Charmonium in the quark–gluon plasma

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Outline

Background

- J/ψ suppression — a probe of the quark–gluon plasma?
- Quenched lattice results indicate that S-waves survive well into the plasma phase
- Sequential charmonium suppression + recombination explains experimental results?
- Uncertainty about which potential to use in potential models, how to treat continuum
- How reliable are quenched lattice simulations?

Quenched vs dynamical

Are quenched lattice results reliable?

- $T_c^{N_f=0} \approx 1.5\,T_c^{N_f=2+1}$, $T_c^{N_f=2} \approx T_c^{N_f=2+1}$
- No $D - \bar{D}$ threshold in quenched QCD
- Light quarks can catalyse $Q\bar{Q}$ dissociation so it occurs at lower temperature
- Lower T_c, lower T_d — conspire to give the same T_d/T_c?
- Potential models indicate little change in T_d/T_c

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- Lower T_c, lower T_d — conspire to give the same T_d/T_c?
- Potential models indicate little change in T_d/T_c
- Only dynamical lattice calculations can give the answer

Dynamical anisotropic lattices

- A large number of points in time direction required
- For $T = 2T_c$, $\mathcal{O}(10)$ points $\Longrightarrow$ $a_t \sim 0.025$ fm
- Far too expensive with isotropic lattices $a_s = a_t$!

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- Introduces 2 additional parameters
- Non-trivial tuning problem [PRD **74** 014505 (2006)]

Spectral functions

- contain information about the fate of hadrons in the medium
  - $\longrightarrow$ stable states $\rho(\omega) \sim \delta(\omega - m)$
  - $\longrightarrow$ resonances or thermal width $\rho(\omega) \sim$ Lorentzian...
  - $\longrightarrow$ continuum above threshold
- can be used to extract transport coefficents

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- can be used to extract transport coefficents
- $\rho_\Gamma(\omega, \vec{p})$ related to euclidean correlator $G_\Gamma(\tau, \vec{p})$ according to

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

- an ill-posed problem — requires a large number of time slices
- use Maximum Entropy Method to determine most likely $\rho(\omega)$

Simulation parameters

[arXiv:0705.2198]

Light quarks	m_π/m_ρ	0.54	
Anisotropy	ξ	6	
Lattice spacing	a_τ	0.025fm	
	a_s	0.17 fm	
Lattice volume	N_s^3	8^3	$\rightarrow 12^3$
Critical Temp	T_c	$1/33.5a_\tau$	210MeV
1/Temperature	N_τ	16	$T \sim 2.1\,T_c$
		18	$T \sim 1.9\,T_c$
		20	$T \sim 1.7\,T_c$
		24	$T \sim 1.4\,T_c$
		32	$T \sim 1.05\,T_c$
		$33\ldots28$	$T \sim 1.02\ldots1.2\,T_c$
		80	$T \sim 0$

