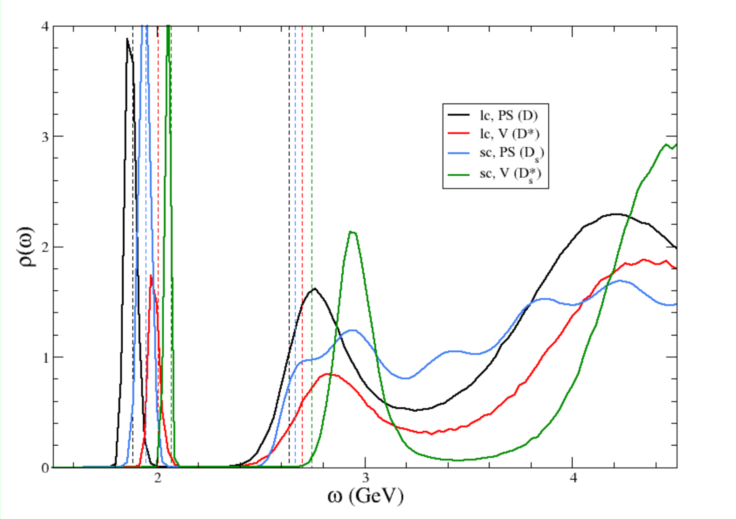
$$K(\omega, \tau) \to K(\omega_i, \tau_j) = K_{ij} = U \Xi V^T$$

Standard MEM (SVD basis): u_k are column vectors of U:
$N_b = N_s \leq N_{\text{data}}$
Extended basis: use N_{ext} additional column vectors of U
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 $\rho(\omega)$

Zero temperature spectral functions



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

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

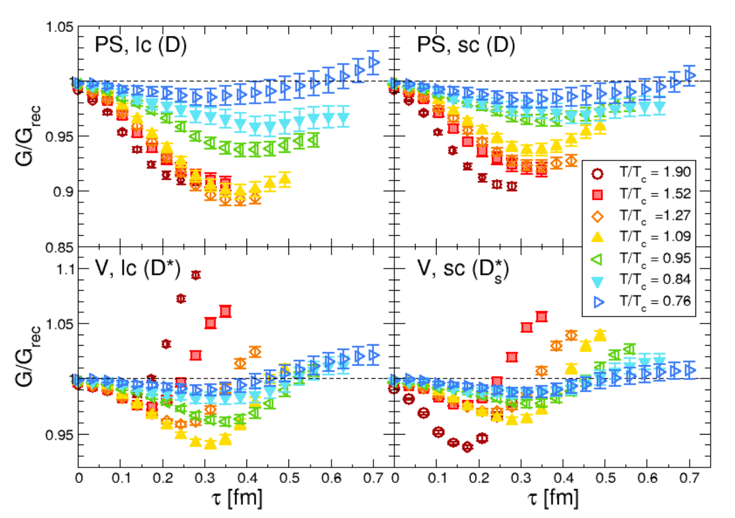
and using

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

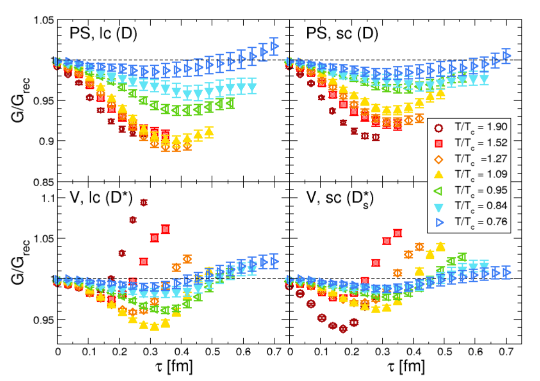
we have

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

Reconstructed correlators

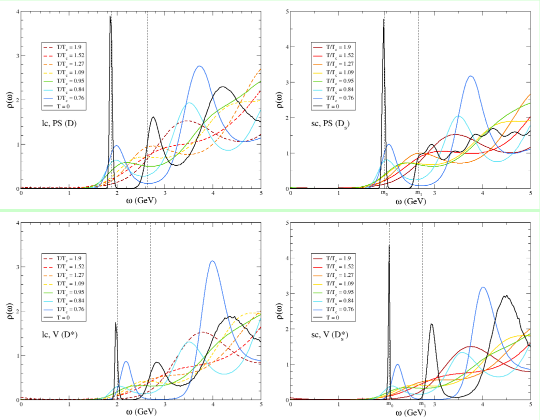


Reconstructed correlators



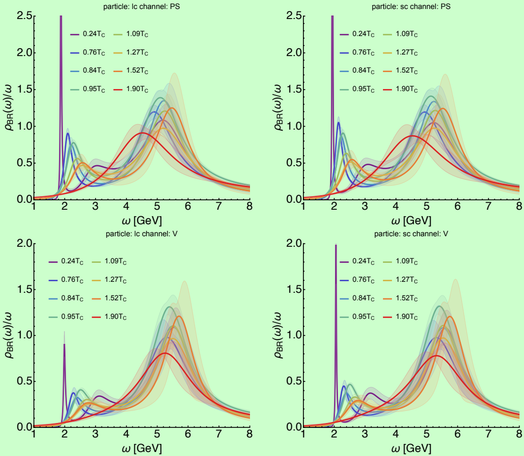
- Significant changes for $T \gtrsim T_c$
- Modifications below T_c?
- Smaller for D_s
- Transport contrib in V channel?

