Heavy quarks in the quark–gluon plasma

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NUI Maynooth / FASTSUM collaboration

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Outline

Background

- J/ψ suppression — a probe of the quark–gluon plasma?
- Heavy quarks: hard probes or thermal?
- Quenched lattice results indicate that S-waves survive well into the plasma phase
- Sequential suppression + recombination explains experimental results?
- Heavy quarks as thermometer of QGP?

Background

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- Quenched lattice results indicate that S-waves survive well into the plasma phase
- Sequential suppression + recombination explains experimental results?
- Heavy quarks as thermometer of QGP?
- 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); PRD **78**, 014505 (2008)]

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 $m_0(\omega)$

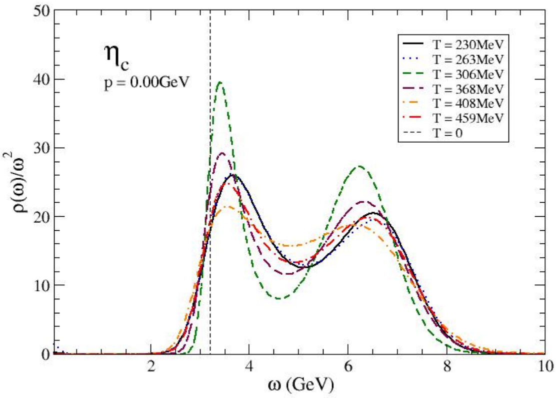
Simulation parameters

[PRD **76** 194513 (2007), arXiv:1005.1209]

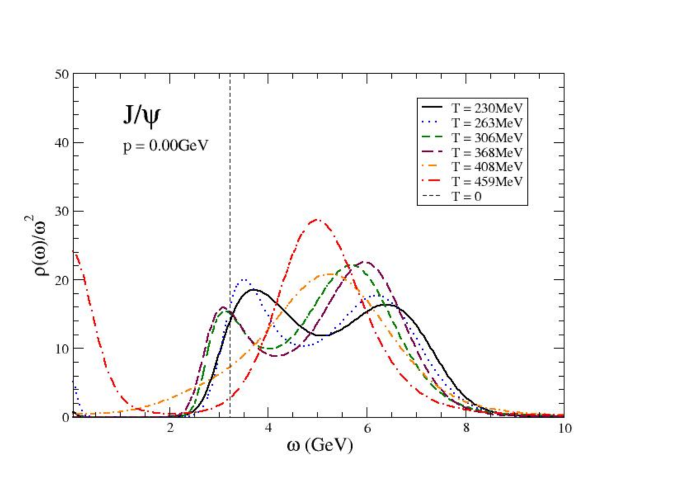
ξ	a_s (fm)	a_t^{-1} (GeV)	m_π/m_ρ	N_s	L_s (fm)
6.0	0.162	7.35	0.54	12	1.94

N_τ	T (MeV)	T/T_c	# configs
80	92	0.42	250
32	230	1.05	1000
28	263	1.20	1000
24	306	1.40	500
20	368	1.68	1000
18	408	1.86	1000
16	459	2.09	1000

S-wave T dependence (η_c)

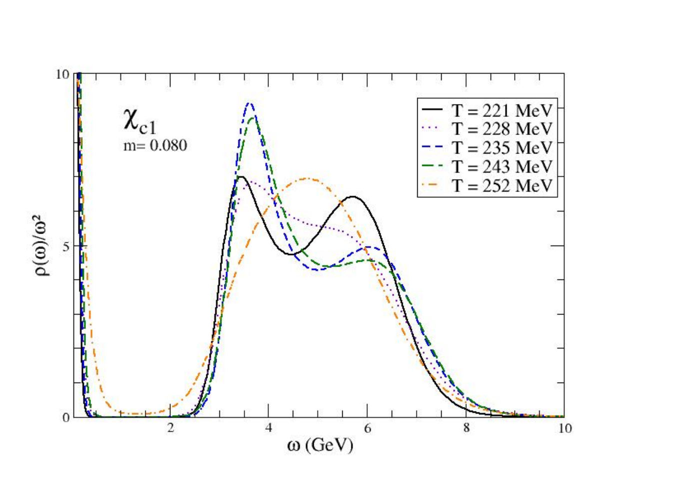


S-wave T dependence (J/ψ)



J/ψ (S-wave) melts at $T \sim 370 - 400$ MeV or $1.7 - 1.9\,T_c$?