Reconstructed correlators

Reconstructed correlator is defined as

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

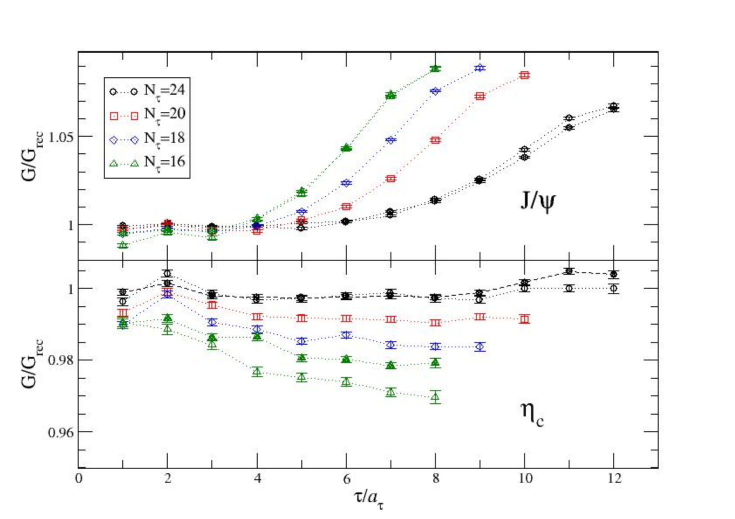
where K is the kernel

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

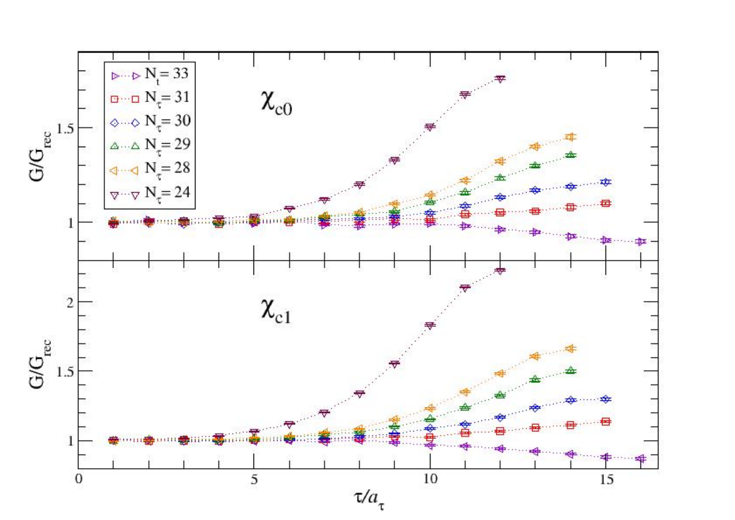
If $\rho(\omega; T) = \rho(\omega; T_r)$ then $G_r(\tau; T, T_r) = G(\tau; T)$

We use $N_\tau = 32$ as our reference temperature

S-waves


N_τ=24
N_τ=20
N_τ=18
N_τ=16
G/G_{rec}
1.05
1
J/ψ
G/G_{rec}
1
0.98
0.96
η_c
0
2
4
6
8
10
12
τ/a_τ

P-waves


N_t = 33
N_τ = 31
N_τ = 30
N_τ = 29
N_τ = 28
N_τ = 24
χ_c0
χ_c1
G/G_rec
1.5
1
2
1.5
1
0
5
10
15
τ/a_τ

MEM systematics

- We performed analysis with a large range of default models $m(\omega)$:
  - $\rightarrow$ $m(\omega) = m_0\omega^2$ with varying m_0
  - $\rightarrow$ $m(\omega) = m_0\omega(1+\omega)$ with varying m_0
  - $\rightarrow$ $m(\omega) = m_0\omega$
  - $\rightarrow$ $m(\omega) = m_0$
- If data are poor, MEM will give $\rho(\omega) \approx m(\omega)$
- Also varied energy cutoff, time range

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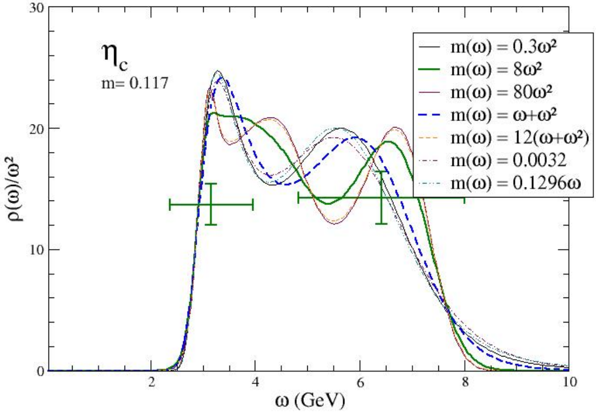
- Also varied energy cutoff, time range
- Statistics analysis to determine width?

