What happens to bottomonium in the quark-gluon plasma?

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FASTSUM collaboration

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Outline

- quarkonia and heavy ion collisions
- bottomonium on the lattice
- bottomonium spectral functions in the QGP
  - S waves: Υ at rest, moving
  - P waves: melting
- conclusion

Quarkonia and the QGP

quarkonia as a thermometer for the quark-gluon plasma

Matsui & Satz 86

- tightly bound states of charm quarks ($J/\psi, \ldots$) or bottom quarks ($\Upsilon, \ldots$) survive to higher temperatures
- broader states melt at lower temperatures

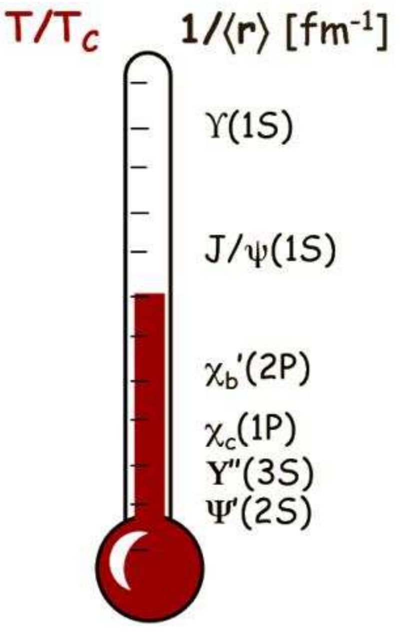


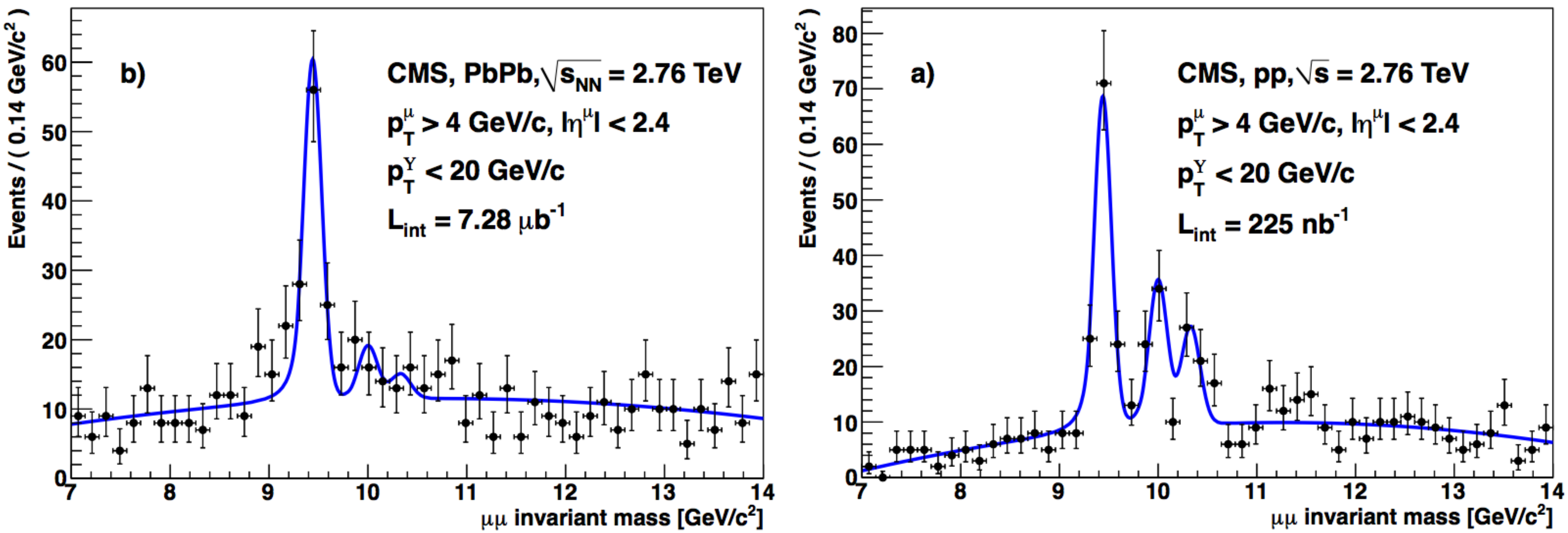
figure by A. Mocsy

melting pattern informs about temperature of the QGP

- relevant for heavy-ion collisions
- quantitative predictions required

Quarkonia and the QGP

- CMS results at the LHC: Υ spectrum
- compare PbPb collisions (left) and pp collisions (right)



- Υ(1S) survives – Υ(2S,3S) suppressed
- sequential melting

Quarkonia and the QGP

how to find the response of quarkonia to the QGP?

- potential models
- lattice QCD

at $T > 0$:

- plethora of potential models: (seemingly) conflicting results
- interpretation of lattice correlators hindered by thermal (periodic) boundary conditions

re-addressed recently using first-principle approach:

- effective field theories (EFTs) and separation of scales

Quarkonia and EFTs

$$M \gg T > \dots$$

hierarchy of scales:

- heavy quark mass M
- temperature T
- inverse size $g^2 M$
- Debye mass gT
- binding energy $g^4 M$

$\longrightarrow$ weak coupling

corresponding EFTs:

- NRQCD
- NRQCD + HTL
- pNRQCD
- pNRQCD + HTL
- $\dots$

Laine, Philipsen, Romatschke & Tassler 07
Laine 07-08 Burnier, Laine & Vepsäläinen 08-09
Beraudo, Blaizot & Ratti 08 Escobedo & Soto 08
Brambilla, Ghiglieri, Vairo & Petreczky 08
Brambilla, Escobedo, Ghiglieri, Soto & Vairo 10
Escobedo, Soto & Mannarelli 11

...

Quarkonia and EFTs

$M \gg T > \dots$

some perturbative results (assuming $\alpha \ll 1$):

- potential obtains an imaginary part

  Laine, Philipsen, Romatschke & Tassler

- thermal corrections to energy and width

  Brambilla, Escobedo, Ghiglieri, Soto & Vairo

- use complex potential models

  Laine et al, Strickland et al, Miao, Mocsy & Petreczky, ...

nonperturbative:

- determine imaginary part of potential in classical limit

  Laine, Philipsen & Tassler

- extract potential from Wilson loop in lattice QCD

  Rothkopf, Hatsuda & Sasaki

Non-relativistic QCD

this talk:

- use NRQCD, one of the EFTs, nonperturbatively
- no potential model / no weak coupling

lattice QCD:

- heavy quarks with NRQCD
  requirement $M \gg T$
  bottomonium: $M_b \sim 4.5$ GeV $\qquad T \sim 150 - 400$ MeV

use of NRQCD very well motivated

Bottomonium in the QGP

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PRL (2011), JHEP (2011, 2013), in preparation

Lattice QCD

- QGP with two light flavours (Wilson-like)
- many time slices: highly anisotropic lattices ($a_s/a_\tau = 6$)
- lattice spacing: $a_\tau^{-1} \simeq 7.35$ GeV, $a_s \simeq 0.162$ fm
- lattice size: $12^3 \times N_\tau$

N_τ	80	32	28	24	20	18	16
T/T_c	0.42	1.05	1.20	1.40	1.68	1.86	2.09
$N_{\rm cfg}$	250	1000	1000	500	1000	1000	1000

