Charmonium spectral functions in full QCD

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Heavy quarkonium production in heavy-ion collisions, ECT*,
Trento, 25–29 May 2009

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?
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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

- $\rho_\Gamma(\omega, \vec{p})$ 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
- use Maximum Entropy Method to determine most likely $\rho(\omega)$
- requires a large number of time slices to have any chance of a reliable determination
- must introduce model function $m_0(\omega)$

Simulation parameters

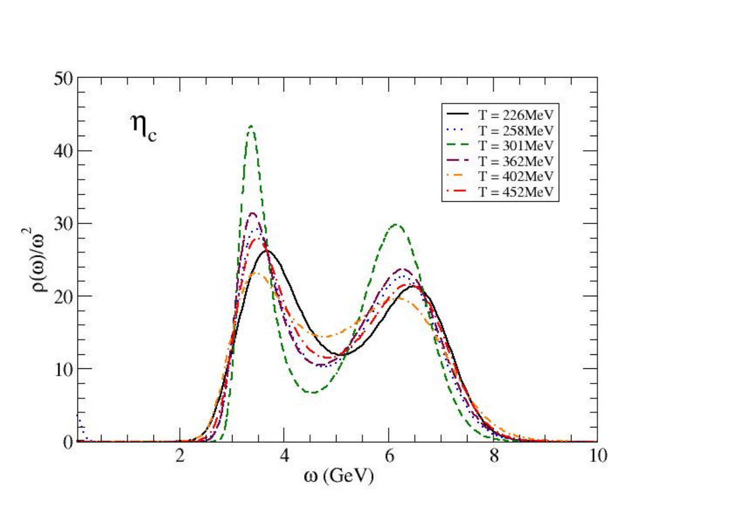
[PRD **76** 194513 (2007)]

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	$1/33.5a_\tau$	$\sim$ 210MeV

Temperature parameters:

N_t	T (MeV)	T/T_c
16	441	2.1
18	392	1.9
20	353	1.7
24	294	1.4
28	252	1.2
32	221	1.05
80	88	0.4

S-wave T dependence (η_c)



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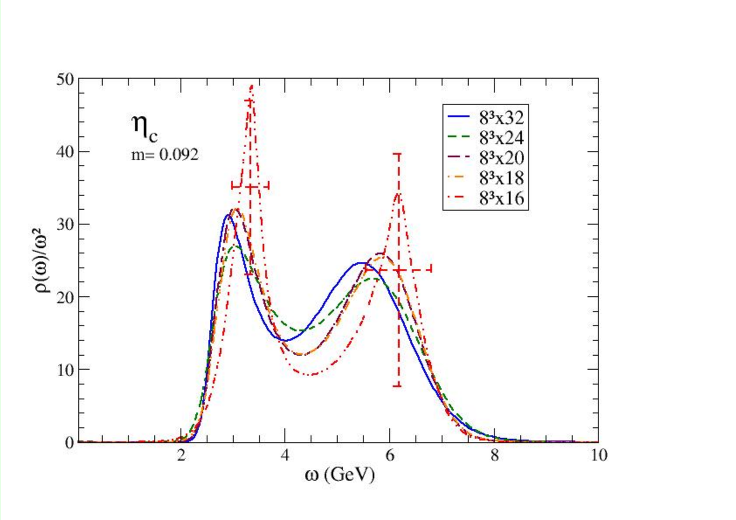

