Charm and beauty in the quark–gluon plasma

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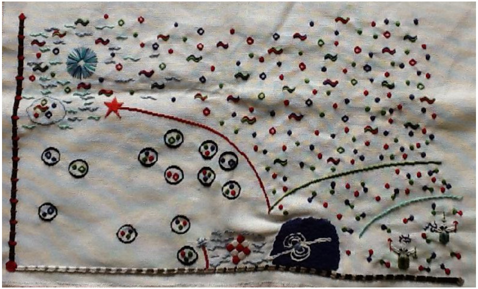
National University of Ireland Maynooth,

Royal Society, Chicheley Hall, 28 Jan 2015

Outline

Quarkonium as probes of QGP



Heavy-ion collisions (SPS, RHIC, LHC) probe the region of high(ish) T, low μ

- Quarkonia probe conditions in early stages of HICs
- Heavy quarks participate less in collective behaviour
- Only $c\bar{c}$ created in large quantities at RHIC
- Many $b\bar{b}$ pairs are created at LHC

Heavy quarkonia as QGP thermometers

QGP thermometers: sequential suppression

- Matsui and Satz (1986): charmonium dissociates at $T \approx T_c$
- Different states dissociate at different temperatures

$$T_\Upsilon > T_{J/\psi} \gtrsim T_{\eta_b} > T_{\Upsilon'} > T_{\chi_c}$$

- May use yields to determine temperature of plasma
- Dynamics crucial: T varies in space and time
- Require detailed knowledge of thermal widths $\sim$ dissociation rates

Methods and topics

Approaches

- Potential models
- Sum rules
- AdS/CFT
- Effective field theories, weak coupling expansion
- Lattice calculations
  - Direct calculation of spectral functions
  - Temporal correlator ratios
  - Spatial correlators
  - Indirect studies: fluctuations, thermodynamics

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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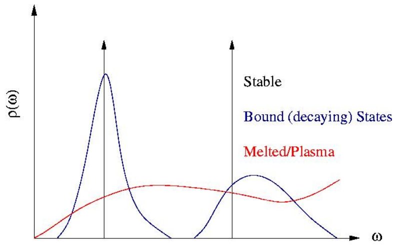


Spectral functions

- 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 Cuniberti, Tikhonov–Morozov

Reconstructed correlators

The systematic uncertainty of the MEM 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 $G_r(\tau; T, T_r) = G(\tau; T)$

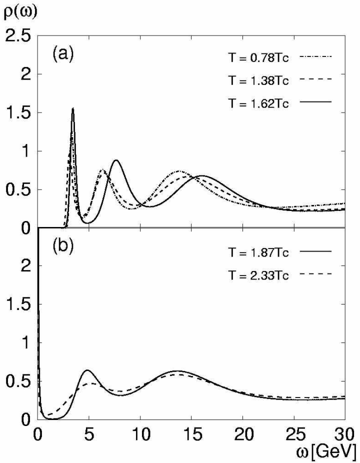
Can be computed directly from the correlators [Ding et al (2012)]
Small changes in correlators is compatible with large changes in spectral function [Mocsy&Petreczky (2007)]

Charmonium: Overview

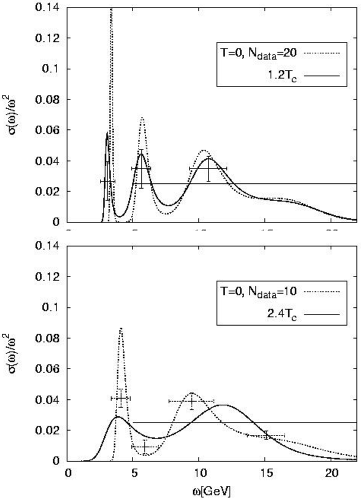
Authors	N_f	ξ	a_s (fm)	Comments
Asakawa & Hatsuda (2003)	0	4	0.039	
Umeda et al (2003)	0	4	0.10	
Ohno et al [WHOT-QCD] (2011)	0	4	0.10	Variational
Datta et al [Bielefeld] (2003)	0	1	0.020–0.048	
Ding et al [Biel–BNL] (2012)	0	1	0.010–0.031	
Ohno, Ding, Kaczmarek (2014)	0	1	0.010, 0.019	c, b corr ratios
Jakovac et al (2006)	0	2, 4	0.056-0.207	
Asakawa et al (2010, 2014)	0	4	0.039	ExtMEM, $p \neq 0$
Aarts et al [Dub–Swan] (2007)	2	6	0.167	
Oktay & Skullerud (2010)	2	6	0.162	$p \neq 0$
Borsányi et al [WB] (2014)	2+1	1	0.057	
Kelly et al [FASTSUM] (2014)	2+1	3.5	0.123	