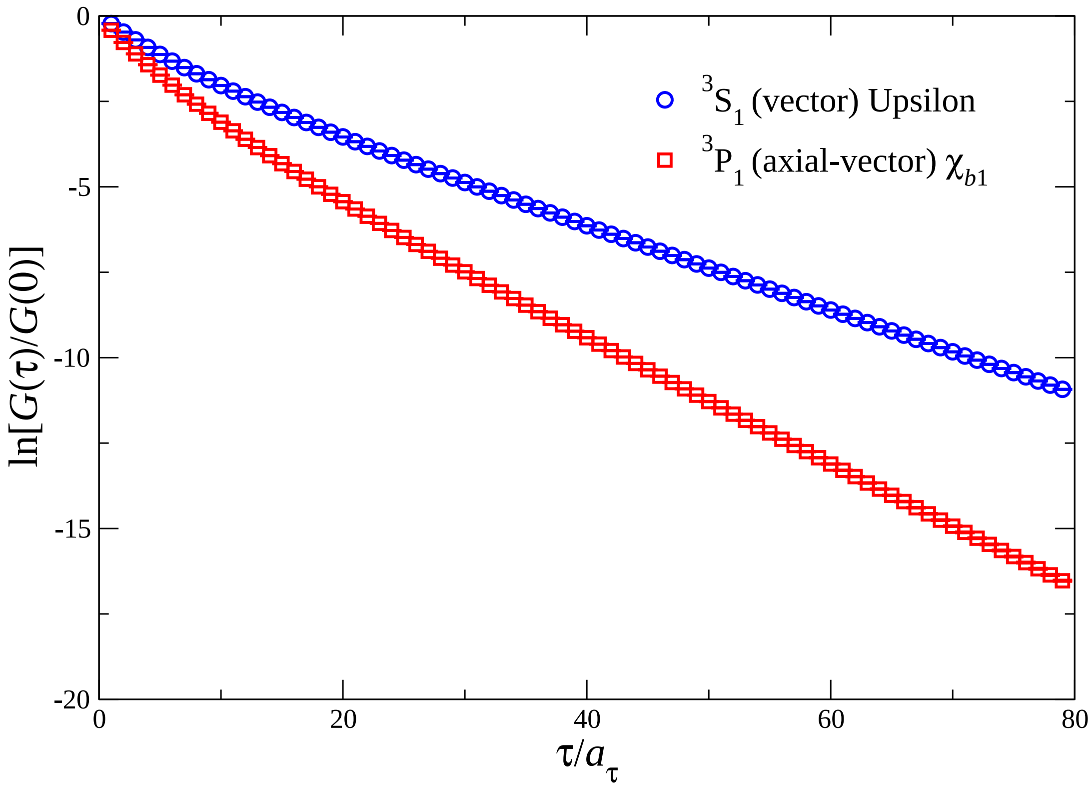
- bottom quark: NRQCD

  mean-field improved action with tree-level coefficients, including up to $\mathcal{O}(v^4)$ terms Davies et al 94
- in progress: extension to $N_f = 2+1$

Spectrum at zero temperature

- euclidean correlators not periodic:

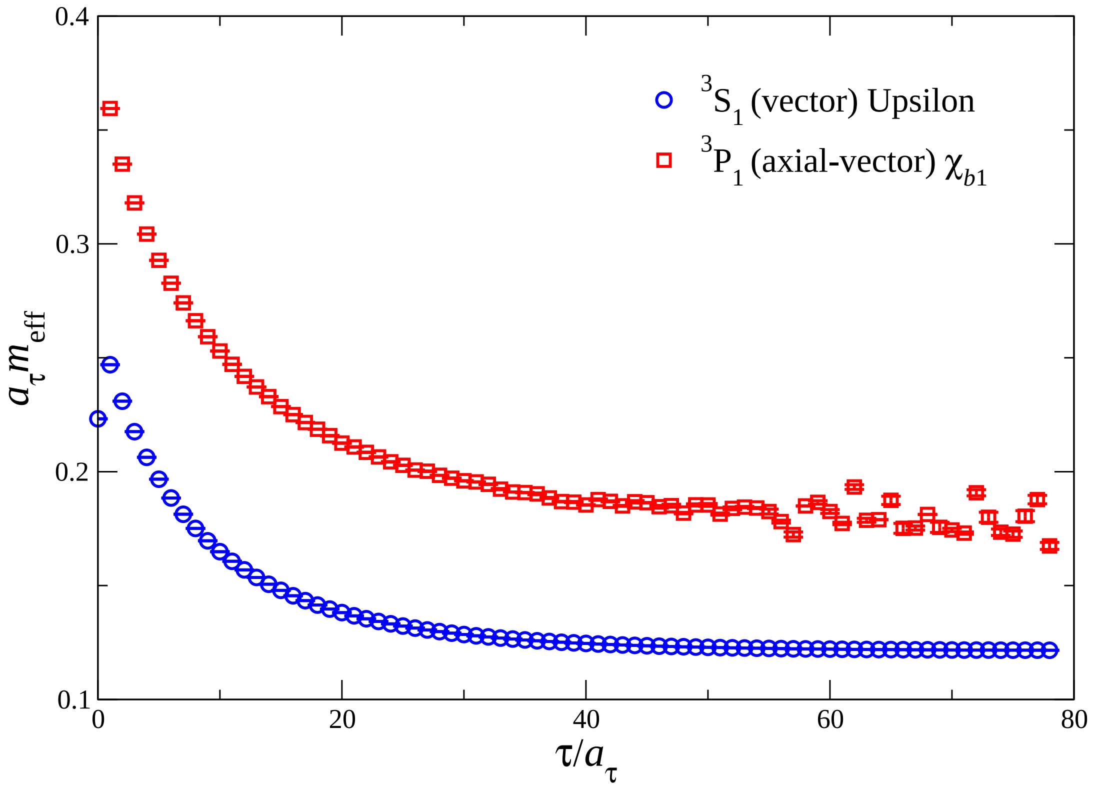
  NRQCD is initial-value problem



Υ (S-wave) and χ_{b1} (P-wave)

Spectrum at zero temperature

- exponential decay $G(\tau) \sim \exp(-m_{\rm eff}\tau)$
  effective mass plot $m_{\rm eff} = -\log[G(\tau)/G(\tau - a_\tau)]$



Υ (S wave) and χ_{b1} (P wave)

Spectrum

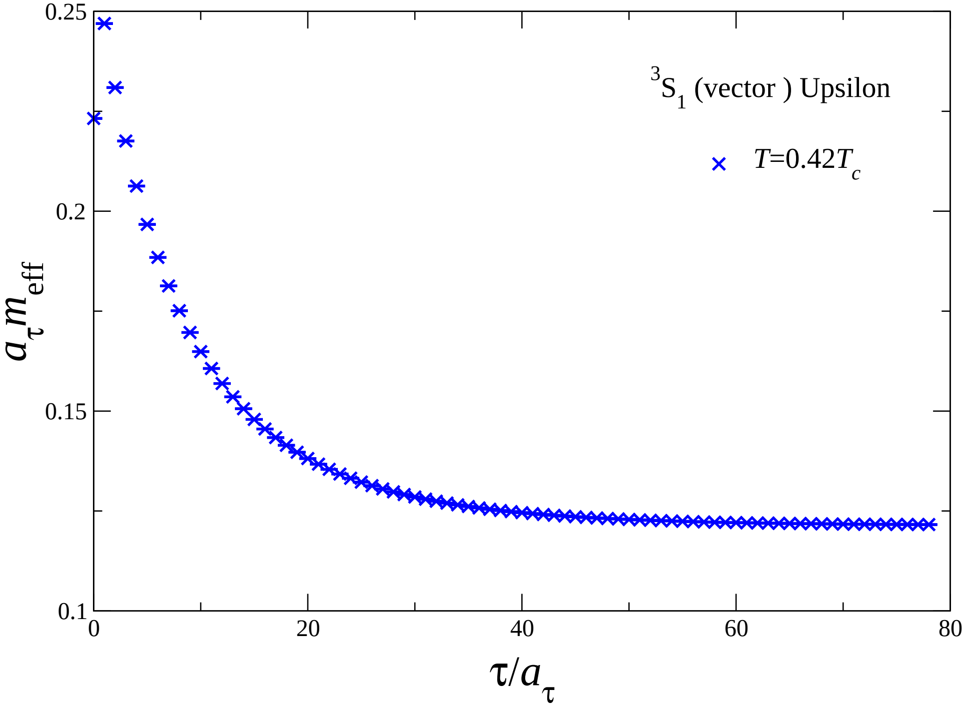
zero temperature: ground and first excited states

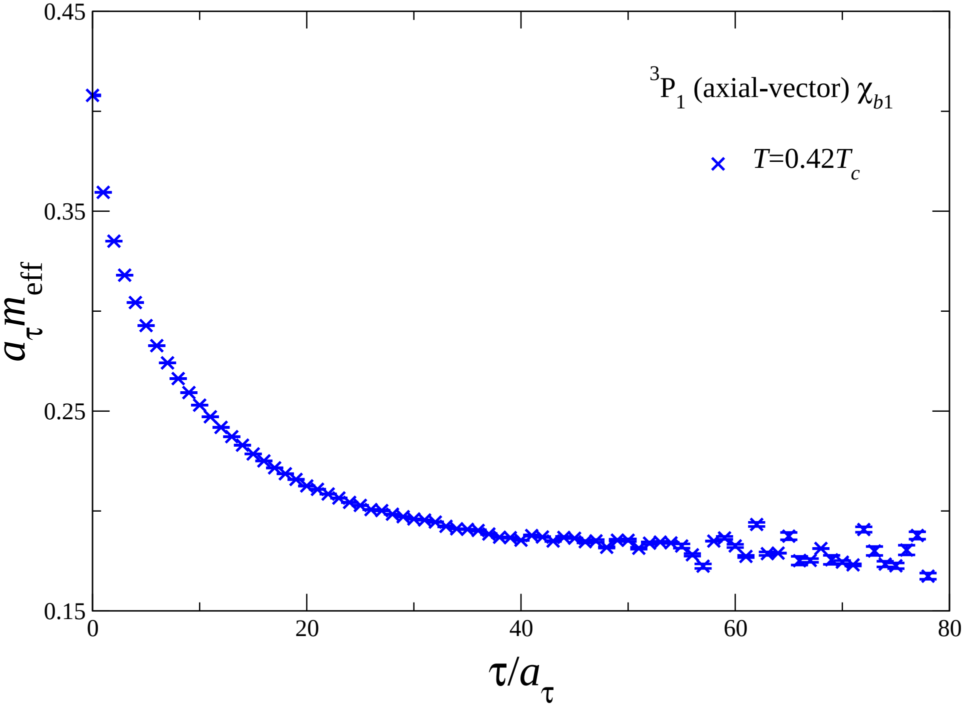
state	$a_\tau \Delta E$	Mass (MeV)	Exp. (MeV)
$1^1S_0(\eta_b)$	0.118(1)	9438(8)	9390.9(2.8)
$2^1S_0(\eta_b(2S))$	0.197(2)	10019(15)	-
$1^3S_1(\Upsilon)$	0.121(1)	9460^*	9460.30(26)
$2^3S_1(\Upsilon')$	0.198(2)	10026(15)	10023.26(31)
$1^1P_1(h_b)$	0.178(2)	9879(15)	9898.3(1.1)(1.1)
$1^3P_0(\chi_{b0})$	0.175(4)	9857(29)	9859.44(42)(31)
$1^3P_1(\chi_{b1})$	0.176(3)	9864(22)	9892.78(26)(31)
$1^3P_2(\chi_{b2})$	0.182(3)	9908(22)	9912.21(26)(31)