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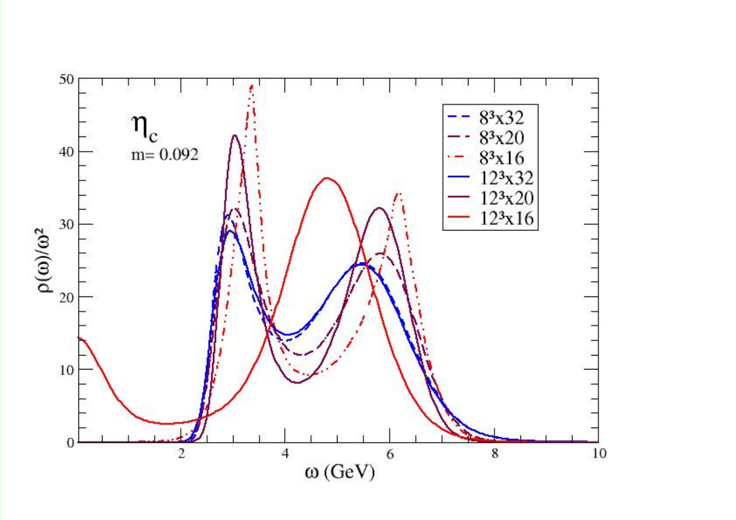
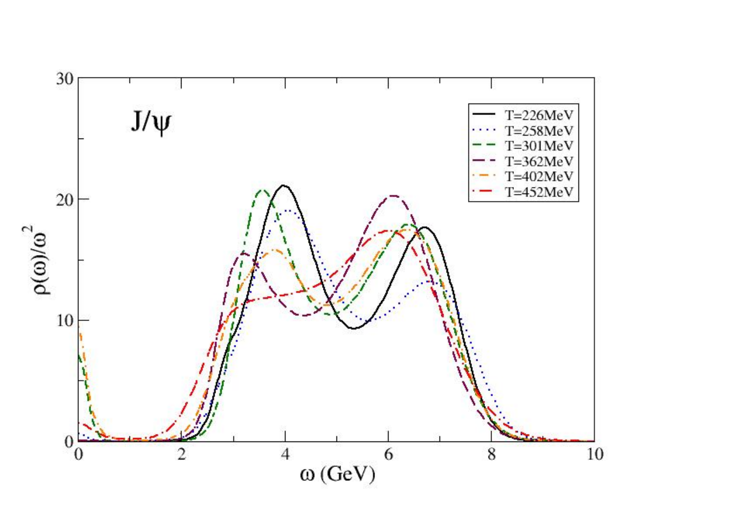


S-wave T dependence (J/ψ)



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

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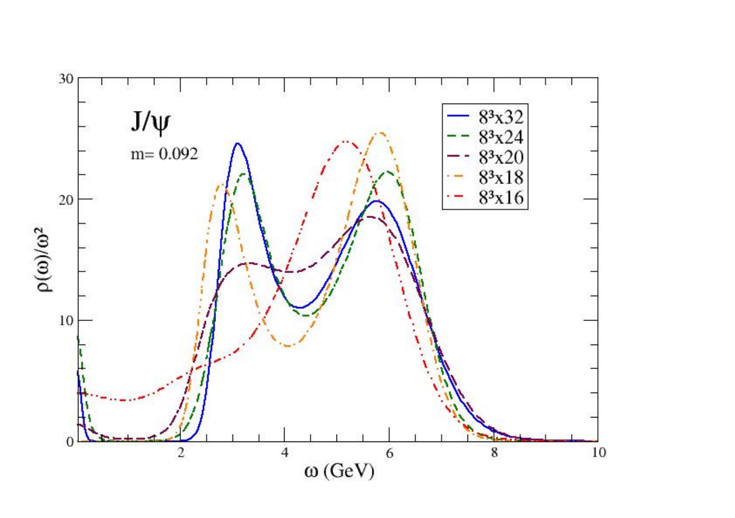

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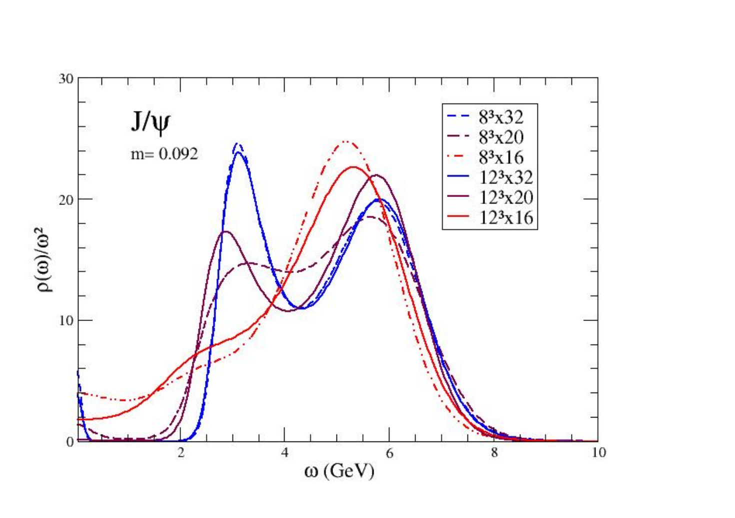