Default model dependence



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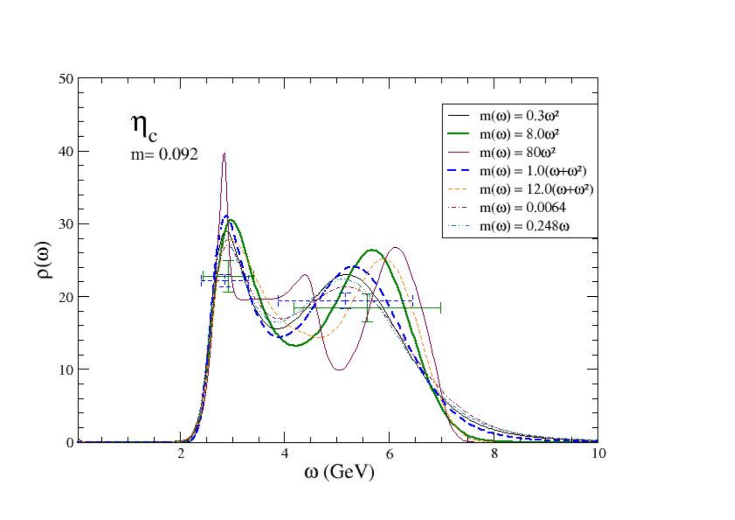
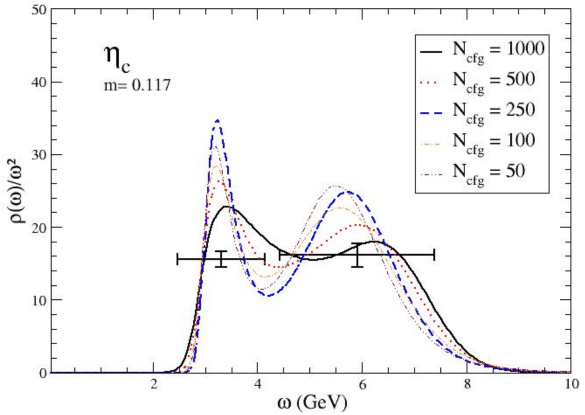
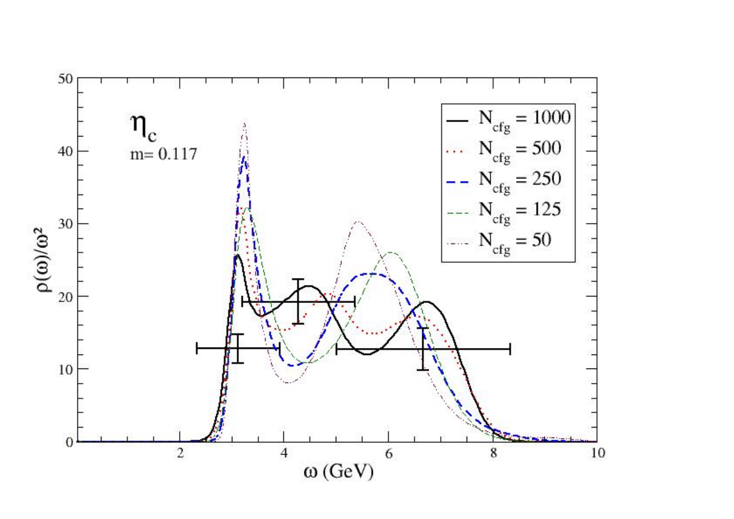


Statistics

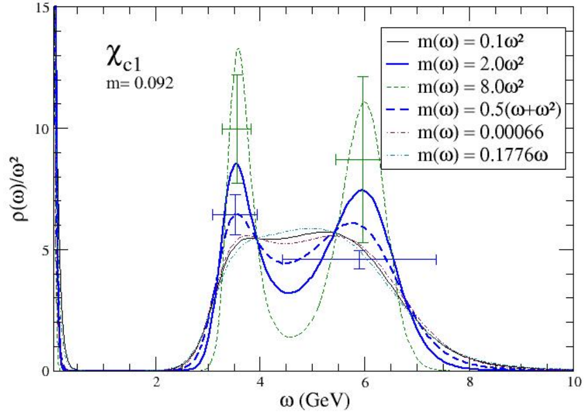

η_c
m= 0.117
N_{cfg} = 1000
N_{cfg} = 500
N_{cfg} = 250
N_{cfg} = 100
N_{cfg} = 50
$\rho(\omega)/\omega^2$
ω (GeV)
0
10
20
30
40
50
2
4
6
8
10

Statistics

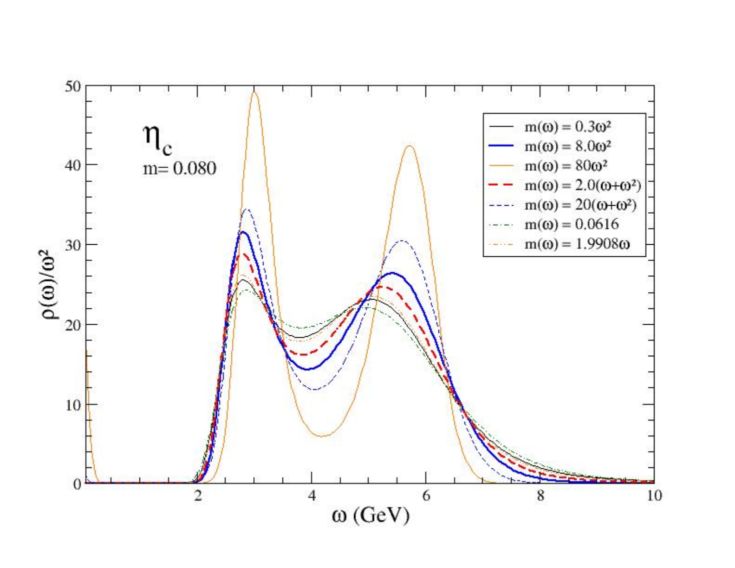


Using $m0 = 16$ — third peak appears for high statistics??