S-waves: Quenched results

Asakawa & Hatsuda (2003):

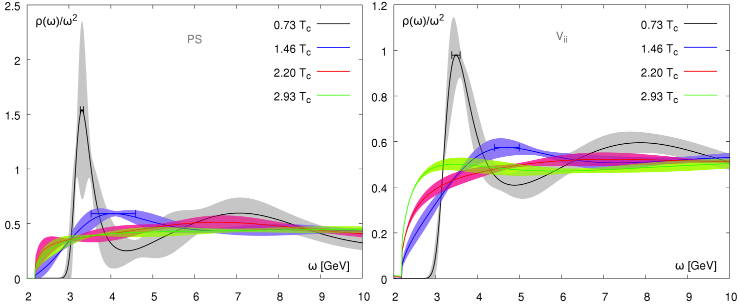


Jakovac et al (2006):



S-waves: Quenched results

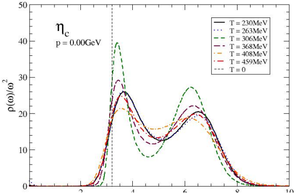
Ding et al (2012)

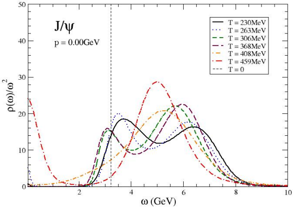


S-wave appears melted already at $1.4\,T_c$
— in contrast with (some) earlier studies

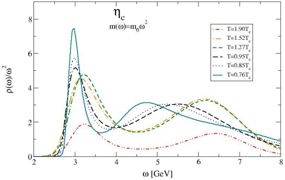
S-waves: $N_f = 2, 2+1$

Oktay and Skullerud (2010)

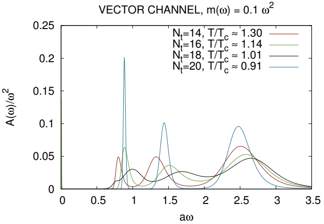




FASTSUM (Kelly et al)

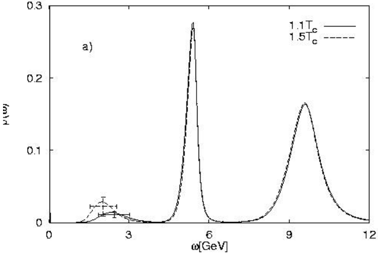


BW (Borsányi et al)

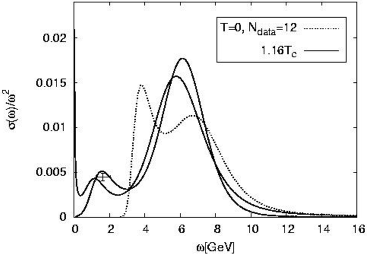


Charm P-waves

Datta et al (2003):



Jakovac et al (2006):

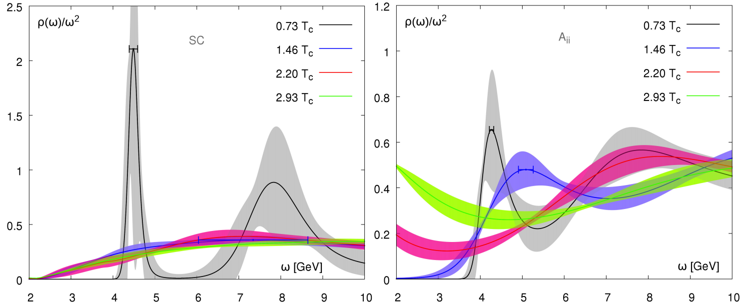


No sign of any χ_c peak above T_c!

