Hadrons at high T

Jon-Ivar Skullerud
with special thanks to Aoife Kelly, Eoghan Murphy, Ryan Quinn

National University of Ireland Maynooth
FASTSUM collaboration

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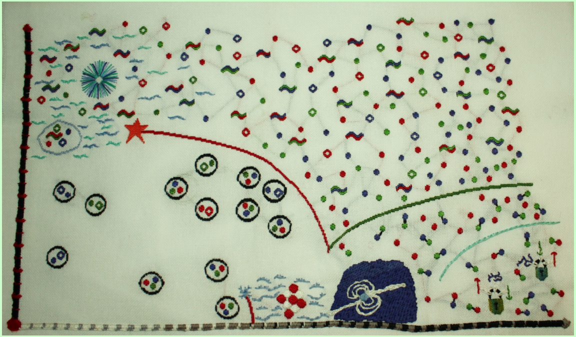
Outline

Hadrons at high T



- Light hadron masses — essential ingredient in HRG
- 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, 3.94

N_τ	T (MeV)	T/T_c	N_{cfg}
128	44	0.24	500
48	117	0.63	250
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	1000
16	352	1.90	1000

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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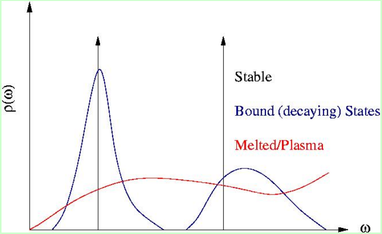


Spectral functions

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

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:

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

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

[Meyer (2010), 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

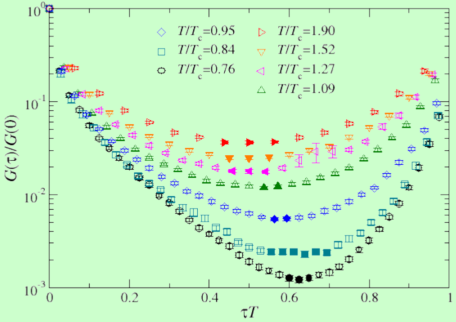
$$\frac{\cosh\left[\omega(\tau - N/2)\right]}{\sinh(\omega N/2)} = \sum_{n=0}^{m-1} \frac{\cosh\left[\omega(\tau + nN + mN/2)\right]}{\sinh(\omega m N/2)}$$

we have

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

Light baryons[PRD**92**(2015)014503; JHEP**1706**034; PRD99(2019)074503]

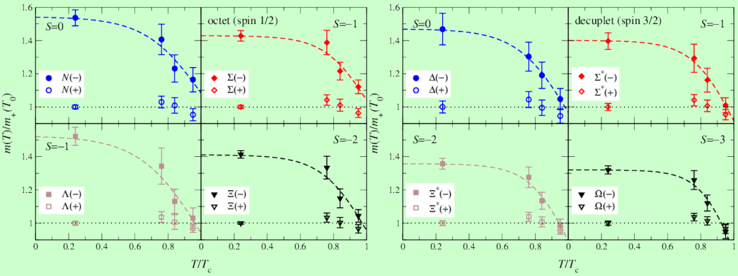
Positive and negative parity states encoded in same correlator



Forward propagating: + parity; Backward propagating: − parity

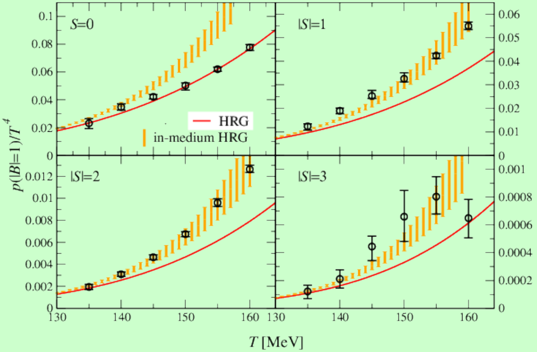
Using smeared (extended) sources to enhance ground state overlaps

Baryon mass modifications



- Positive parity ground state masses unaffected by T up to T_c
- Negative parity masses decrease
- Parity restoration near T_c?