Open charm: spectral functions from MEM



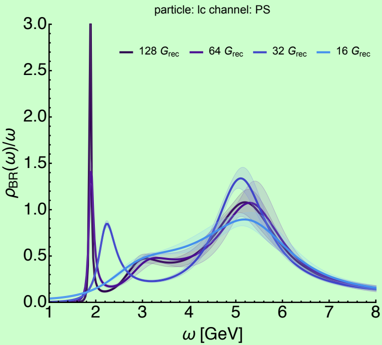
- Both D and D_s mesons dissociate close to T_c
- Thermal mass shift below T_c?
  — stronger in vector channel?

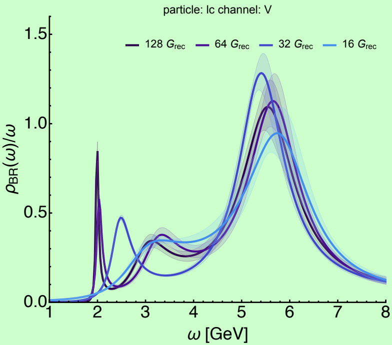
Open charm: spectral functions from BR



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

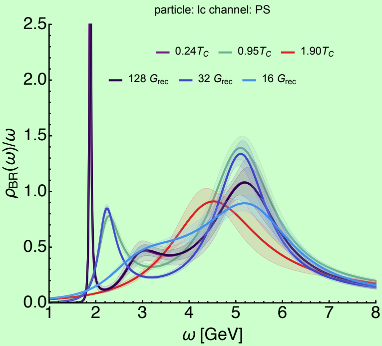
Spectral functions from reconstructed correlators





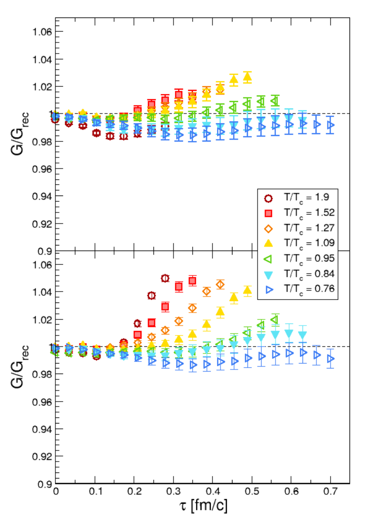
Systematic shift and weakening is an effect of the reduced temporal extent!

Comparison of reconstructed and thermal correlators



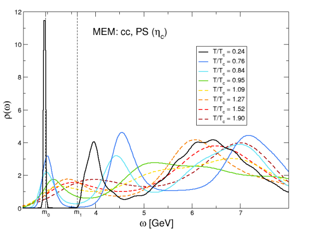
- No significant modification below T_c
- Clear difference at $T \approx 1.9\,T_c$

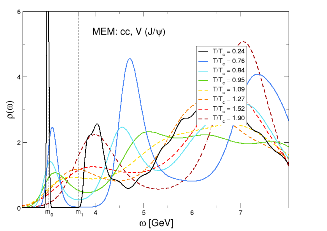
Charmonium: reconstructed correlators

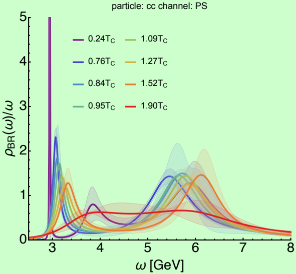


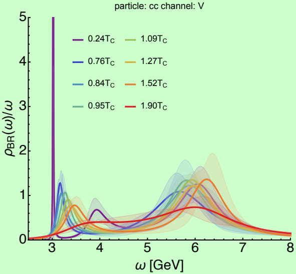
- $T \lesssim T_c$ consistent with no change
- Much smaller modifications above T_c
- P-wave analysis in progress

Charmonium spectral functions: S-waves

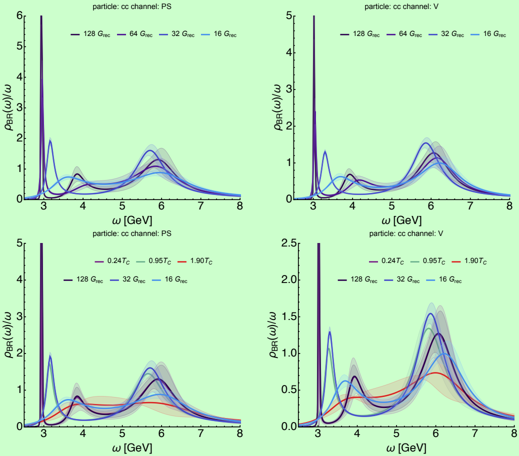






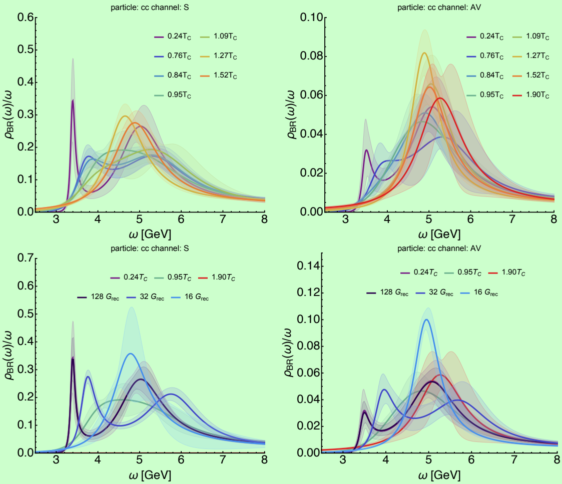


Comparison with reconstructed correlators



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

Charmonium spectral functions: P-waves



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

Summary and outlook

Summary

- First lattice study of open charm temporal correlators and spectral functions
- Thermal modifications already below T_c
- Possible thermal mass shift observed in MEM analysis?
- No sign of thermal mass shift in BR analysis
- No sign of surviving bound states above T_c?

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Outlook

- Improved statistics
- Repeat with smaller a_τ
- Open beauty?