Note that peaks at 6 GeV, 10 GeV, ... are lattice artefacts

Charm P-waves

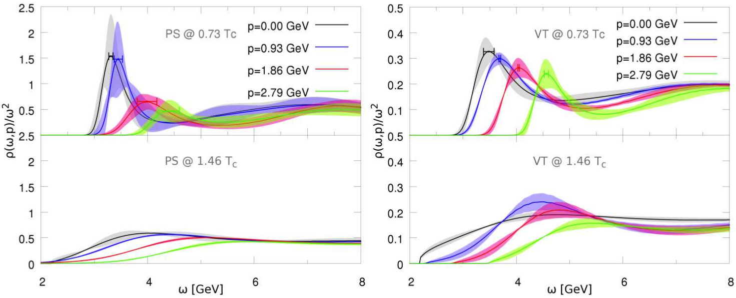
Ding et al (2012)



Nonzero momentum

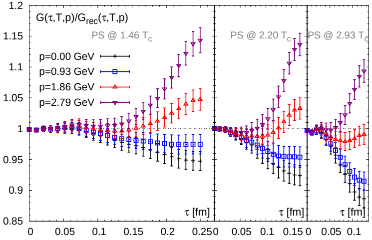
- $c\bar{c}$ pairs produced at nonzero momentum
- Transverse momentum (and rapidity) distributions important to distinguish between models
- Momentum dependent binding?

Ding (2012)

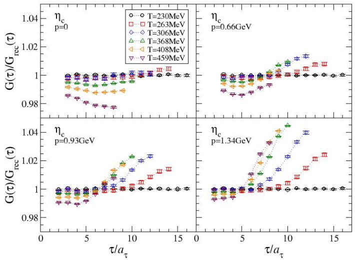


Nonzero momentum — PS correlator ratios

Ding (2012)



Oktay and Skullerud (2010/2014)

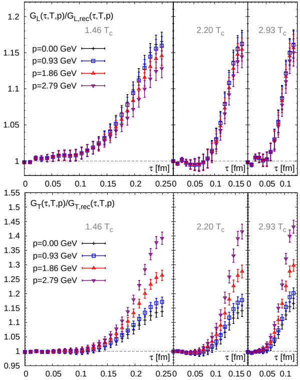


Consistent picture:

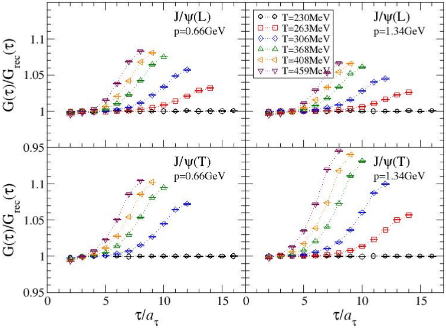
- small suppression at low momenta
- larger enhancement at high momenta

Nonzero momentum — V correlator ratios

Ding (2012)



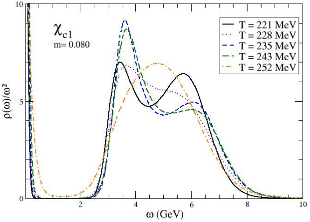
Oktay and Skullerud (2010/2014)



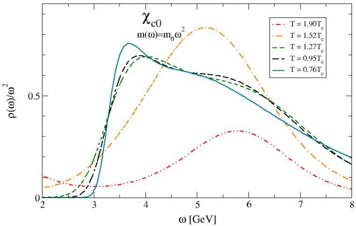
- Less momentum dependence in longitudinal correlator
- Transverse correlator gets more enhanced at larger p

Charm P-waves

Aarts et al (2007)



Kelly [FASTSUM] (2012)