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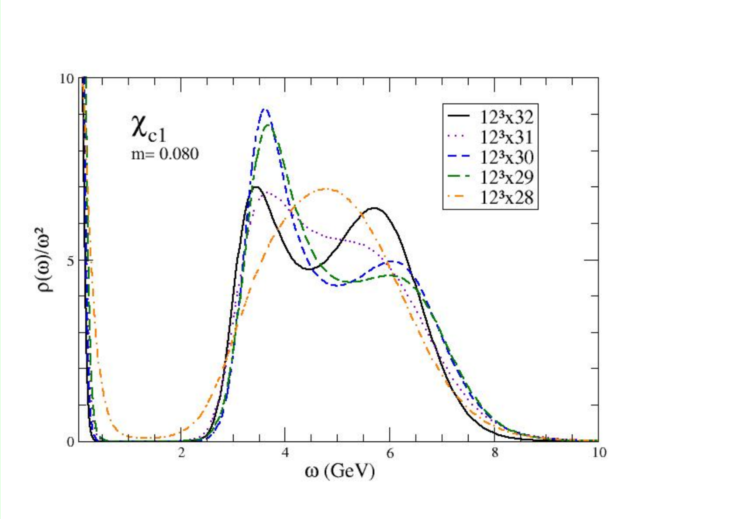
P-waves



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

Reconstructed correlators

Reconstructed correlator is defined as

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

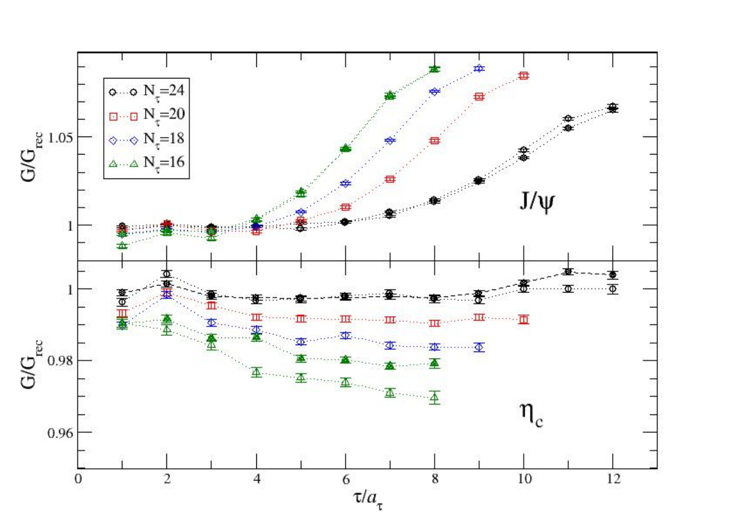
where K is the kernel

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

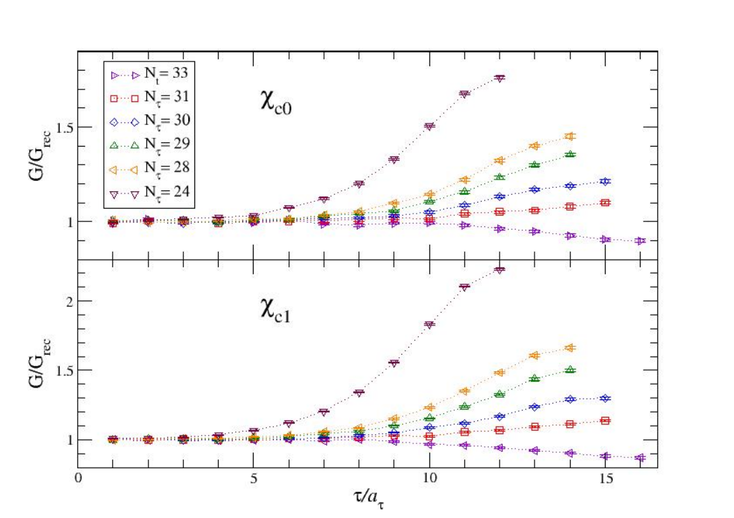
If $\rho(\omega; T) = \rho(\omega; T_r)$ then $G_r(\tau; T, T_r) = G(\tau; T)$