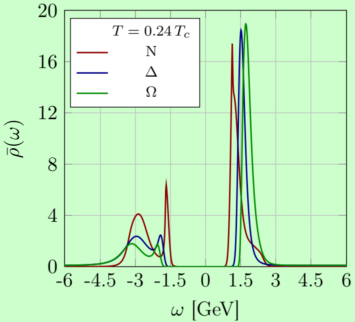
Hadron resonance gas

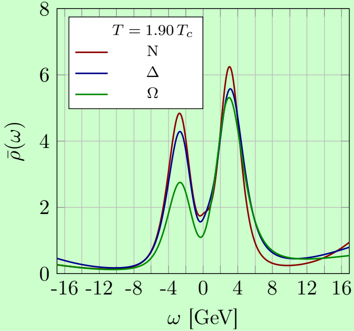


Data points from BW collaboration

Note mismatch in quark masses

Spectral functions





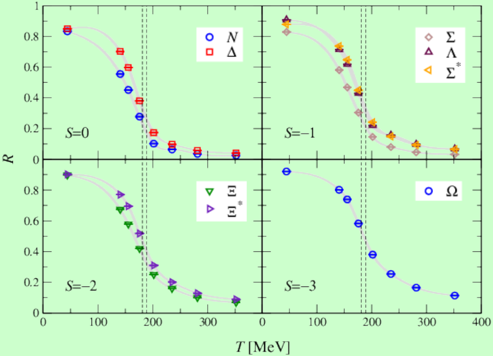
Agreement with correlator analysis, parity doubling at hit T

Parity restoration

Measure of parity restoration:

$$R(\tau) = \frac{G(\tau) - G\beta - \tau)}{G(\tau) + G(\beta + \tau)}$$

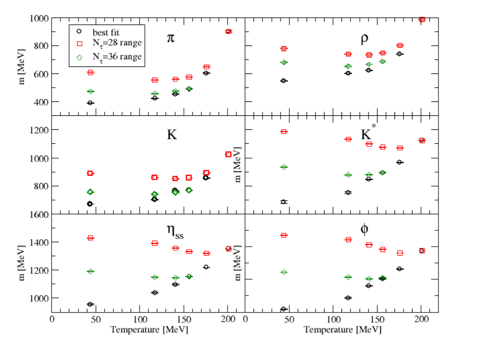
$$R = \frac{\sum_{n=0}^{\beta/2-1} R(\tau_n)/\sigma^2(\tau_n)}{\sum_{n=0}^{\beta/2-1} 1/\sigma^2(\tau_n)}$$



Parity restoration crossover slightly below deconfinement, consistent with chiral crossover

Light mesons

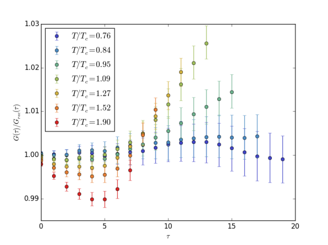
- Simplistic single-state fit
- High-T fit ranges
- Not shown:
  - two-state fits
  - spectral reconstruction
- Mass reduction or excited state suppression

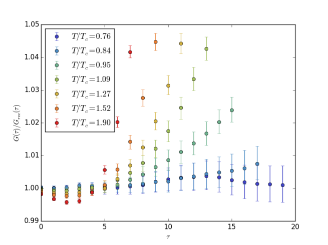


Charm

- J/ψ suppression — a probe of the quark–gluon plasma? [Matsui & Satz 1986]
- Quantitative results for broadening and melting?
- To what extent do c quarks thermalise?
- How reliable are quenched lattice simulations?
- Are potential models valid?

Charmonium: reconstructed correlators

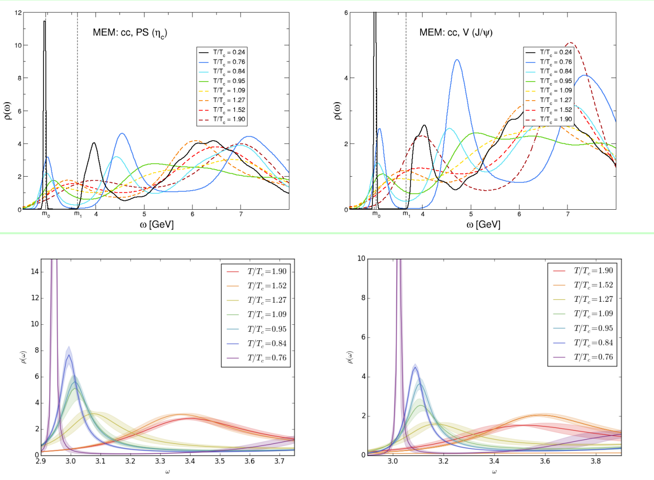




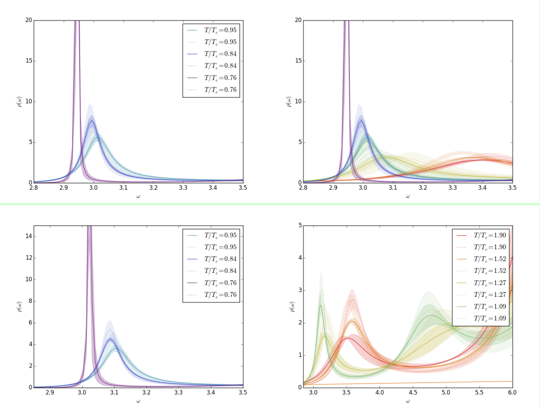
Top: pseudoscalar (η_c)
Bottom: vector (J/ψ)