P-waves disappear at $T \lesssim 1.2\, T_c$

Summary of charmonium results

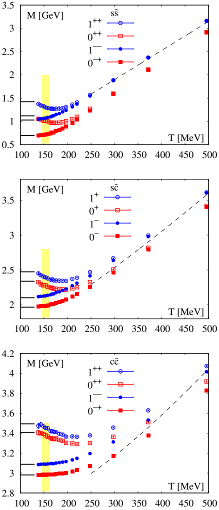
- Still no consensus on S-wave dissociation temperature: $1.2T_c \lesssim T_d^S \lesssim 2T_c$
- Continuum limit for $N_f = 0$ is in sight
- P-waves disappeared by $1.15T_c$
- Drastic changes in spectral functions is consistent with little change in correlators
- Permille precision required to pin down spectral features
- No reliable results yet for thermal mass shift, width

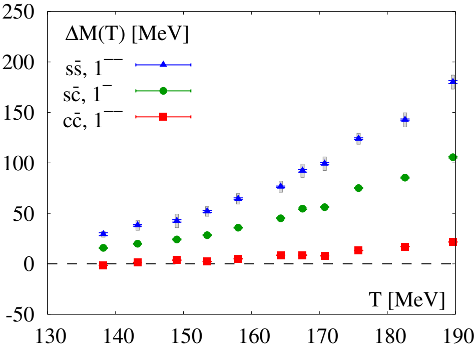
Open charm

Authors	N_f	a_s	ξ	N_τ	Method
Bazavov et al [BBC] (2014)	2+1	0.107	1	6, 8	Cumulants
		0.055	1	4–12	
Bazavov et al (2014)	2+1	0.107	1	12	Screening corrs
Kelly [FASTSUM] (2015)	2+1	0.125	3.5	16–40	Spectral fns

Cumulant results suggest open charm degrees of freedom become deconfined close to T_c.
But are they sensitive to a single surviving bound state?

Open charm: screening masses





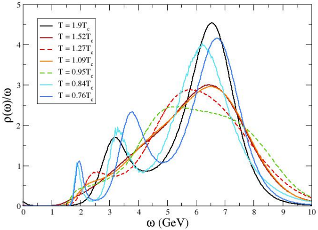
$s\bar{c}$ mesons behave qualitatively like $s\bar{s}$ mesons

Different behaviour from $c\bar{c}$ mesons!

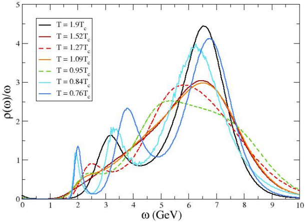
Open charm: spectral functions

Aoife Kelly (2015)

$l\bar{c}$



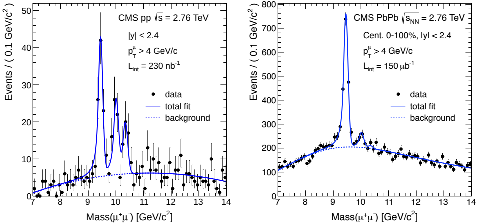
$s\bar{c}$



Both D and D_s mesons dissociate close to T_c

Beauty

- 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)?

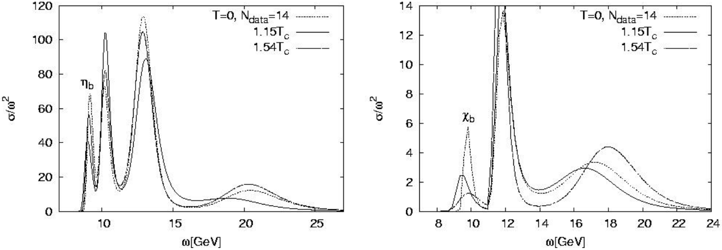


Beauty at high T

- Quenched, relativistic
  - Jakovac et al (2006): Anisotropic Fermilab, $\xi = 4, a_s = 0.134, 0.096, 0.072\text{fm}$ $T = 1.15 - 2.31\,T_c$.
  - Ohno, Ding, Kaczmarek (2014) Isotropic Clover, $a = 0.019, 0.0097$ fm. [Correlator ratios]
- NRQCD
  - FASTSUM (2010–2013): $N_f = 2, \xi = 6, a_s = 0.17\text{fm}$
  - FASTSUM (2014): $N_f = 2 + 1, \xi = 3.5, a_s = 0.125$ fm
  - Kim, Petreczky, Rothkopf (2014): $N_f = 2 + 1, \xi = 1, N_\tau = 12[a_s(T_c) = 0.107\mathrm{fm}]$

