Thermal D mesons from anisotropic lattice QCD

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FASTSUM collaboration

Quark Confinement and the Hadron Spectrum, $\Theta\epsilon\sigma\sigma\alpha\lambda o\nu\iota\kappa\eta$
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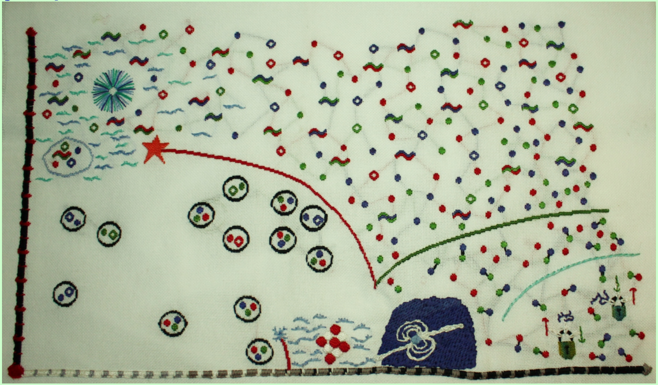
Outline

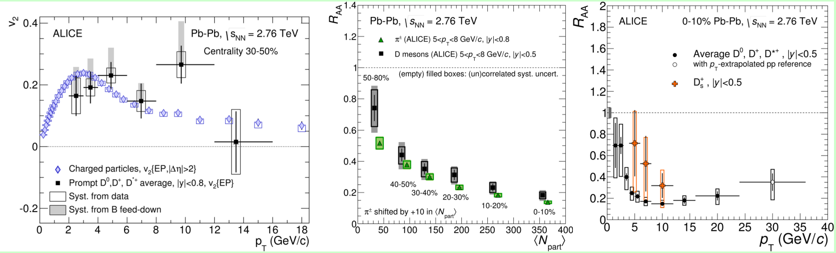
Why open charm?



- 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:
Talks by Elisa Mennino (Mon), Shingo Sakai (Tue)



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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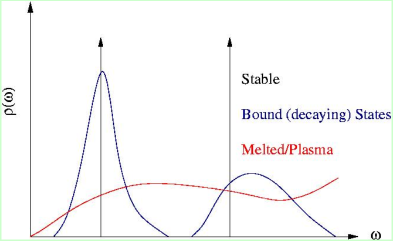

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- $\rho_\Gamma(\omega, \vec{p})$ related to euclidean correlator $G_\Gamma(\tau, \vec{p})$ according to

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

- 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

Lattice simulations

- QGP near crossover is strongly interacting: nonperturbative methods required
- Equilibrium thermal field theory formulated in euclidean space — suitable for Monte Carlo simulations

$$\langle \mathcal{O} \rangle = \int \mathcal{D}[\Phi]\mathcal{O}[\Phi]e^{-S[\Phi]}$$

- Temperature $T = \frac{1}{L_\tau} = (N_\tau a_\tau)^{-1}$
- 2+1 active light flavours required for quantitative predictions!

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 $m(\omega)$

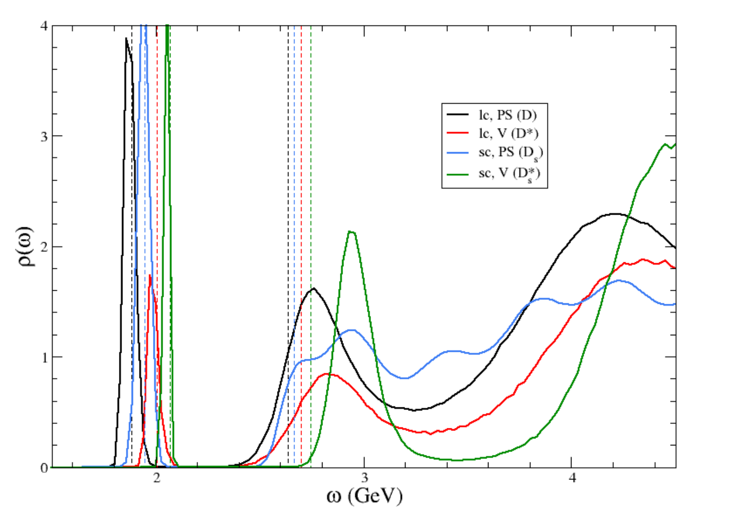
$$\rho(\omega) = m(\omega) \exp[\sum_{k=1}^{N_b} b_k u_k(\omega)]$$