$*$ Υ(1S) used to set the scale

Increasing the temperature

Υ S wave $\qquad\qquad$ χ_{b1} P wave

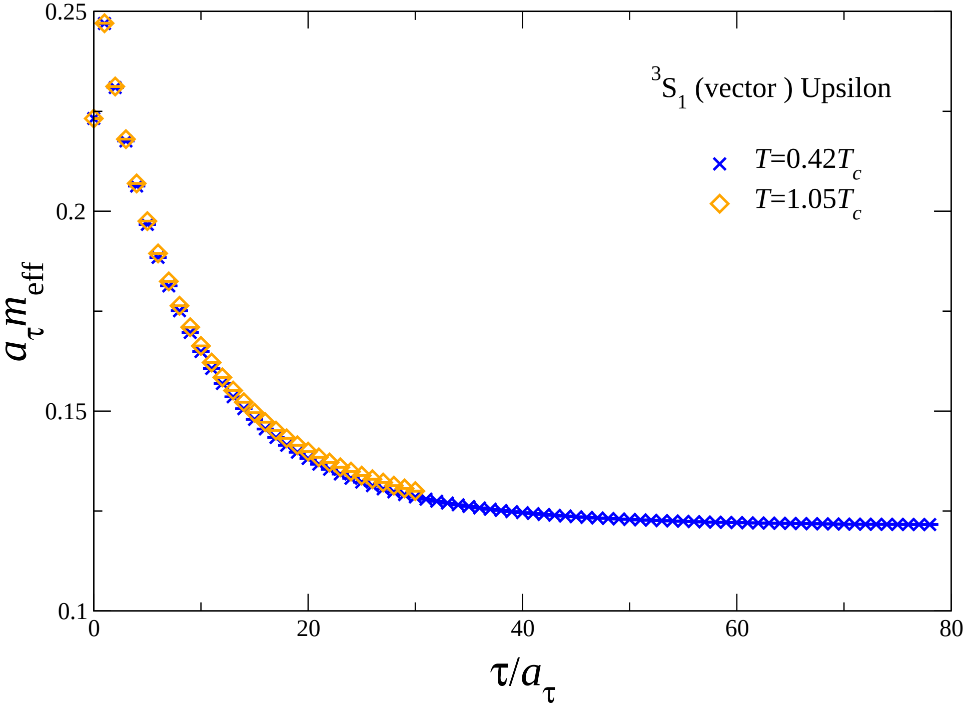


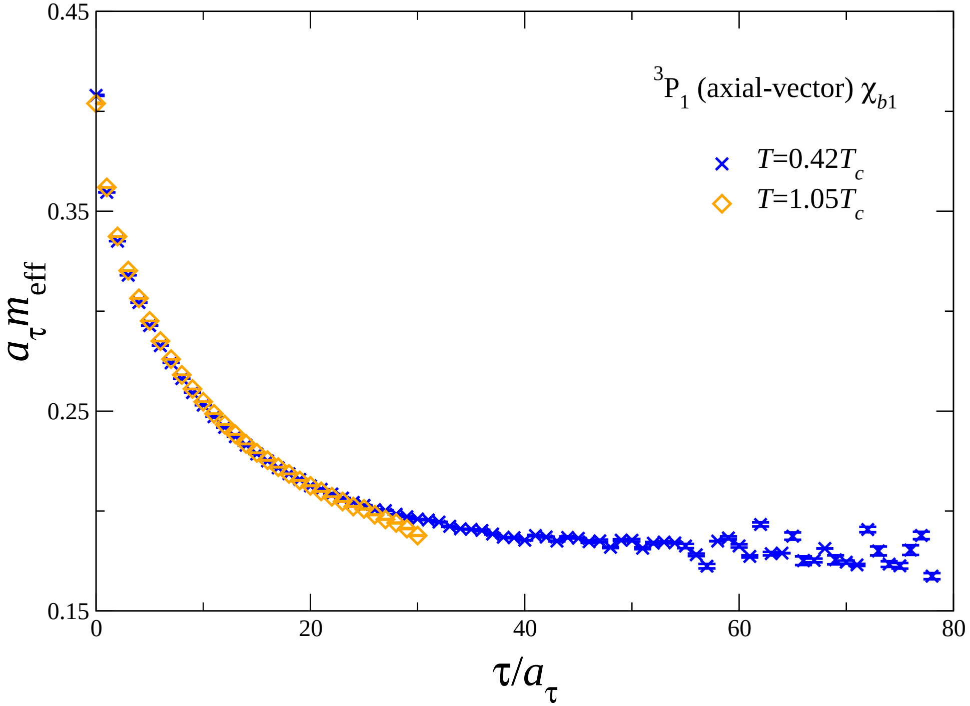


$$T/T_c = 0.42$$

Increasing the temperature

Υ S wave $\qquad\qquad$ χ_{b1} P wave

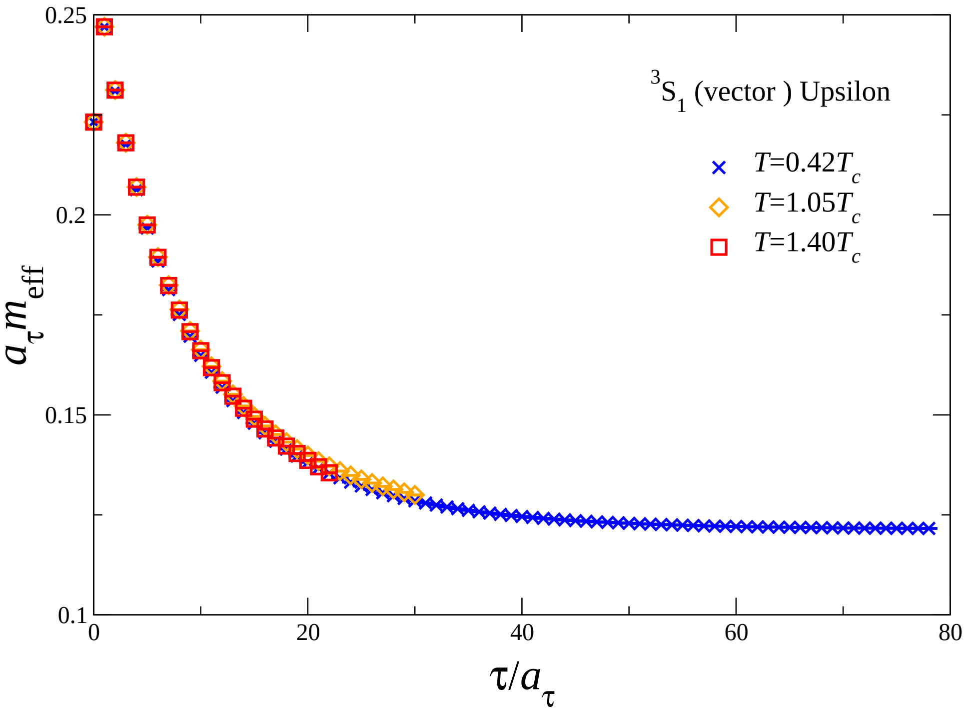


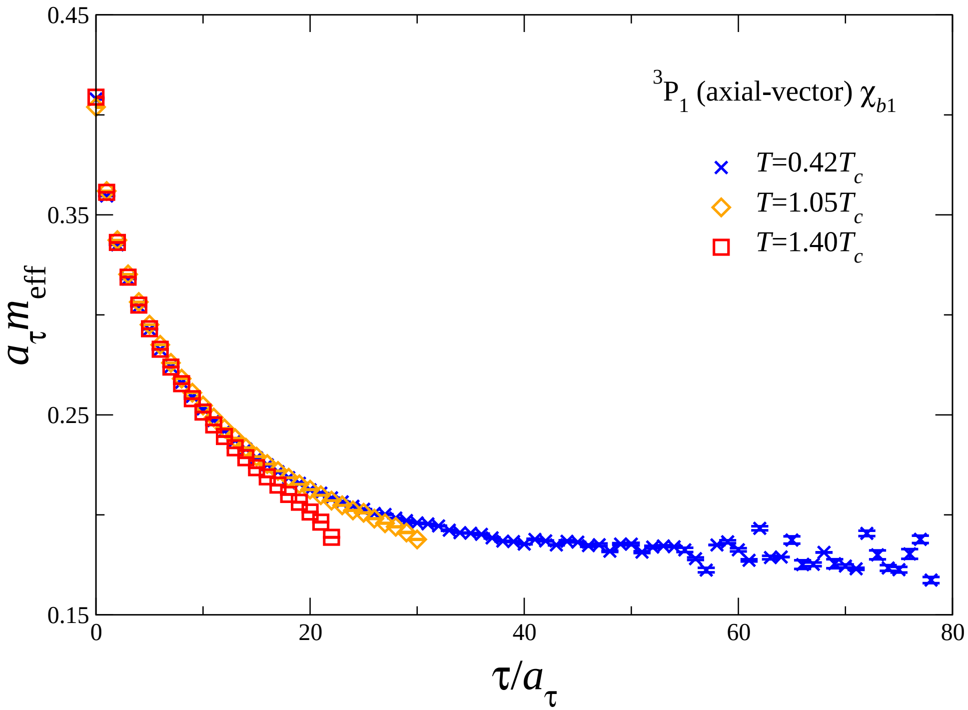


$$T/T_c = 1.05$$

Increasing the temperature

Υ S wave χ_{b1} P wave



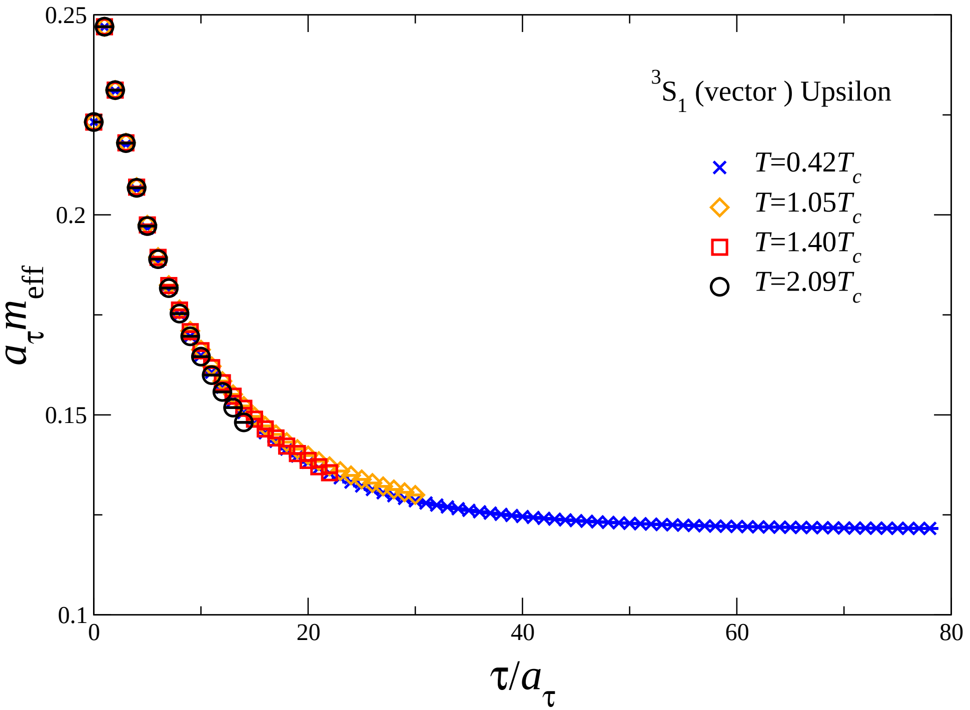


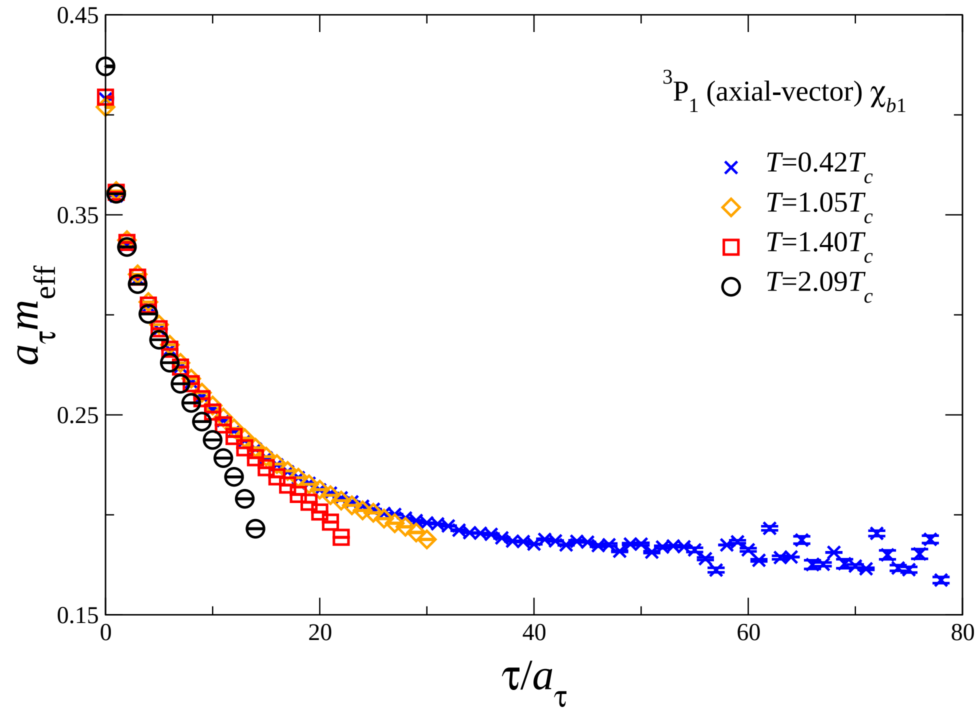
$$T/T_c = 1.40$$

Increasing the temperature

Υ S wave

χ_{b1} P wave





$$T/T_c = 2.09$$

little T dependence

substantial T dependence
no exponential decay
melting

Quarkonia at finite temperature

from euclidean correlators to spectral functions

$$G(\tau, \mathbf{p}) = \int d\omega\, K(\tau, \omega)\rho(\omega, \mathbf{p}) \qquad K(\tau, \omega) = \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}$$