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

Charmonium spectral functions: S-waves



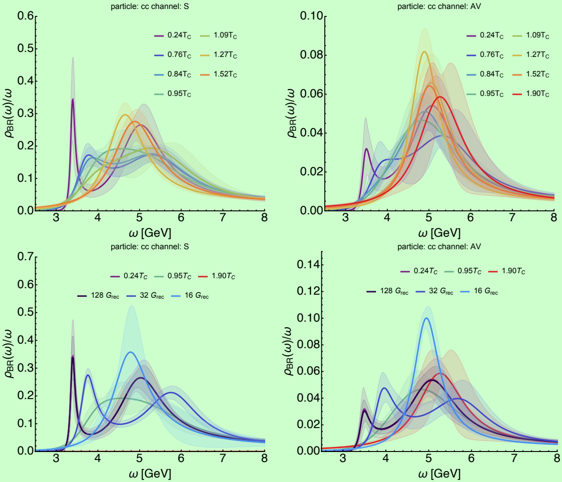
Comparison with reconstructed correlators



Top: pseudoscalar
Bottom: vector

- Consistent with no change below T_c
- Possible weakening or melting for $T \gtrsim 1.5 T_c$

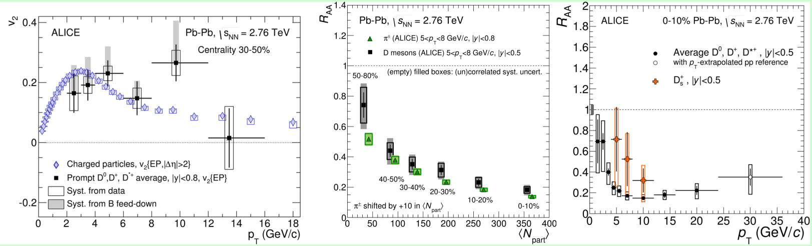
Charmonium spectral functions: P-waves



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

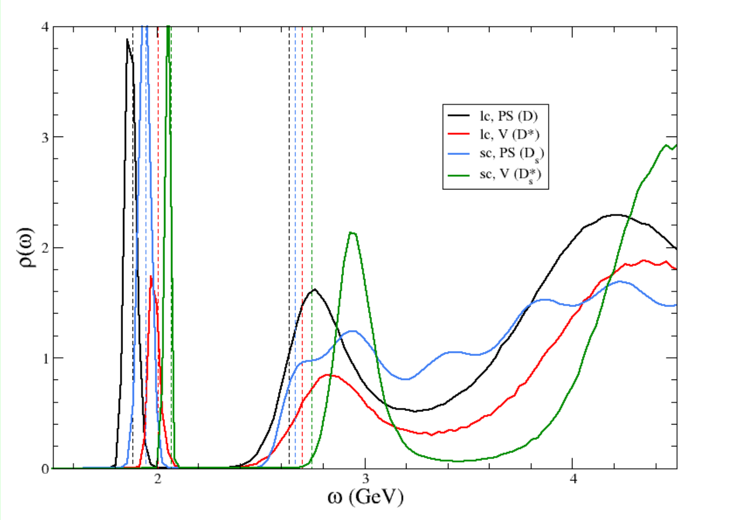
Cannot study $c\bar{c}$ in isolation from open charm

- Recombination at freeze-out
- Increased yield of D mesons relative to J/ψ?
  $\longrightarrow R_{AA}$ vs $\frac{[N(J/\psi)/N(D)]_{AA}}{[N(J/\psi)/N(D)]_{pp}}$
- Thermal modifications of D mesons may be important
- Charm quark diffusion $\leftrightarrow$ D meson flow