Singular value decomposition:

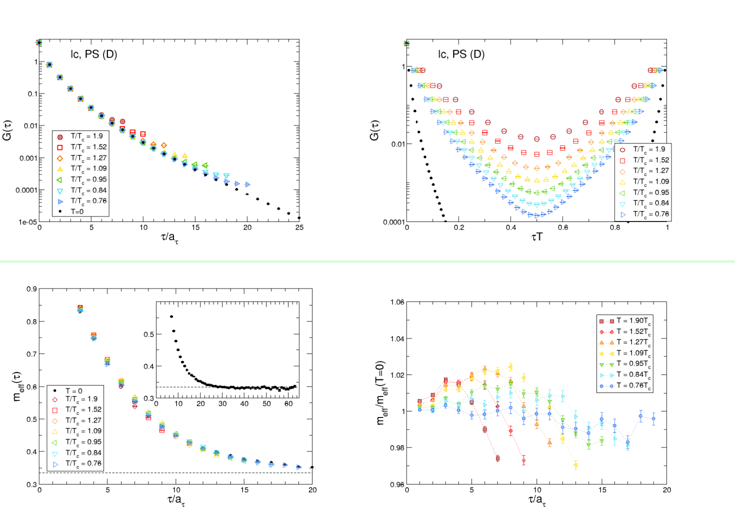
$$K(\omega, \tau) \to K(\omega_i, \tau_j) = K_{ij} = U \Xi V^T$$

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
Using MEM analysis code from Alexander Rothkopf