P-waves



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

Reconstructed correlators

Reconstructed correlator is defined as

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

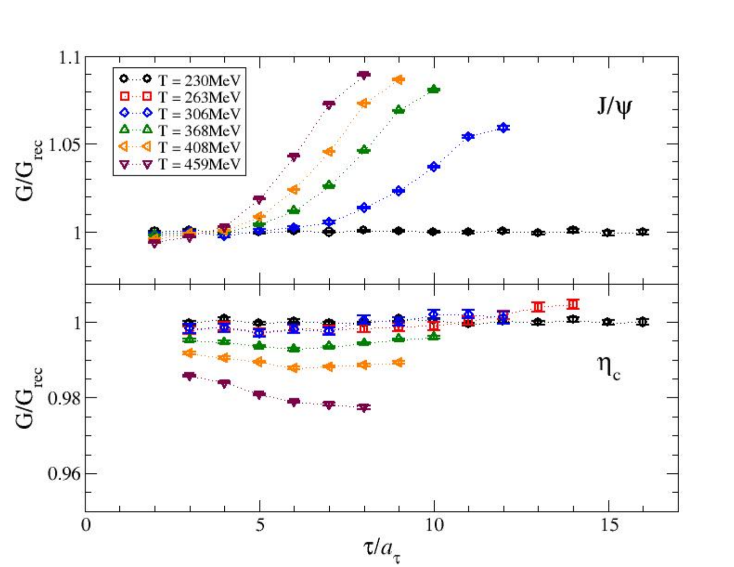
where K is the kernel

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

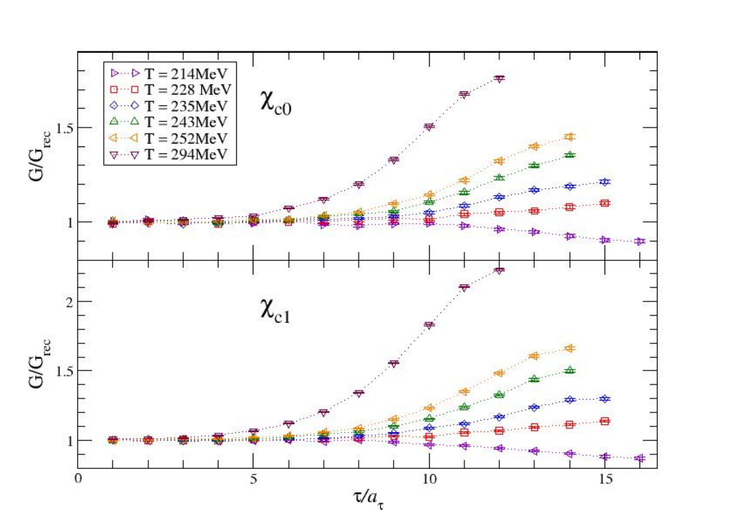
If $\rho(\omega; T) = \rho(\omega; T_r)$ then $G_r(\tau; T, T_r) = G(\tau; T)$

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

S-waves


T = 230MeV
T = 263MeV
T = 306MeV
T = 368MeV
T = 408MeV
T = 459MeV
J/ψ
η_c
G/G_rec
1.1
1.05
1
0.98
0.96
0
5
10
15
τ/a_τ

P-waves


T = 214MeV
T = 228 MeV
T = 235MeV
T = 243MeV
T = 252MeV
T = 294MeV
χ_{c0}
χ_{c1}
G/G_{rec}
τ/a_τ
0
5
10
15
1
1.5
2

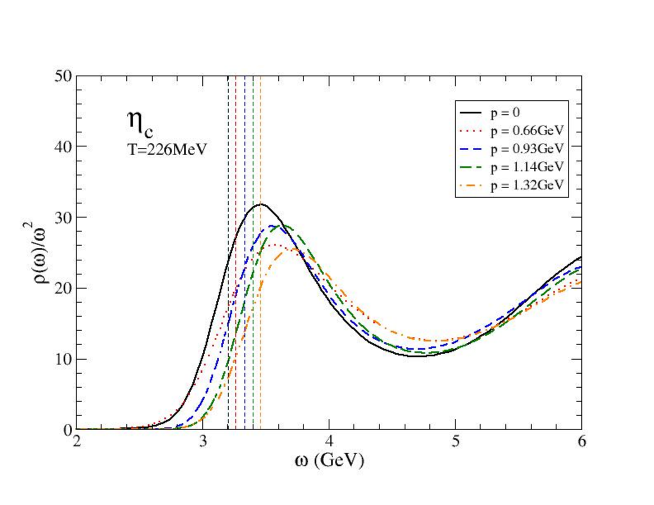
Nonzero momentum

[With MB Oktay, arXiv:1005.1209]