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


$N_t = 33$
$N_\tau = 31$
$N_\tau = 30$
$N_\tau = 29$
$N_\tau = 28$
$N_\tau = 24$
χ_{c0}
χ_{c1}
G/G_{rec}
τ/a_τ
1
1.5
2
0
5
10
15

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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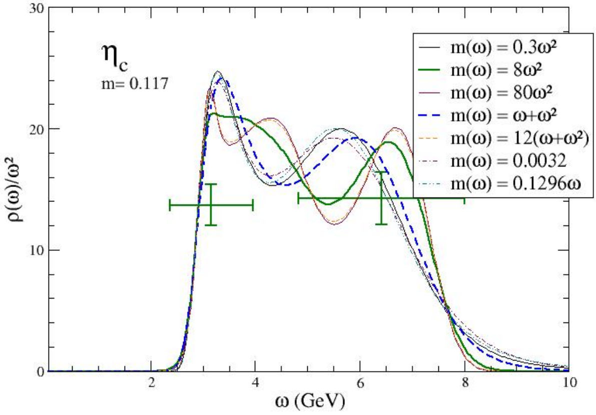
- If data are poor, MEM will give $\rho(\omega) \approx m(\omega)$
- Also varied energy cutoff, time range
- Statistics analysis to determine width?

Default model dependence



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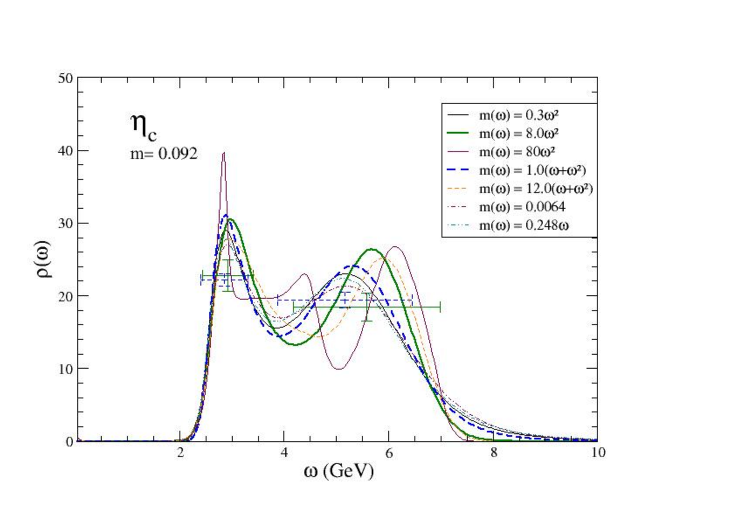
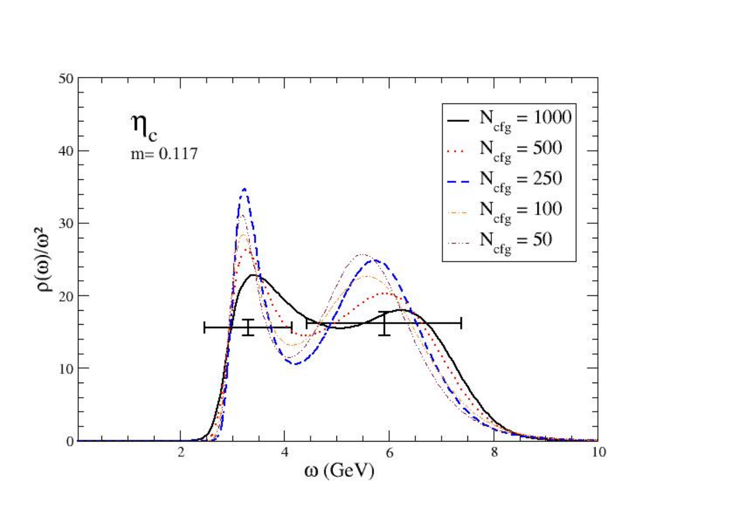
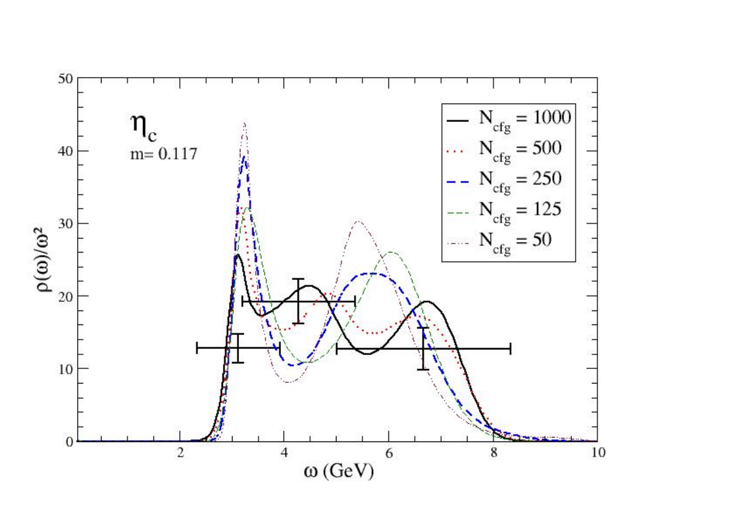