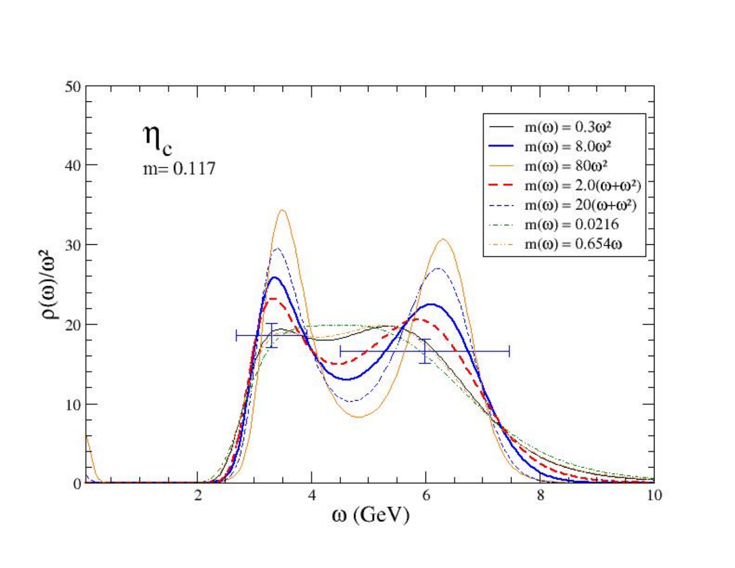
P-wave systematics



Systematics at $N_\tau = 28$



Systematics at $N_\tau = 24$



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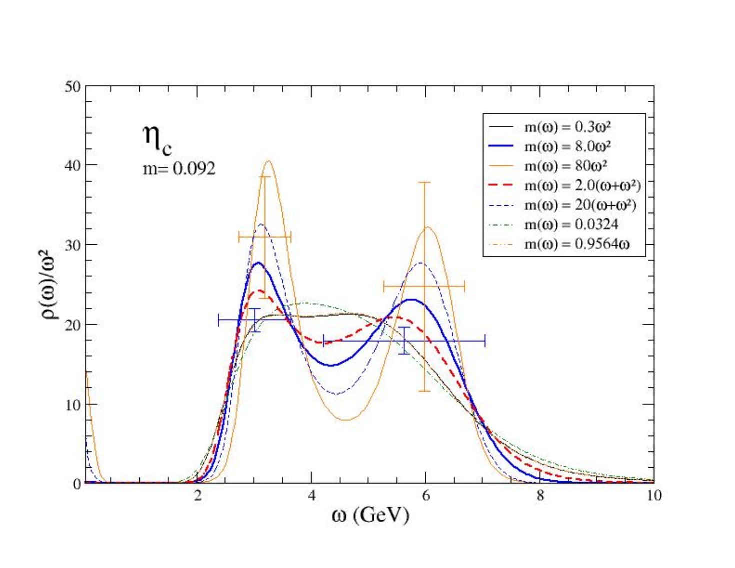
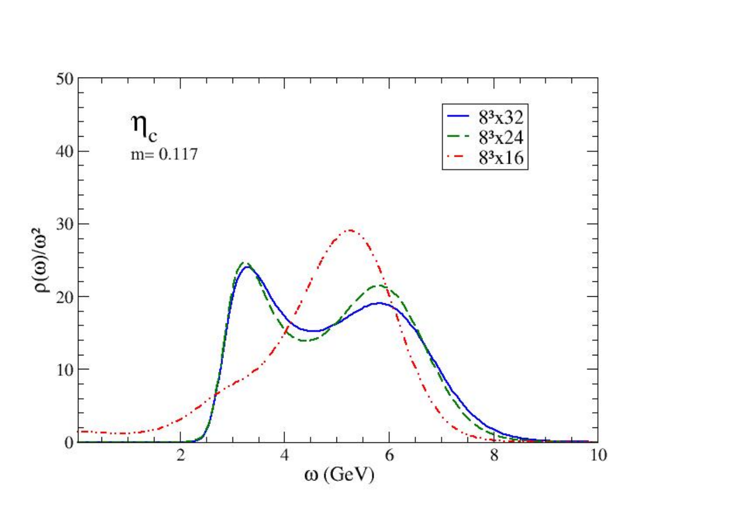