- 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

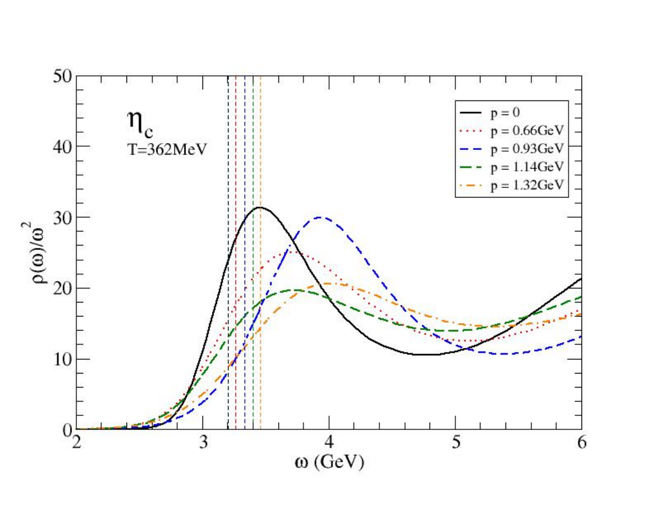
Nonzero momentum results

$\eta_c, 12^3 \times 32$

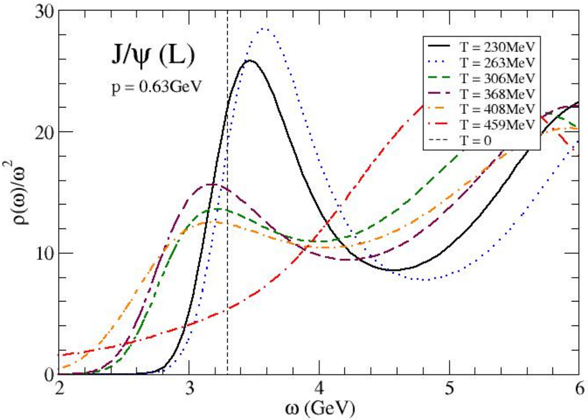


Nonzero momentum results

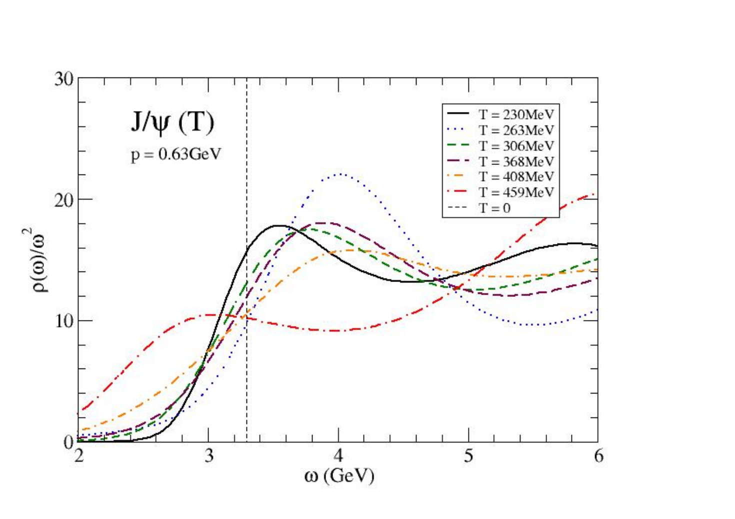
$\eta_c, 12^3 \times 20$



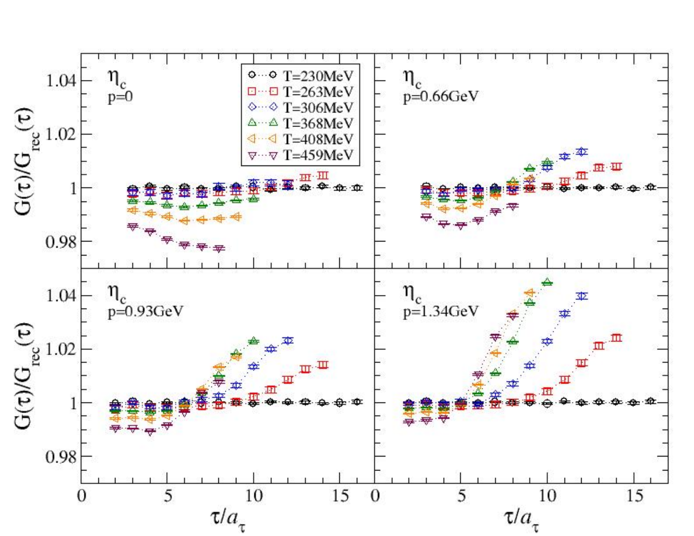
Transverse vs longitudinal



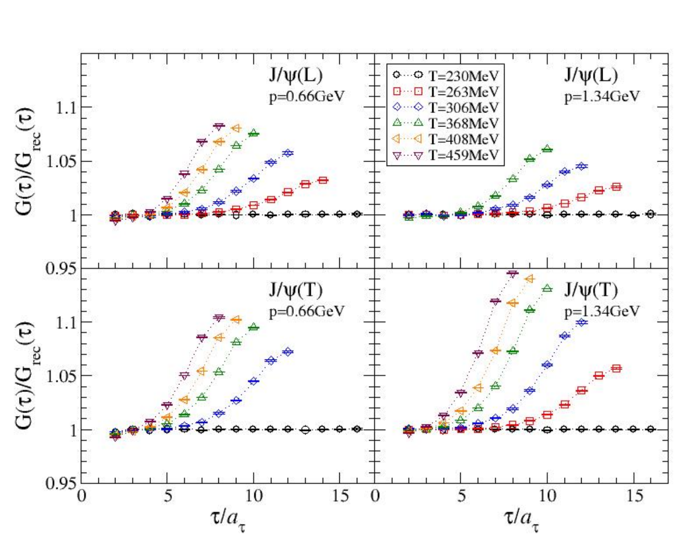
Transverse vs longitudinal



Reconstructed correlators