- use Maximal Entropy Method (MEM)
- first discussed quite some time ago ...

  Asakawa & Hatsuda 1999, 2001

  Karsch, Petreczky et al 2002

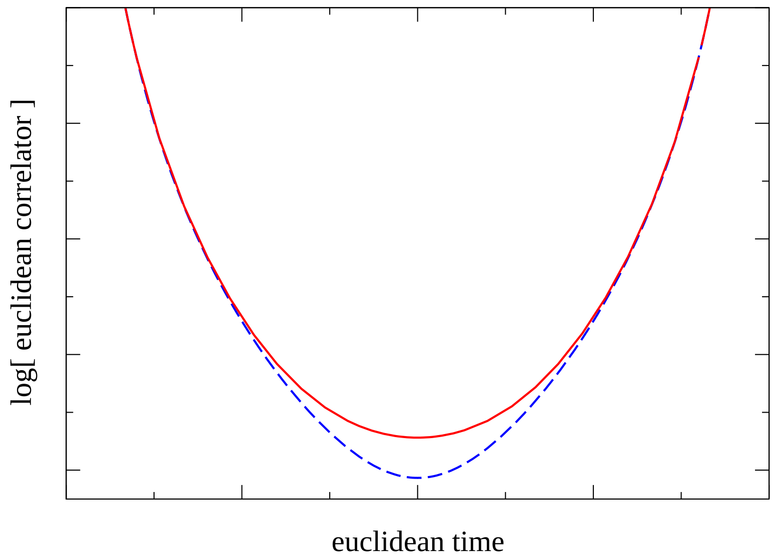
  ...
- ... but full of pitfalls and obstacles

Quarkonia at finite temperature

- in equilibrium: thermal boundary conditions
- euclidean correlators periodic
- spectral relation

$$G(\tau) = \int d\omega\, K(\tau,\omega)\rho(\omega)$$

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



- problematic small ω region: constant contribution

  transport, susceptibilities

G.A. & Martinez Resco 02, Petreczky & Teaney 05

Quarkonia at finite temperature

relativistic formulation:

- melting of quarkonia obscured by constant contribution

Umeda 07, Petreczky et al 07-09

NRQCD:

- constant contribution absent
- no thermal boundary condition
- simple spectral relation $G(\tau) = \int d\omega\, e^{-\omega\tau} \rho(\omega)$

why?