Statistics

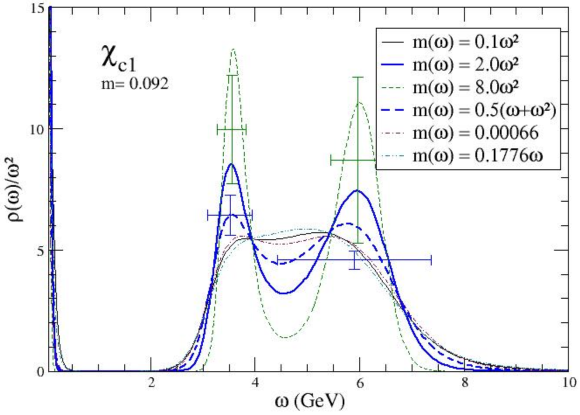

η_c
m= 0.117
N_{cfg} = 1000
N_{cfg} = 500
N_{cfg} = 250
N_{cfg} = 100
N_{cfg} = 50
$\rho(\omega)/\omega^2$
ω (GeV)
0
10
20
30
40
50
2
4
6
8
10

Statistics

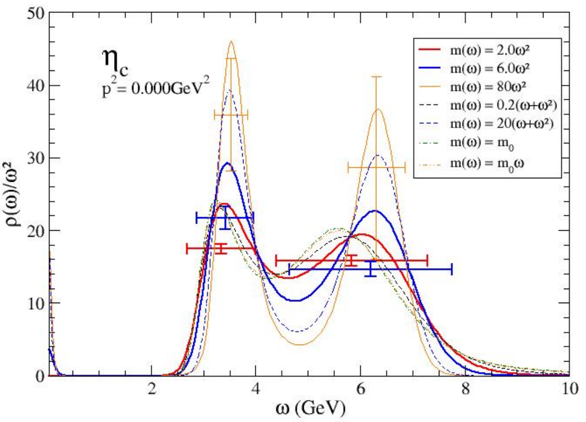


Using $m0 = 16$ — third peak appears for high statistics??