Reconstructed correlators



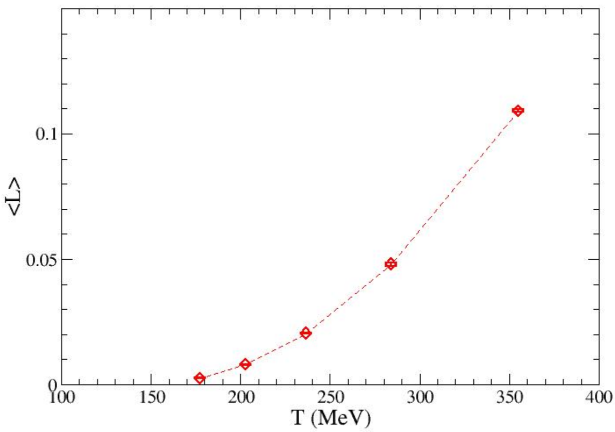
Towards the physical limit

Anisotropic clover-improved Wilson fermions, 2+1 flavours
[HadSpec Collab, PRD **79** 034502 (2009)]

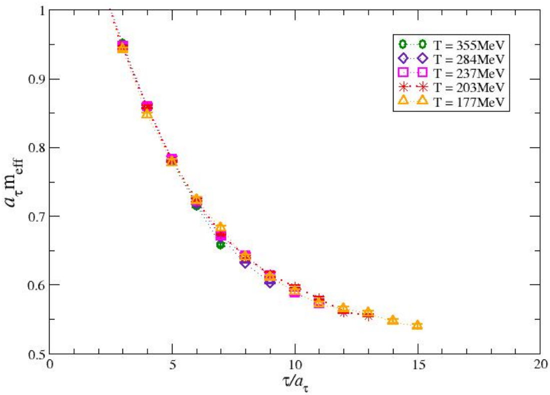
ξ	a_s (fm)	a_t^{-1} (GeV)	m_π/m_ρ	N_s	L_s (fm)
3.5	0.122	5.68	0.45	24	2.93

N_τ	T (MeV)	T/T_c	# configs	used
160	35	0.2	—	—
32	177	1.0	242	38
28	203	1.1	306	100
24	237	1.3	259	57
20	284	1.6	625	539
16	355	2.0	289	102