- factor out heavy quark mass scale: $\omega = 2M + \omega'$
- $M \gg T$: thermal effects exponentially suppressed

Quarkonia at finite temperature

- no thermal boundary conditions
- simple spectral relation $G(\tau) = \int d\omega \, e^{-\omega\tau} \rho(\omega)$

example:

correlators for free quarks with kinetic energy $E_{\mathbf{p}} = \frac{\mathbf{p}^2}{2M}$

$$G_S(\tau) \sim \int d^3p \, \exp\left(-2E_{\mathbf{p}}\tau\right) \qquad \rho_S(\omega) \sim \int d^3p \, \delta(\omega - 2E_{\mathbf{p}})$$

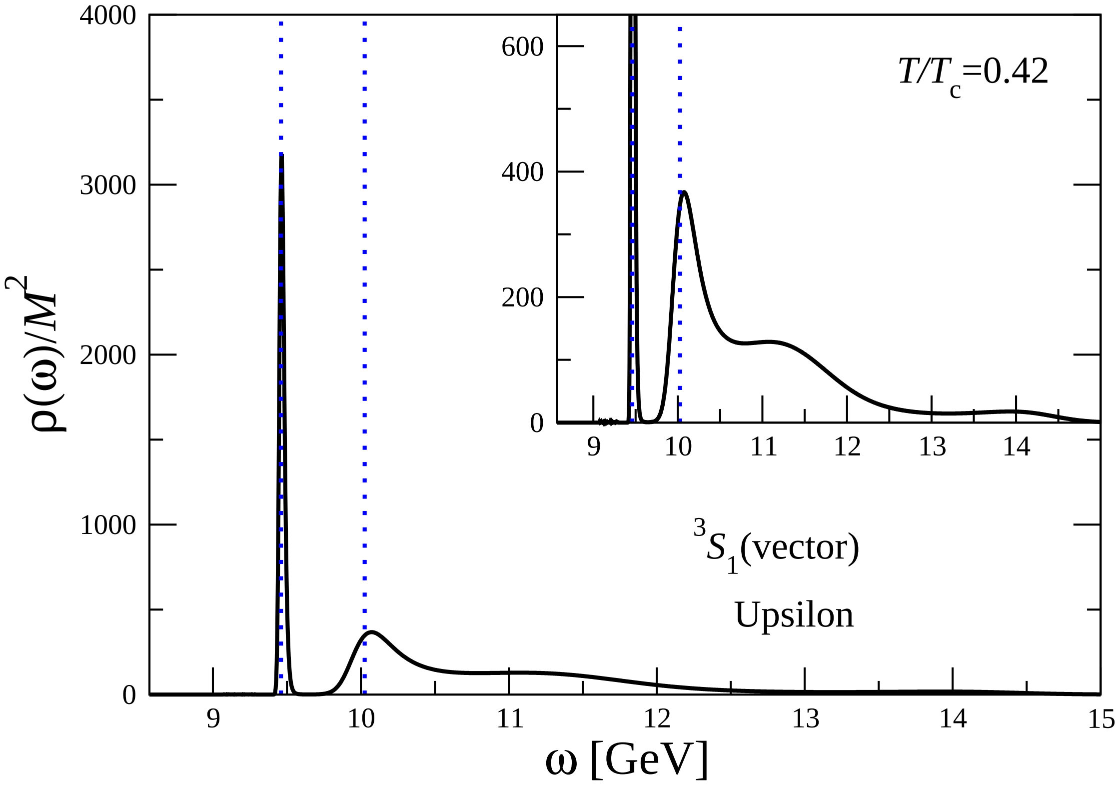
$$G_P(\tau) \sim \int d^3p \, \mathbf{p}^2 \exp\left(-2E_{\mathbf{p}}\tau\right) \qquad \rho_P(\omega) \sim \int d^3p \, \mathbf{p}^2 \delta(\omega - 2E_{\mathbf{p}})$$

Burnier, Laine & Vepsäläinen 08

- temperature dependence only enters via medium !