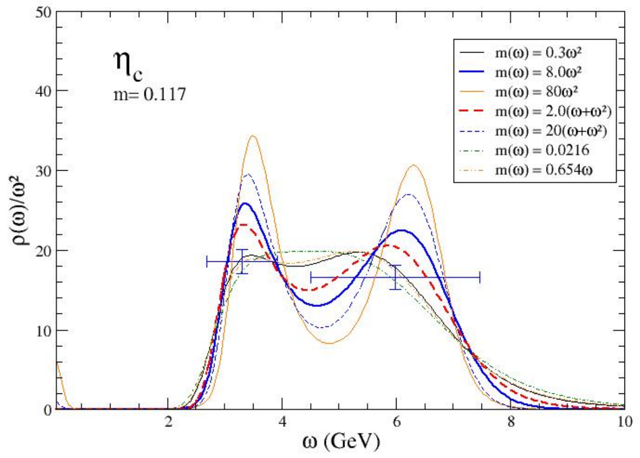
P-wave systematics



Systematics at $N_\tau = 28$



Systematics at $N_\tau = 24$



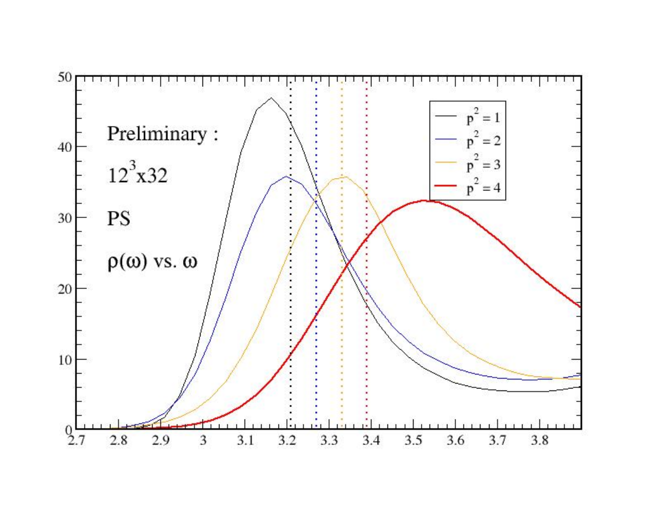
Nonzero momentum

[With MB Oktay, work in progress]

- 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
- Work in progress!