S-wave T dependence (η_c)



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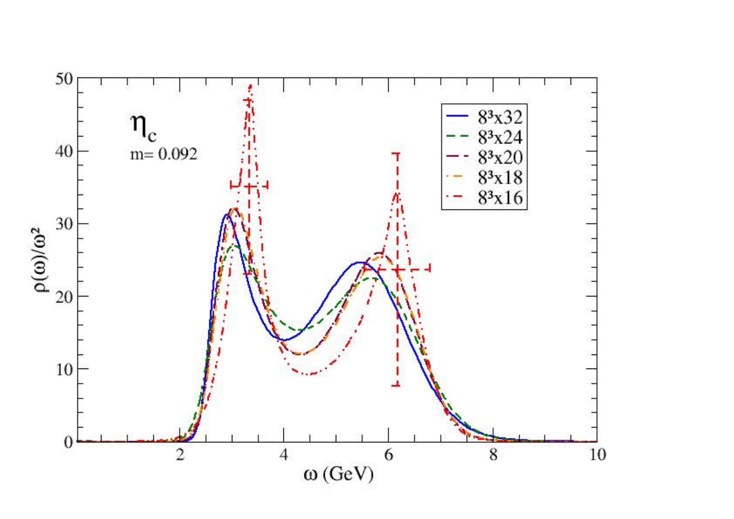

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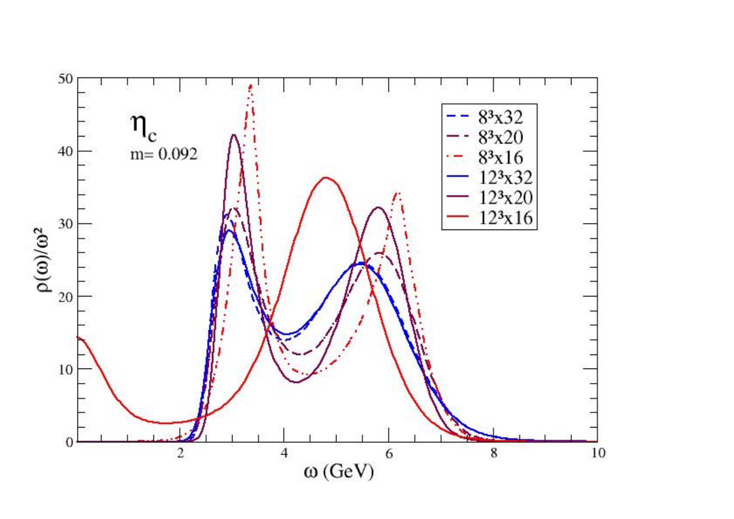
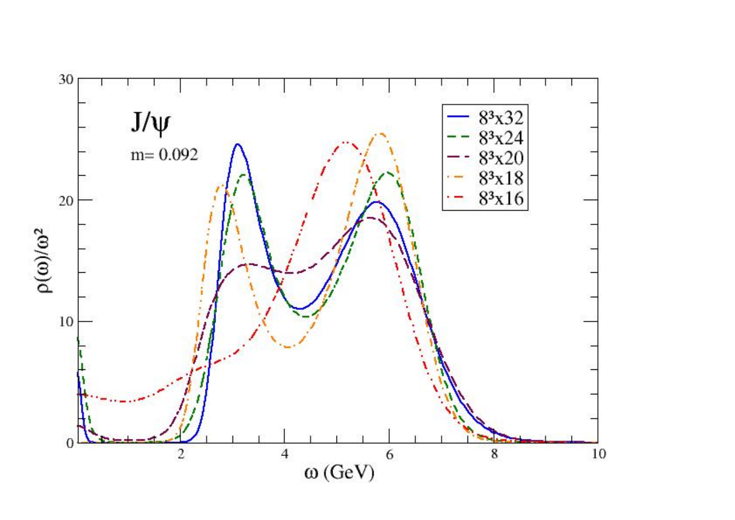


S-wave T dependence (J/ψ)



J/ψ (S-wave) melts at $T > 400$ MeV or $2T_c$?