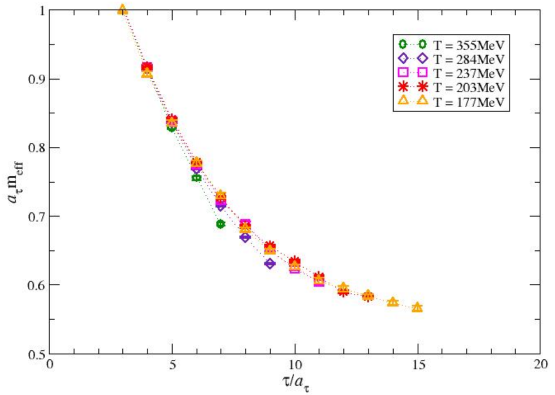
Polyakov loop



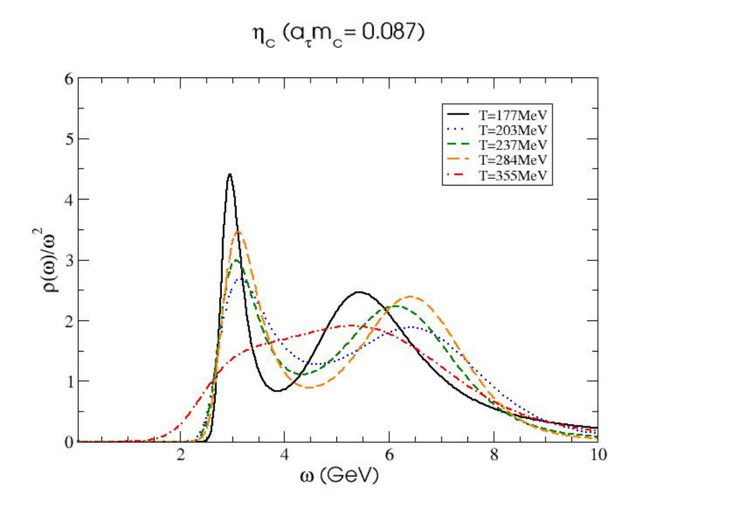
Pseudoscalar effective mass



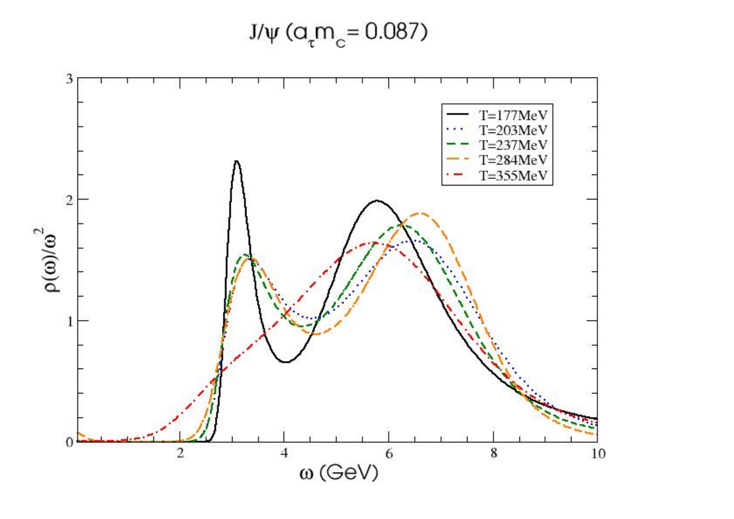
Vector effective mass



Pseudoscalar spectral function



Vector spectral function



Charm diffusion

How fast do charm quarks thermalise?

The heavy quark diffusion constant D is given by

$$D = \frac{1}{\chi^{00}} \lim_{\omega \to 0} \frac{\rho_V(\omega)}{\omega},$$

ρ_V is the spectral function of the conserved-current operator V_i

$$\chi^{00} = \frac{1}{T} \int \langle V_0(\overrightarrow{x}, t) V_0(\overrightarrow{0}, t) d^3x$$