Zero temperature spectral functions



D meson correlators



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

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

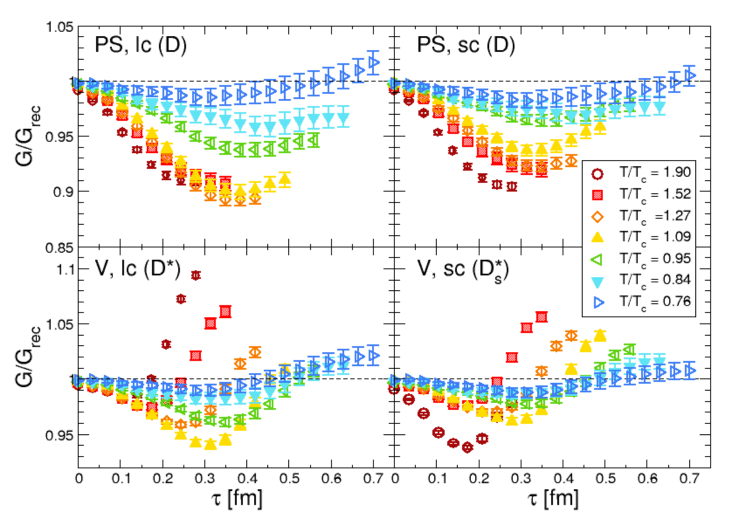
and using

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

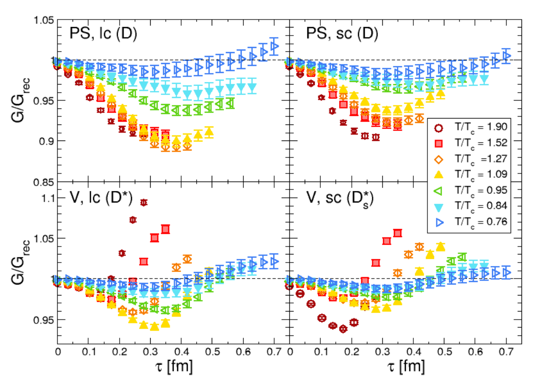
we have

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

Reconstructed correlators



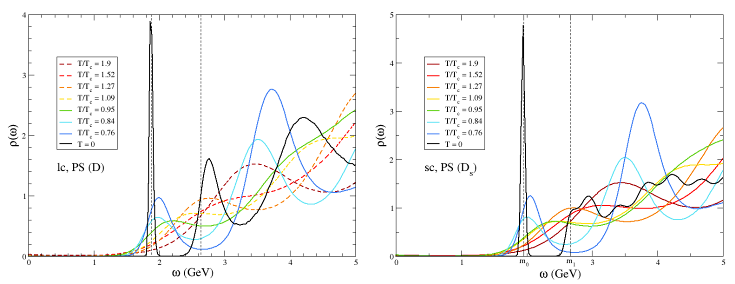
Reconstructed correlators



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

Open charm: spectral functions

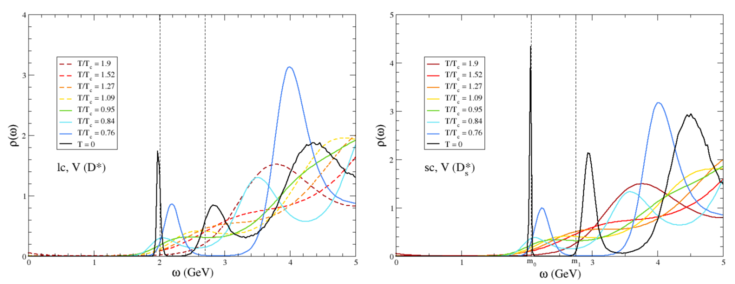
Pseudoscalar channel



- Both D and D_s mesons dissociate close to T_c
- Thermal mass shift below T_c?

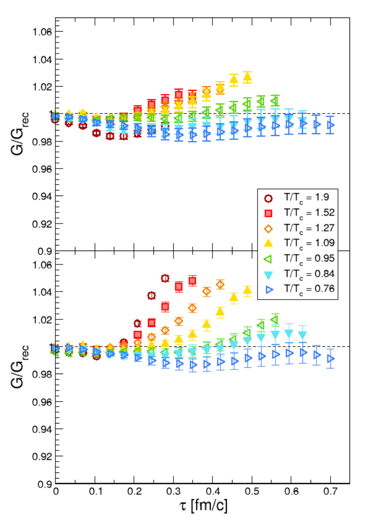
Open charm: spectral functions

Vector channel



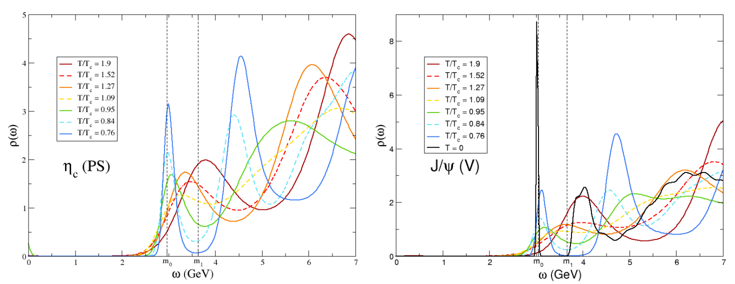
- Thermal mass shift stronger in vector channel?

Charmonium: reconstructed correlators



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

Charmonium


η_c (PS)
J/ψ (V)
$\rho(\omega)$
ω (GeV)
m_0
m_1
$T/T_c = 1.9$
$T/T_c = 1.52$
$T/T_c = 1.27$
$T/T_c = 1.09$
$T/T_c = 0.95$
$T/T_c = 0.84$
$T/T_c = 0.76$
$T = 0$

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?
- No sign of surviving bound states above T_c

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Outlook

- Complete study of MEM systematics
- Improved statistics
- Repeat with smaller a_τ
- Open beauty?