Beauty: quenched relativistic studies

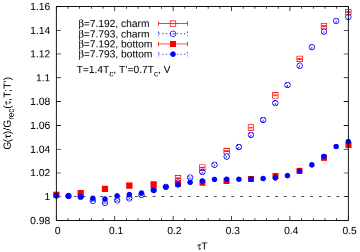
Jakovac et al (2006):

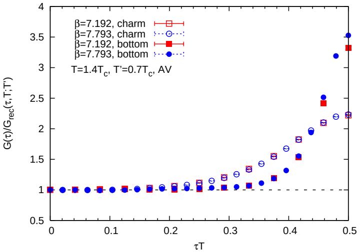


Results suggest little if any modification in S-waves, but melting of P-waves

Beauty: quenched relativistic studies

Ohno, Ding, Kaczmarek (2014):





- Far smaller modifications observed in beauty than charm
- Beauty P-wave correlators are strongly modified

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

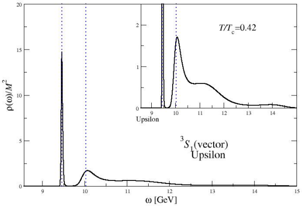
- No temperature-dependent kernel, $G(\tau) = \int \rho(\omega) e^{-\omega\tau} \frac{d\omega}{2\pi}$
- No zero-modes
- Longer euclidean time range
- Appropriate for probes not in thermal equilibrium

Disadvantages

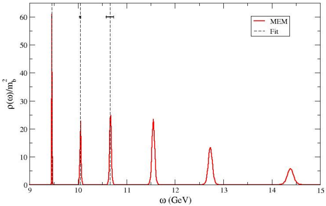
- Not renormalisable, requires $Ma_s \gtrsim 1$
- Does not incorporate transport properties

Spectral functions — $T = 0$

1st generation
[JHEP **1111** 103 (2011)]

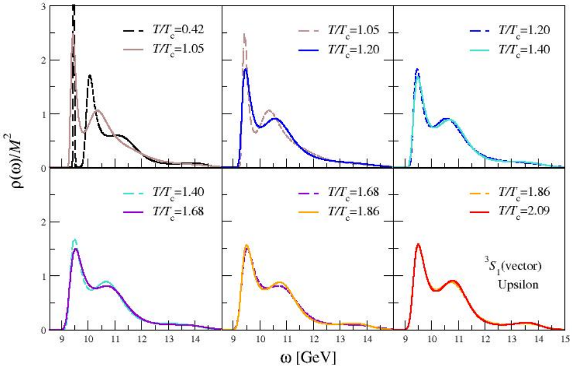


2nd generation
[JHEP **1407** 097 (2014)]]

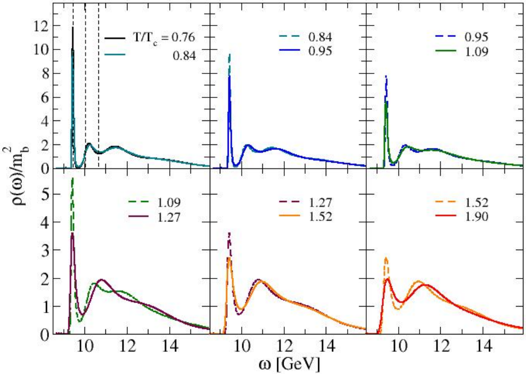


Υ (1S), Υ (2S) clearly identified
[3rd peak does not coincide with physical Υ (3S)]

Spectral functions — First generation



Spectral functions — Second generation



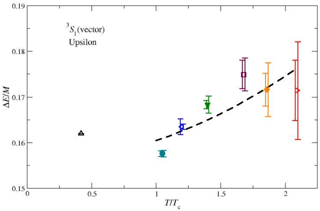
Υ (2S) melts, but ground state remains robust