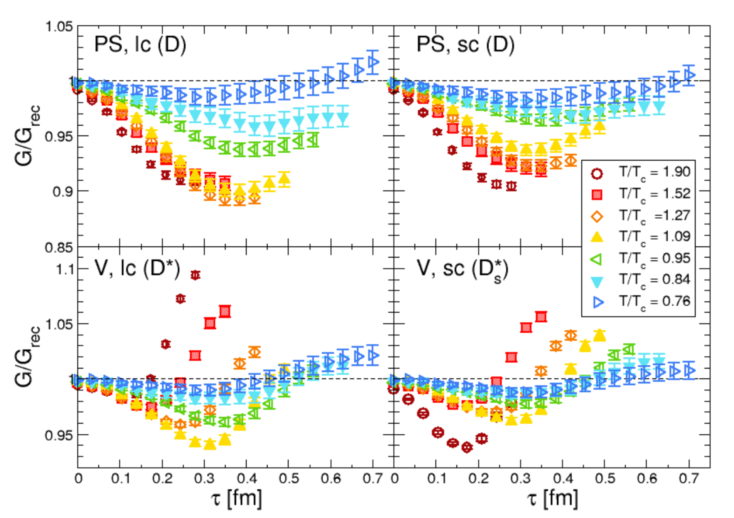
Open charm — issues

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

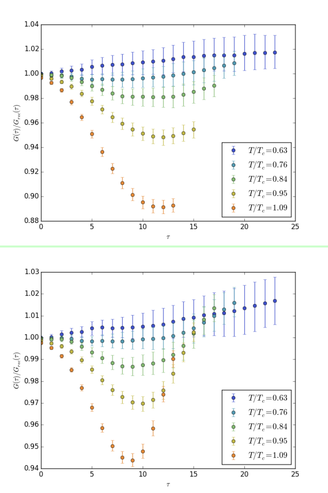
Zero temperature spectral functions



Reconstructed correlators



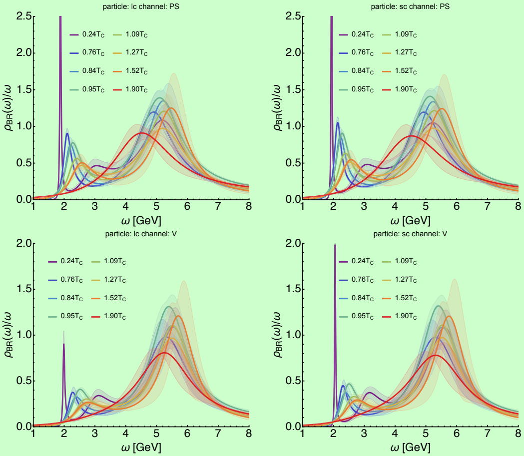
Reconstructed correlators



Top: D, Bottom: D^*

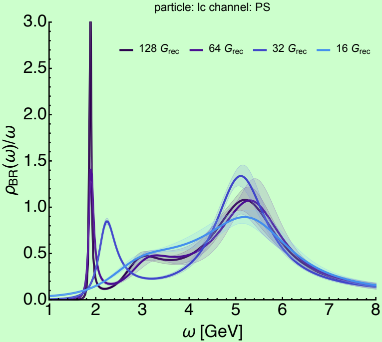
- Significant changes for $T \gtrsim T_c$
- Modifications below T_c
- Smaller for D_s
- Transport contribution in V channel?

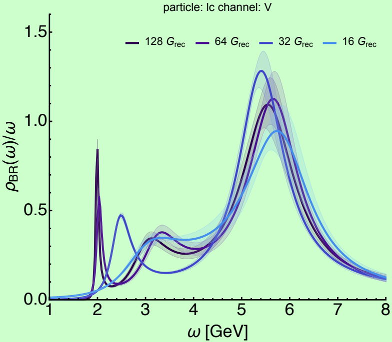
Open charm: spectral functions from BR



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

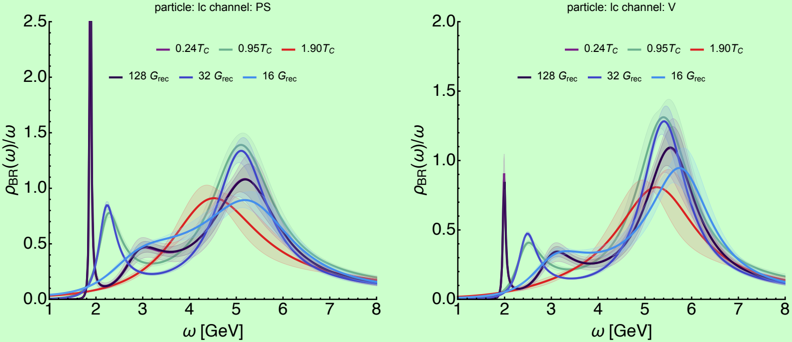
Spectral functions from reconstructed correlators