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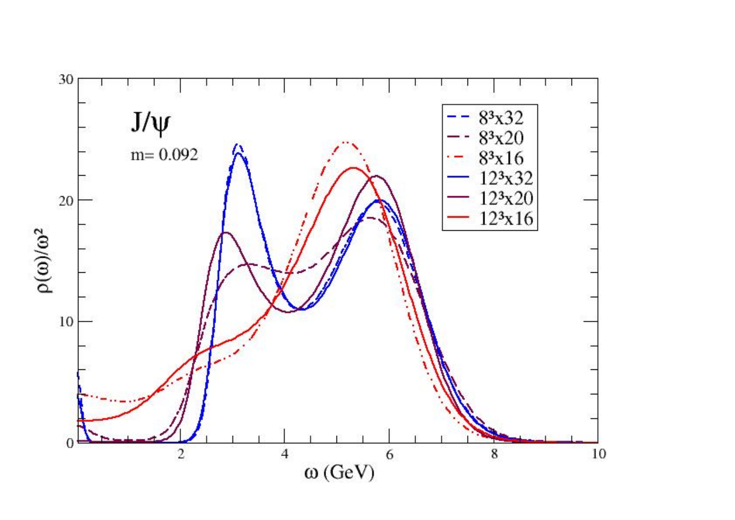

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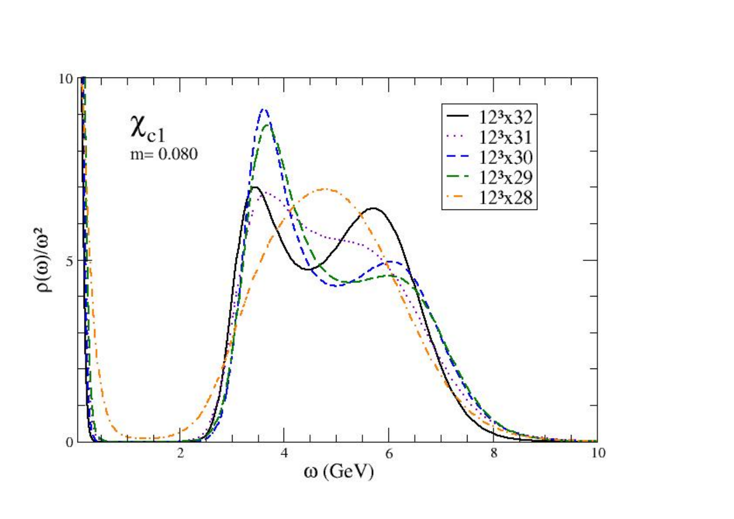

P-waves melt at $T < 250$ MeV or $1.2T_c$?

Outlook

- Charm flow
  - $\longrightarrow$ Diffusion constant related to $\lim_{\omega \to 0} \rho_V(\omega)/\omega$
  - $\longrightarrow$ Can this be determined using MEM?
  - $\longrightarrow$ Use $m(\omega) = m_0 \omega(b + \omega)$, vary b

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- Nonzero momentum
  - → Charmonium is produced at nonzero momentum
  - → Transverse momentum (and rapidity) distributions important to distinguish between models
  - → Momentum dependent binding?
  - → Gives an additional window to transport properties
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- D and B mesons
- non-zero chemical potential
- ...

Beauty (and the beast?)

- Many b quarks will be produced at ALICE
- $T_d^{\Upsilon} \sim 5T_c$ — hard to do on the lattice
- χ_b melts at $T_d^{\chi_b} \lesssim 1.2T_c$?
- Use NRQCD and relativistic action, compare two approaches
- Simulations underway

Summary

- Charmonium S-waves survive to $T \sim 2T_c$
- P-waves melt at $T < 1.3T_c$
- Consistent with sequential suppression:
  - $\longrightarrow$ 60% of J/ψ production is direct, the rest is feed-down from ψ', χ_c
  - $\longrightarrow$ Observed suppression at SPS, RHIC is feed-down
  - $\longrightarrow$ Direct suppression not yet observed — may be seen at ALICE?
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- Charmonium regeneration complicates picture!
- Systematic uncertainties:
  - $\longrightarrow$ Dependence on default model?
  - $\longrightarrow$ Coarse lattice $\rightarrow$ doubler peak uncomfortably close
  - $\longrightarrow$ Cannot distinguish bound state vs threshold
  - $\longrightarrow$ Coarse lattice $\rightarrow$ hard to reach high temperatures
- Simulations on finer lattices planned
- Simulations with lighter sea quarks in preparation