S wave at finite temperature

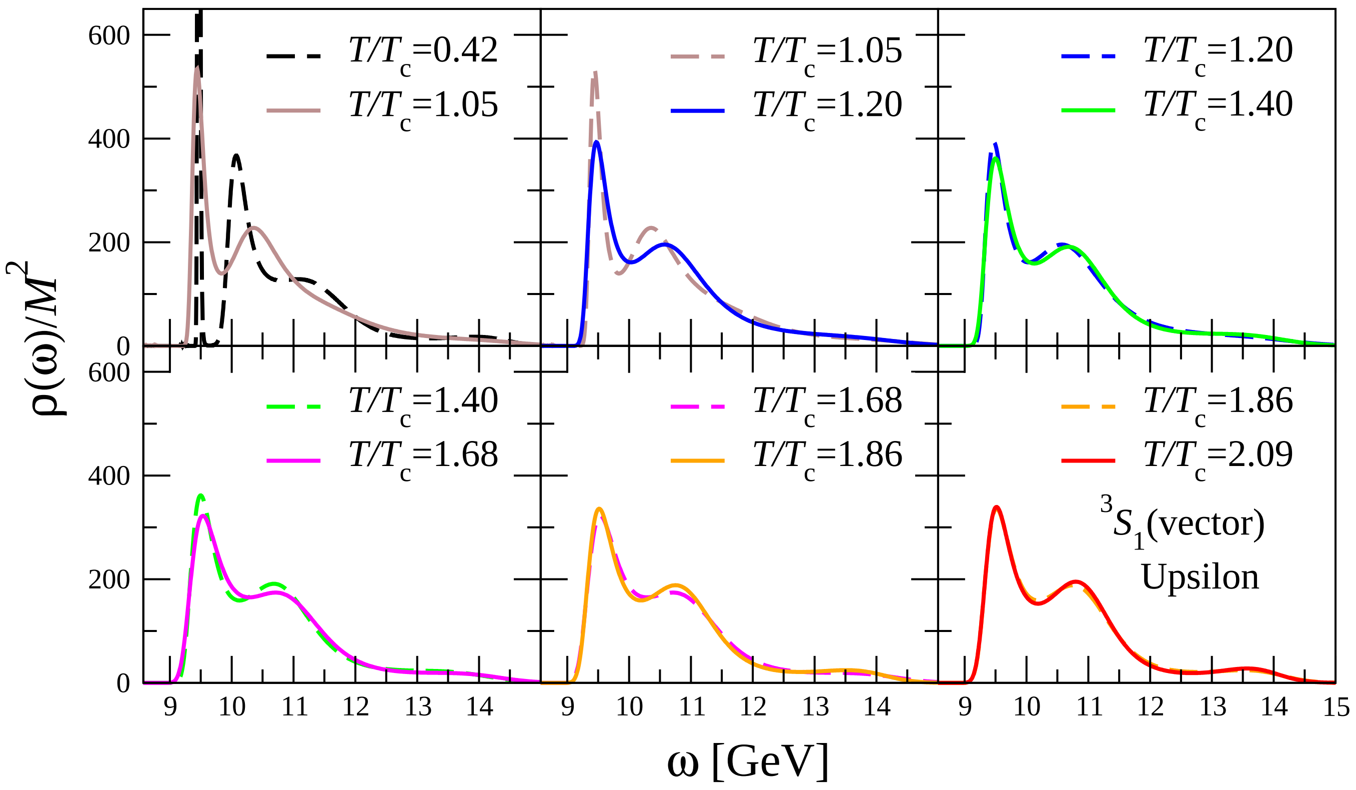
- Υ spectral function: zero temperature



- dotted: ground and first excited states from exp. fits

S wave at finite temperature

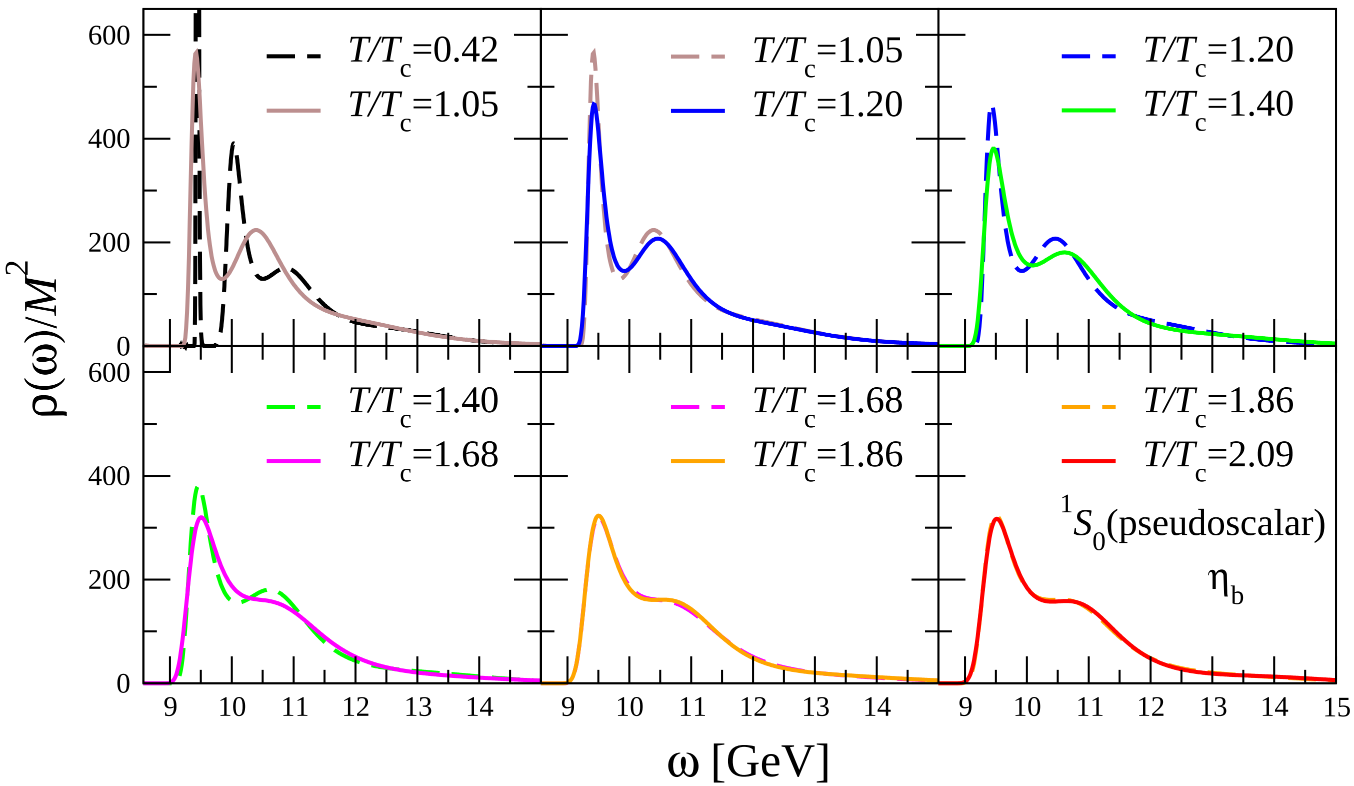
- temperature dependence in Υ channel



- Υ ground state survives – excited states suppressed
compare with CMS results

S wave at finite temperature

- temperature dependence in η_b channel



- η_b ground state survives – excited states suppressed

Υ at finite temperature

- extract mass shift and width of the ground state
- compare with EFT calculations
- assume weakly coupled plasma with scale separation

results (at leading order in α_s):

- thermal width

$$\Gamma = \frac{1156}{81}\alpha_s^3 T$$

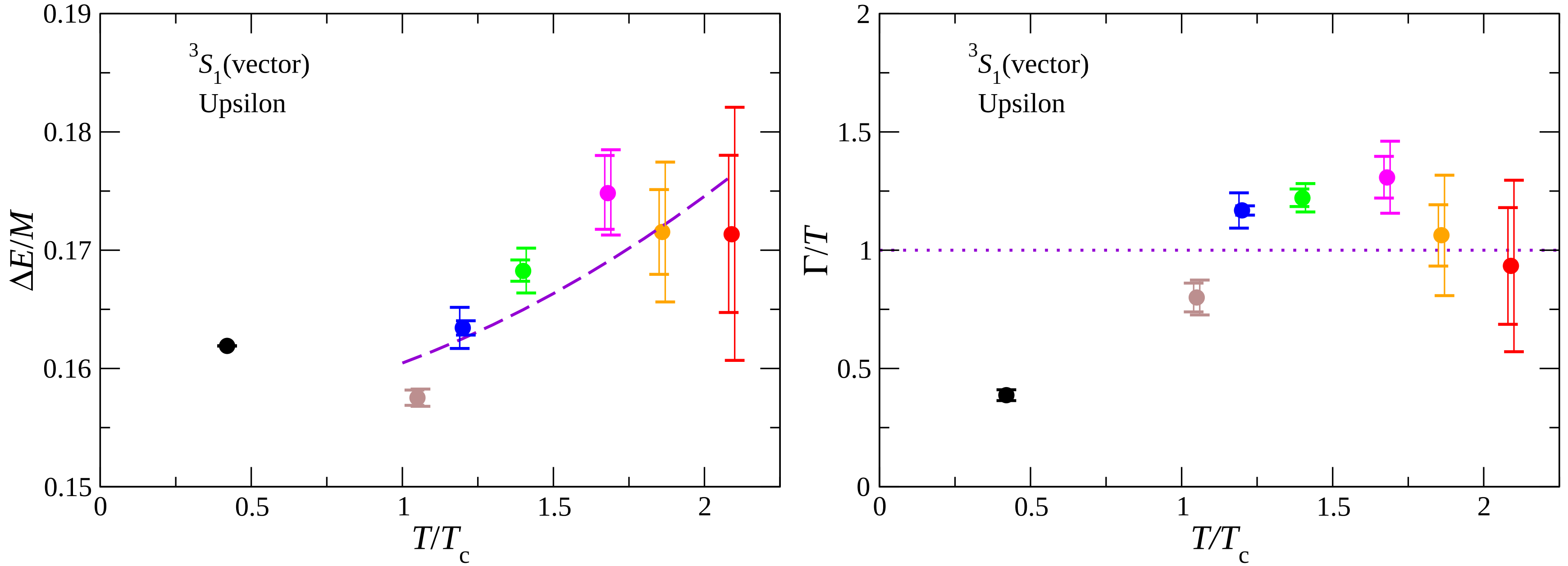
- thermal mass shift

$$\Delta E_{\rm th} = \frac{17\pi}{9}\alpha_s \frac{T^2}{M}$$

Brambilla, Escobedo, Ghiglieri, Soto & Vairo 10

Υ at finite temperature

- extract mass shift and width of the ground state



- compare with EFT

$$\Delta E \sim \alpha_s T^2/M \qquad\qquad \Gamma/T \sim \alpha_s^3$$

- one free parameter: $\alpha_s \sim 0.4$

moving Υ at finite temperature

non-zero momentum: moving through the QGP

- predictions from EFT, AdS/CFT, potential models, ...
- no clear picture: e.g. dissociates at lower/higher temperatures

on the lattice

$$a_s p_i = \frac{2\pi n_i}{N_s} \qquad\qquad n_i \lesssim \frac{N_s}{4}$$

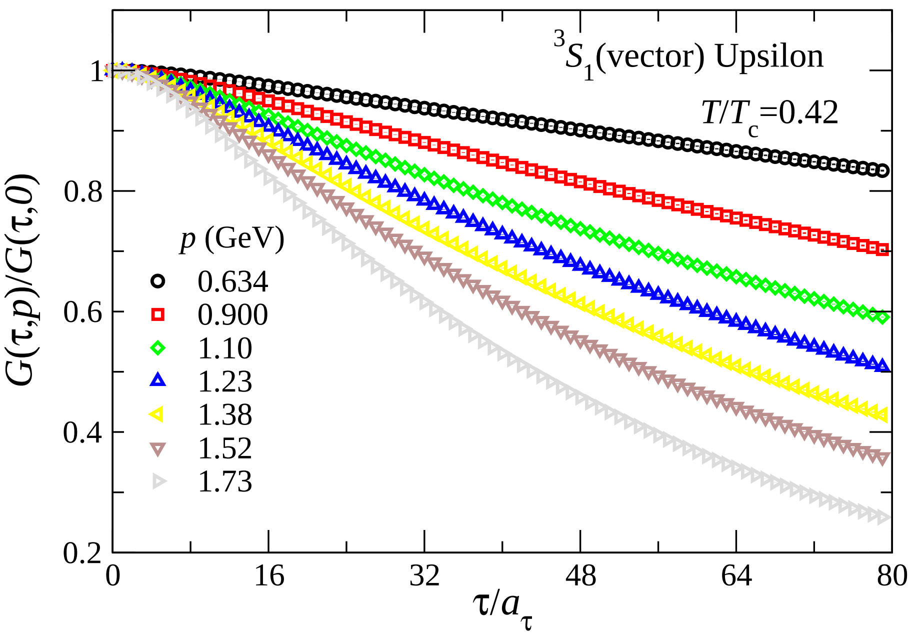
in our case:

- maximal momentum: $p_{\rm max} \sim 1.7$ GeV
- maximal velocity of ground state: $v = p/M_S \lesssim 0.2$

non-relativistic

moving Υ at finite temperature

- non-relativistic speeds: $v/c \lesssim 0.2$

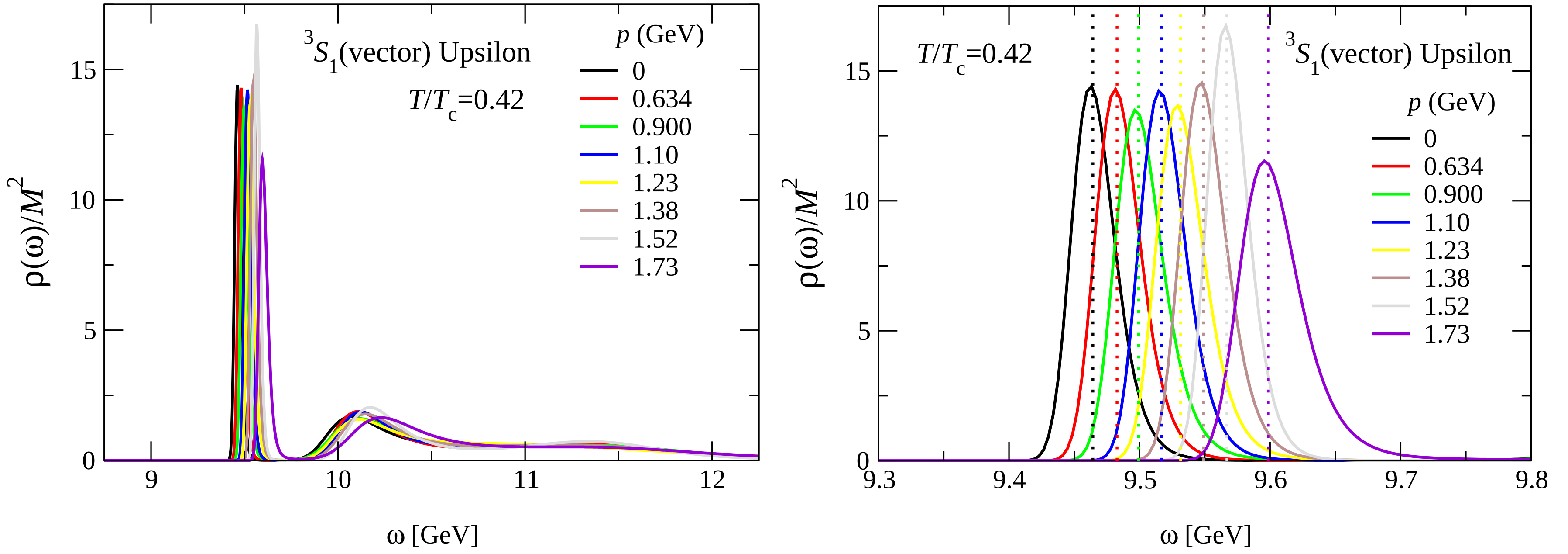


ratio $G(\tau,\mathbf{p})/G(\tau,\mathbf{0})$:

- clear momentum dependence in correlators
- expected from dispersion relation $M(p) = M + p^2/(2M)$

moving Υ at finite temperature

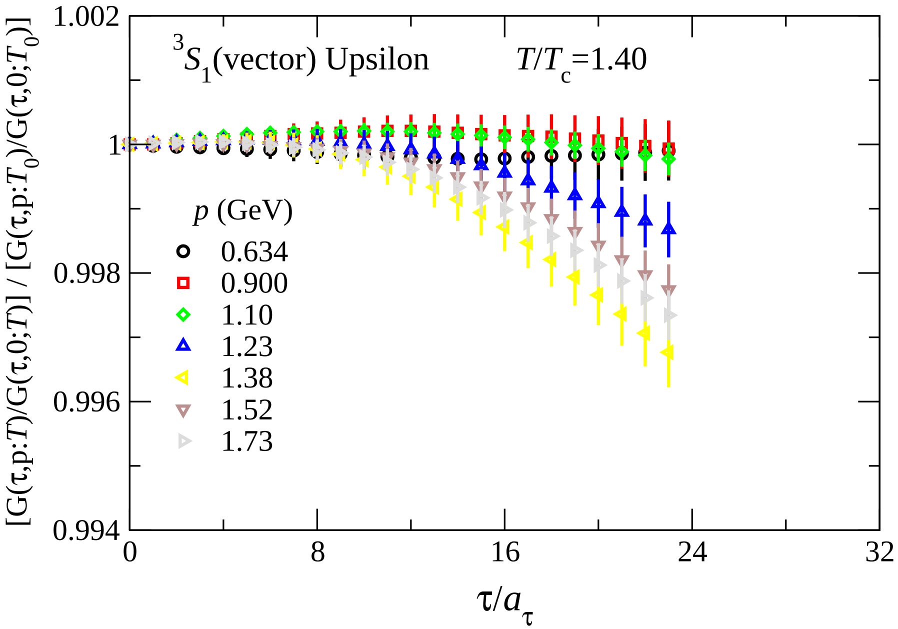
- non-relativistic speeds: $v/c \lesssim 0.2$



- momentum dependence reflected in spectral functions
- agreement with exponential fits

moving Υ at finite temperature

- non-relativistic speeds: $v/c \lesssim 0.2$

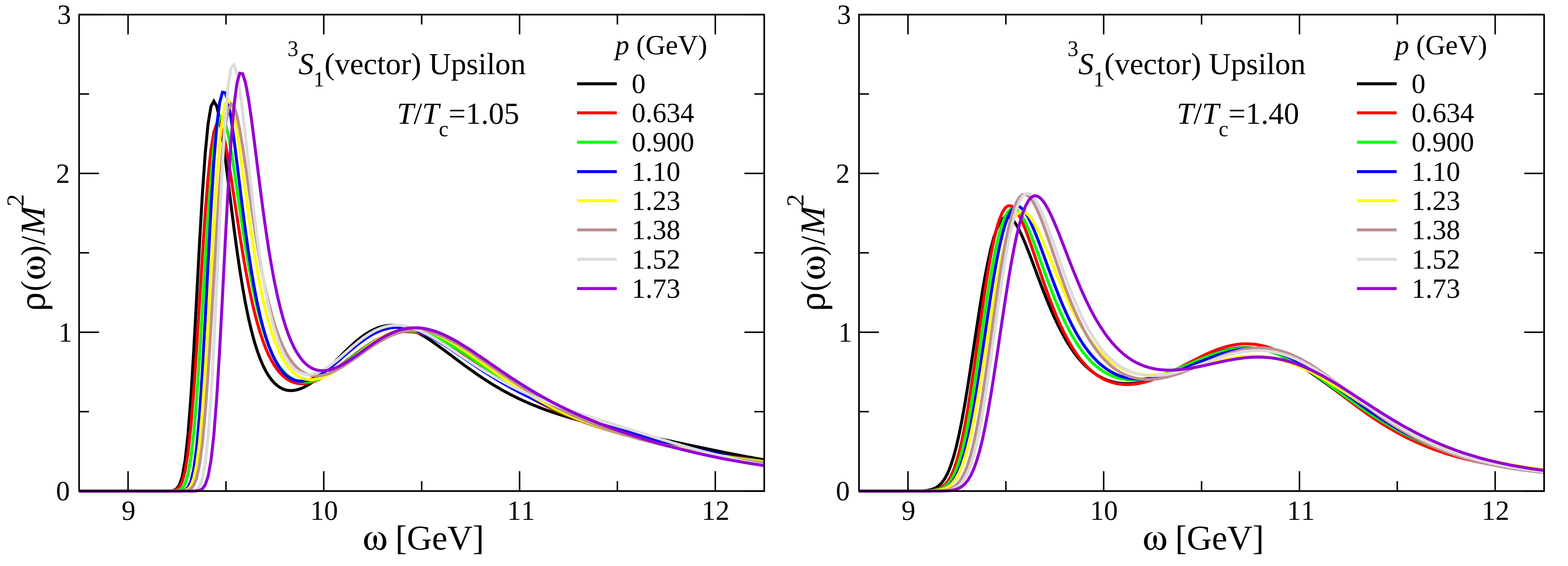


double ratio $[G(\tau,\mathbf{p};T)/G(\tau,\mathbf{0};T)]/[G(\tau,\mathbf{p};T_0)/G(\tau,\mathbf{0};T_0)]$