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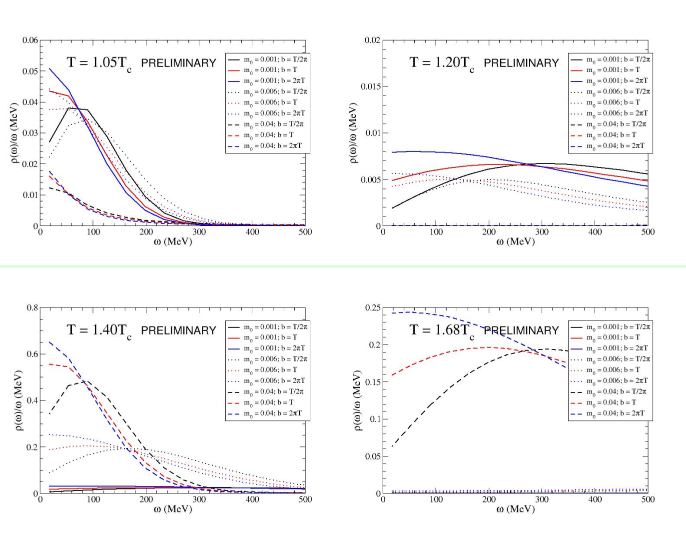
Preliminary results using default model $m(\omega) = m_0\omega(b + \omega)$

Results


T = 1.05T$_c$ PRELIMINARY
T = 1.20T$_c$ PRELIMINARY
T = 1.40T$_c$ PRELIMINARY
T = 1.68T$_c$ PRELIMINARY
m$_0$ = 0.001; b = T/2π
m$_0$ = 0.001; b = T
m$_0$ = 0.001; b = 2πT
m$_0$ = 0.006; b = T/2π
m$_0$ = 0.006; b = T
m$_0$ = 0.006; b = 2πT
m$_0$ = 0.04; b = T/2π
m$_0$ = 0.04; b = T
m$_0$ = 0.04; b = 2πT
ρ(ω)/ω (MeV)
ω (MeV)

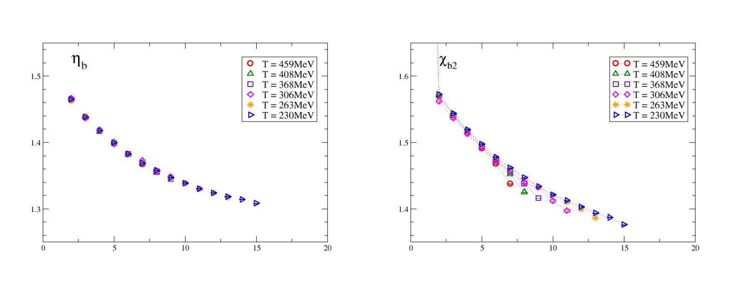
Beauty (and the beast?)

[See also talk by Gert Aarts]

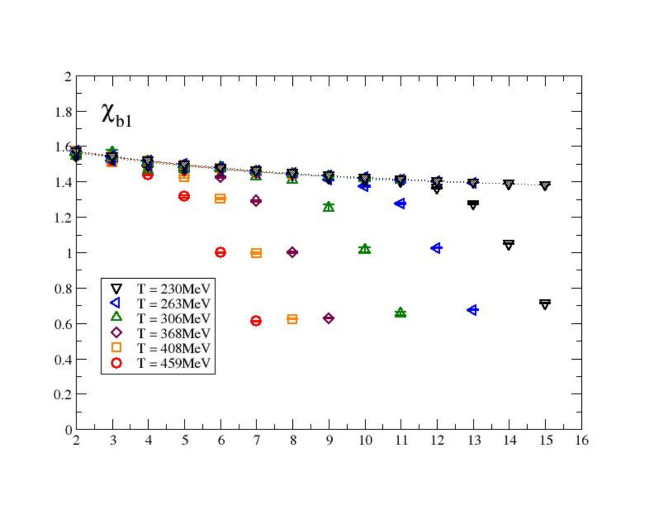
- Many b quarks will be produced at ALICE
- $T_d^{\Upsilon} \sim 5T_c$ — hard to do on the lattice
- χ_b melts at $T_d^{\chi_b} \lesssim 1.2T_c$?
- Use NRQCD and relativistic action, compare two approaches

Results from relativistic beauty

- Used the same action as for charm (and light quarks)
- Used both point and derivative operators for P-waves



Operator dependence



Derivative operators better behaved — smaller constant mode?

Summary

- Charmonium S-waves survive to $T \sim 1.6 - 2T_c$
- P-waves melt at $T < 1.3T_c$
- Significant momentum dependence in reconstructed correlators
- Transverse vector correlators are more sensitive to temperature and momentum
- Charm diffusion feasible from lattice simulations
- Relativistic beauty results compatible with NRQCD
- Simulations on finer lattices with realistic quark content underway