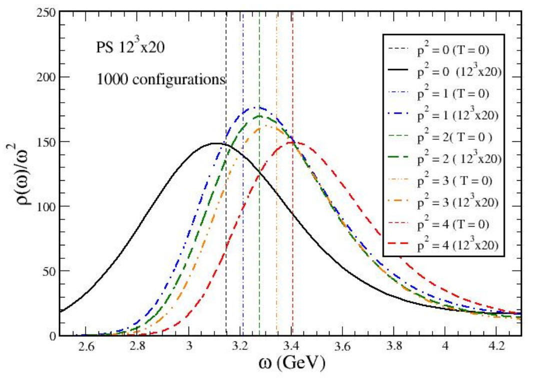
Nonzero momentum results

$\eta_c, 12^3 \times 32$

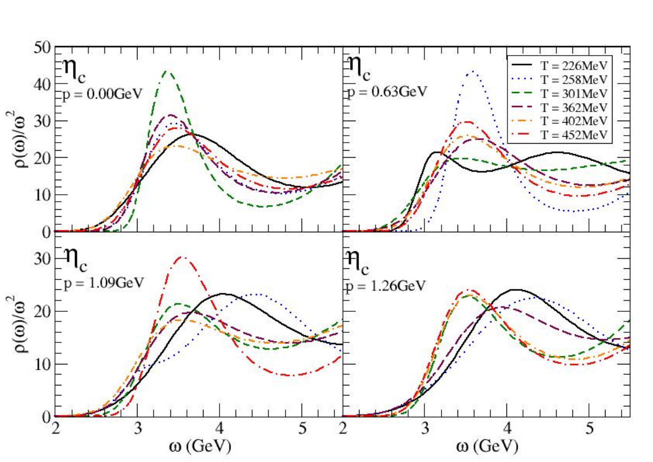


Nonzero momentum results

$\eta_c, 12^3 \times 20$



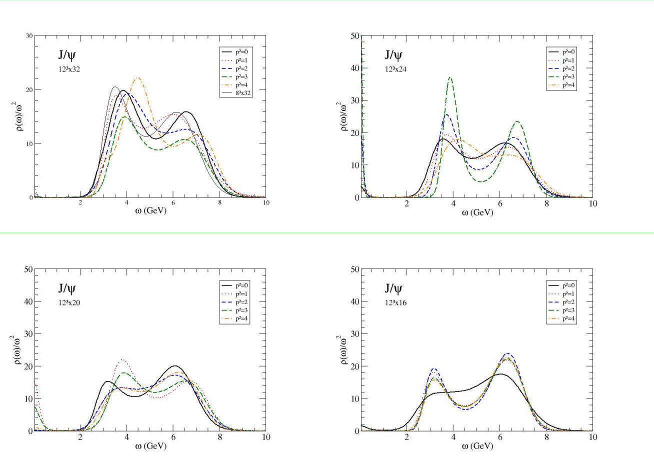
Nonzero momentum results



$\eta_c, 12^3 \times N_\tau$

Nonzero momentum results

$J/\psi, 12^3 \times N_\tau$



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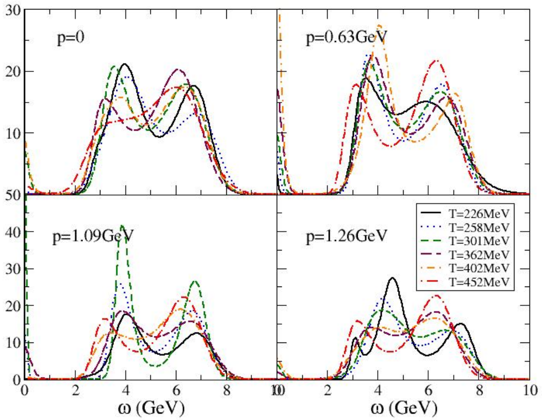
$J/\psi, 12^3 \times N_\tau$



Transverse vs longitudinal

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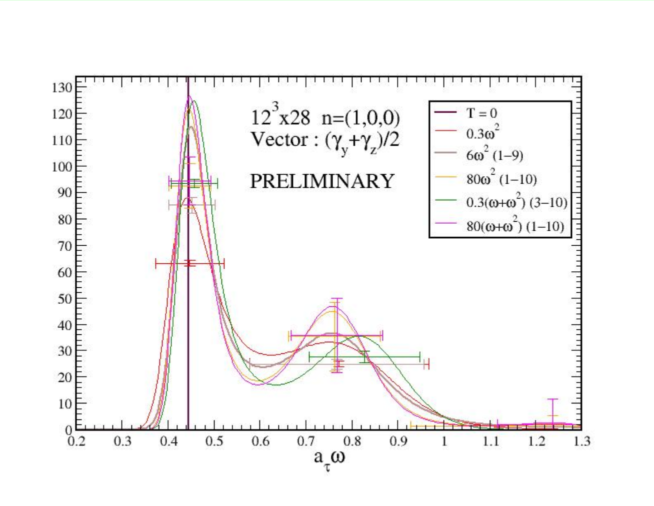

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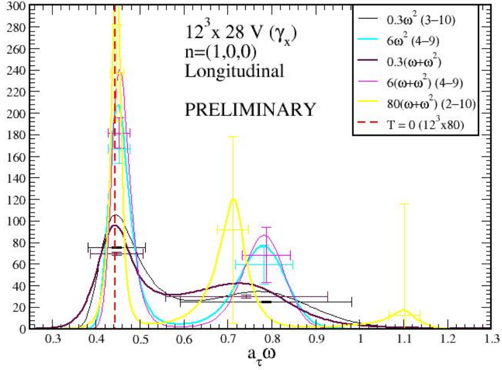

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- Systematic uncertainties:
  - $\longrightarrow$ Dependence on default model?
  - $\longrightarrow$ Coarse lattice $\longrightarrow$ doubler peak uncomfortably close
  - $\longrightarrow$ Cannot distinguish bound state vs threshold (but is this really important?)
  - $\longrightarrow$ Coarse lattice $\longrightarrow$ hard to reach high temperatures
- Simulations on finer lattices underway
- Simulations with lighter sea quarks planned

Outlook

- Beauty (and the beast?)
  - → Many b quarks will be produced at ALICE
  - → $T_d^{\Upsilon} \sim 5T_c$ — hard to do on the lattice
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- D and B mesons
- non-zero chemical potential
- . . .