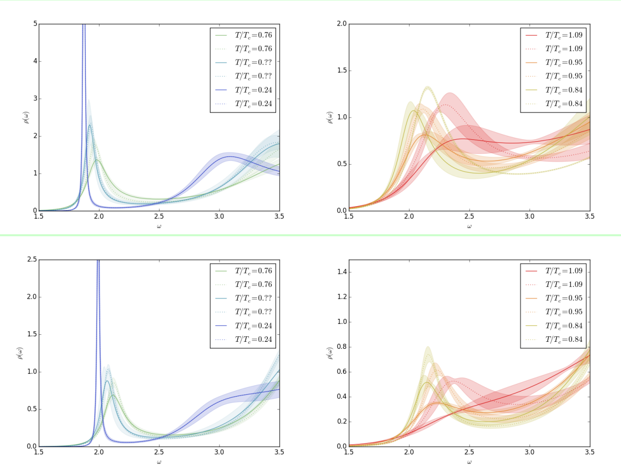
Systematic shift and weakening is an effect of the reduced temporal extent!

Comparison of reconstructed and thermal correlators



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

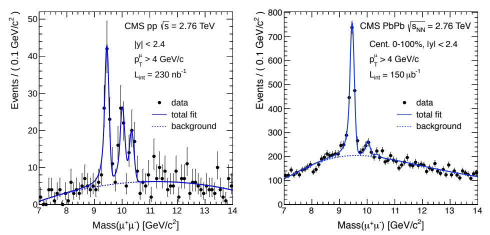
Comparison of reconstructed and thermal correlators



Significant modifications already around $0.9T_c$

Beauty (and the beast?)

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

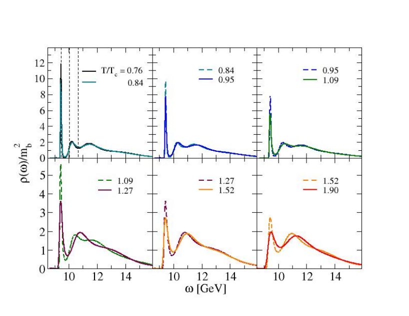
- No temperature-dependent kernel, $G(\tau) = \int \rho(\omega) e^{-\omega\tau} \frac{d\omega}{2\pi}$
- No zero-modes
- Longer euclidean time range
- Appropriate for probes not in thermal equilibrium

Disadvantages

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

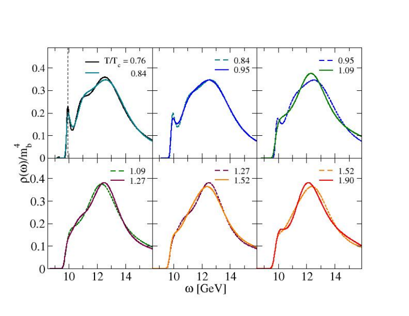
Spectral functions — MEM analysis

S-waves



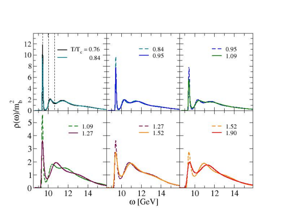
Υ (2S) melts, but ground state remains robust

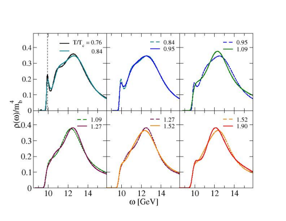
P-waves

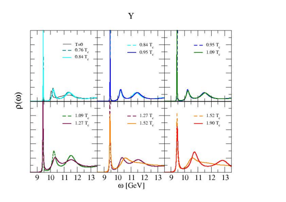


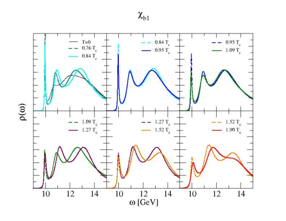
P-waves dissociate close to T_c

MEM vs BR method









Known discrepancy: BR produces more peak structures
[See subsequent discussion by Kim, Petrezcky, Rothkopf]

Summary

- Results for light baryons, (light mesons), open charm, charmonium, beautonium
- Baryons:
  - Observed parity restoration
  - impact on hadron resonance gas
- Open charm:
  - thermal modifications already below T_c
  - no bound states above T_c
- Charmonium:
  - no significant modification in S-waves below T_c
  - suggested survival up to $1.5T_c$
- Beautonium:
  - S wave survival up to $T > 2T_c$, moderate mass shift
  - P wave dissociation near T_c, still disputed

Outlook

- Complete understanding of systematics
- Towards the physical limit with lighter quarks — underway
- Repeat with smaller a_τ
- Open beauty