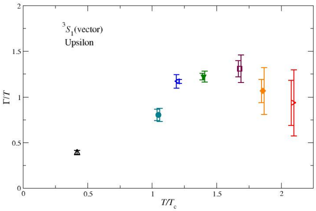
Mass shift and width

Fit (left side of) peaks to gaussian

$\longrightarrow$ determine peak position (mass) and width

Width is upper bound





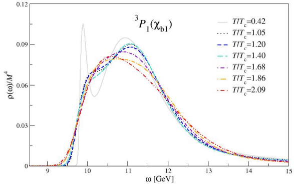
Results are consistent with perturbation theory,

$$\frac{\Gamma}{T} = \frac{1156}{81}\alpha_s^3\,, \qquad \frac{\delta E}{M} = \frac{17\pi}{9}\alpha_s T^2 M^2\,, \qquad \alpha_s \sim 0.4\,.$$

P-waves

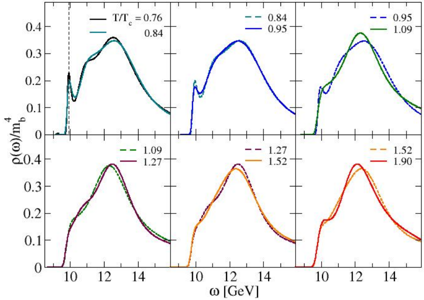
1st generation

[JHEP **1312** 064 (2013)]



2nd generation

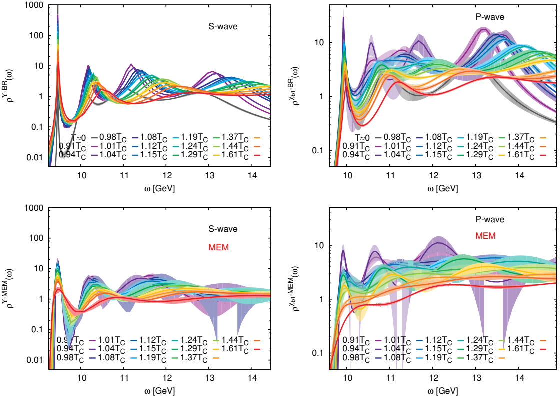
[JHEP **1407** 097 (2014)]



P-waves dissociate close to T_c

MEM and BR method on HotQCD configs

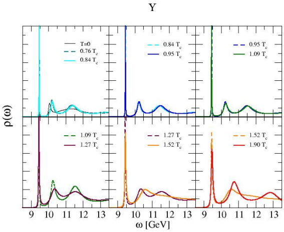
Kim, Petreczky, Rothkopf (2014)

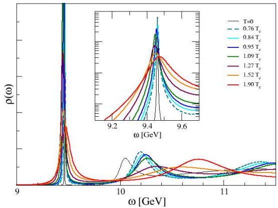


BR has

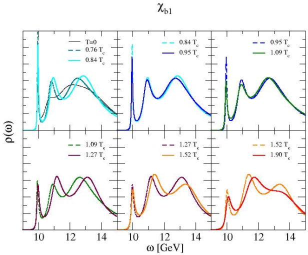
- sharper features
- surviving P-wave?

BR method on FASTSUM configs





[Tim Harris (2014)]



P-wave appears to survive to higher T?

Summary

- S-wave ground states survive to at least $T \sim 2T_c$
- Excited state disappears near T_c
- Mass shift and width consistent with perturbation theory
- Qualitative agreement between NRQCD and relativistic
- Fate of P-waves still unclear
- Discrepancy MEM vs BR needs to be resolved

Summary

- Charmonium studies still dominated by systematic uncertainties
- Requires high precision and control over lattice spacing effects
- D meson studies are in their infancy
- Beautonium can be studied quantitatively thanks to NRQCD
- MEM still method of choice, but systematics needs further understanding

Outlook

- Clarify strengths / weaknesses MEM, BR and other methods
- Can variational methods, extended operators yield useful information?
- Can we identify radial excitations (ψ', $\Upsilon(2S)$)?
- Relativistic beauty studies to complement NRQCD
- Your favourite idea goes here