- very little temperature dependence in the momentum dependence

moving Υ at finite temperature

- non-relativistic speeds: $v/c \lesssim 0.2$

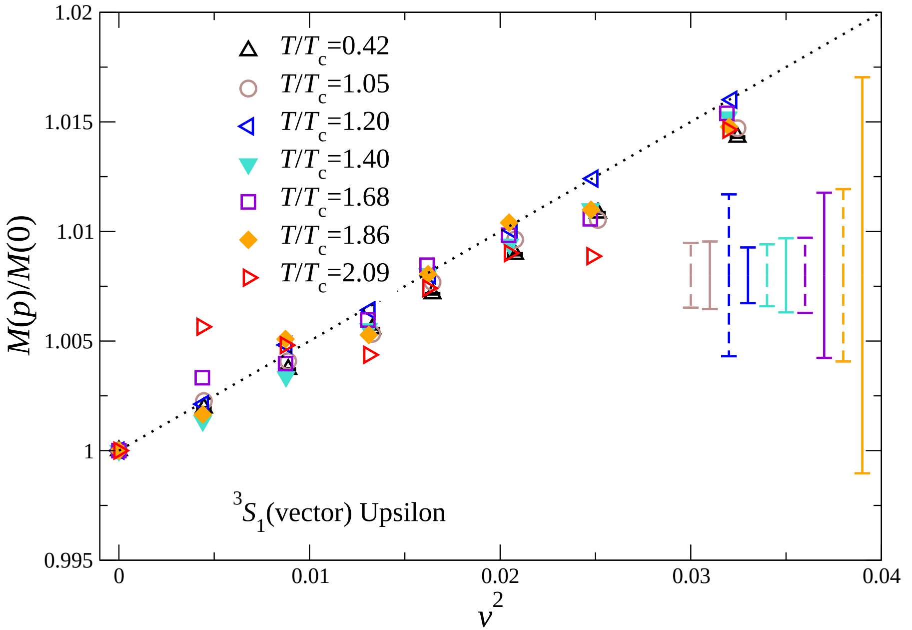


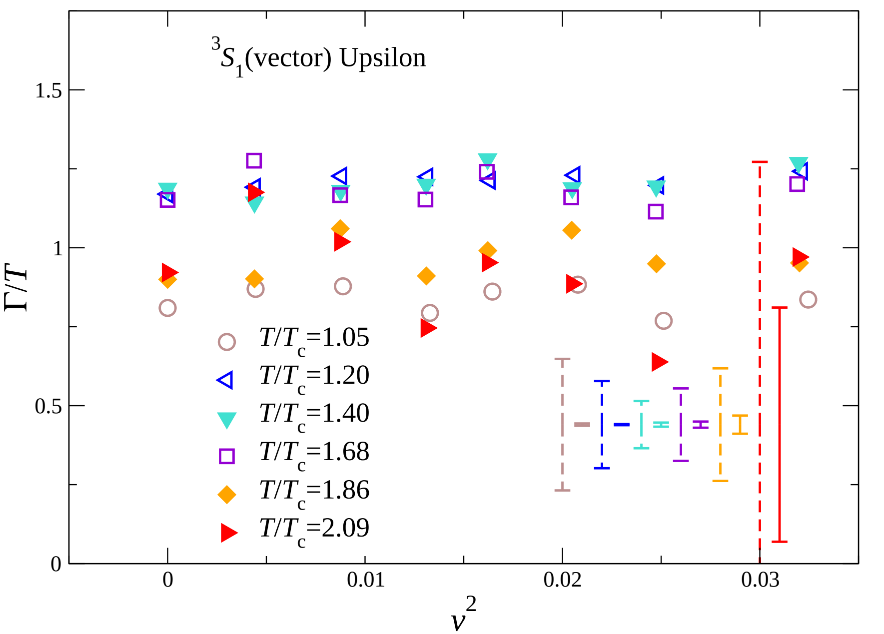
spectral functions:

- survival of moving groundstate

moving Υ at finite temperature

- non-relativistic speeds: $v/c \lesssim 0.2$

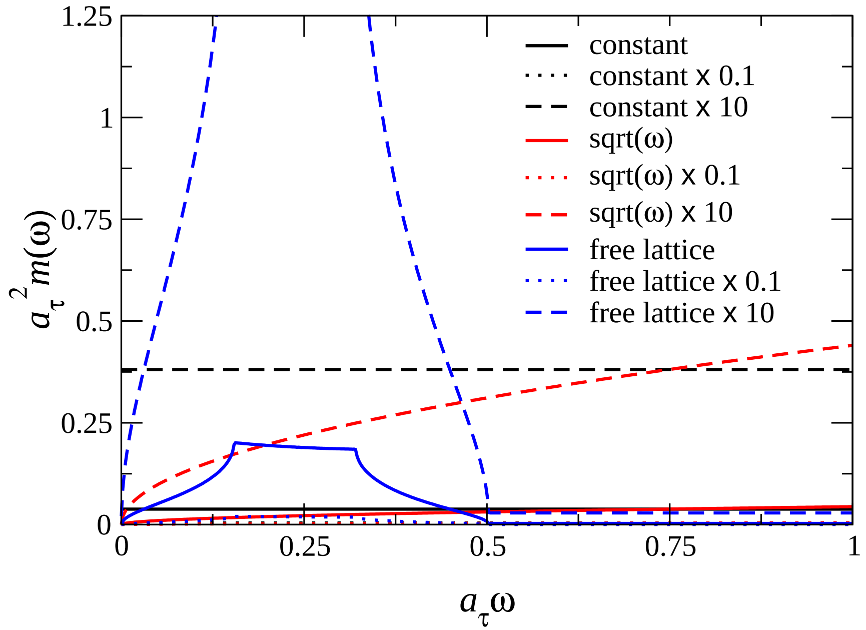




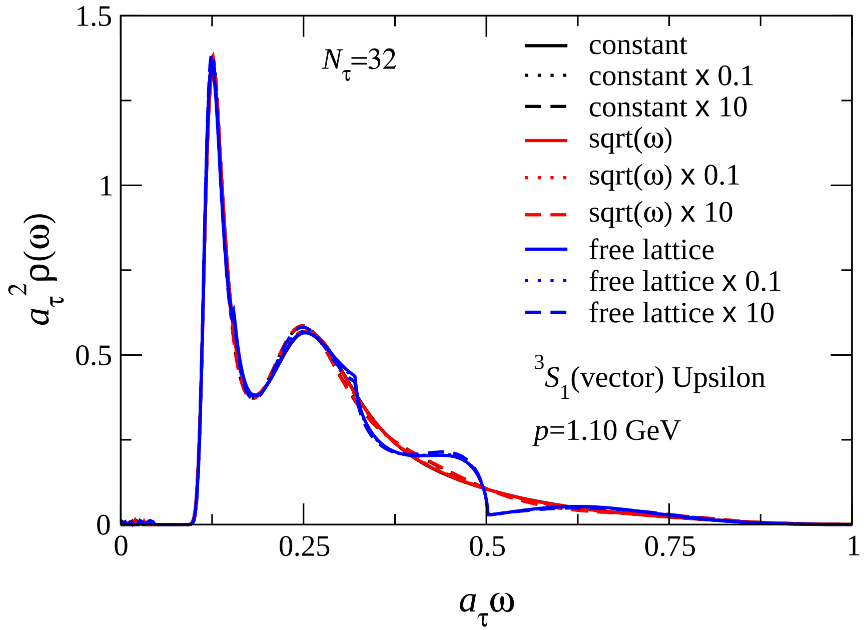
- extract dispersion relation $E(p)/M = 1 + \frac{1}{2}v^2$ and thermal width in the QGP
- thermal deviations? need to control uncertainties

moving Υ at finite temperature

- non-relativistic speeds: $v/c \lesssim 0.2$



MEM input



MEM output

- insensitivity to default model
- some sensitivity to maximal τ used

P waves at finite temperature

NRQCD:

no exponential decay – what to expect?

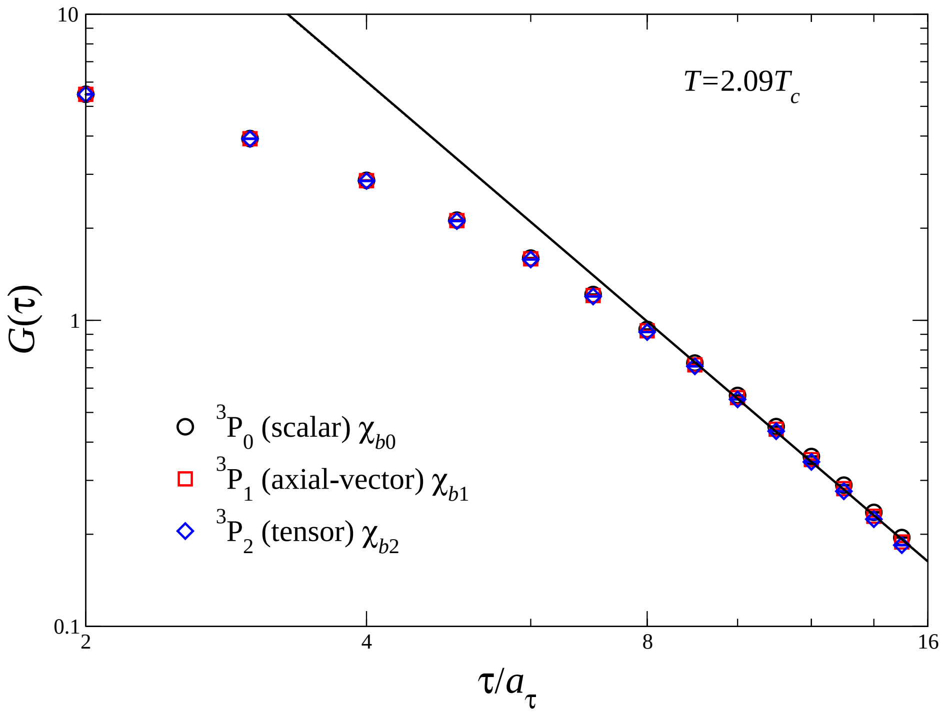
- consider free quarks with kinetic energy $E_{\mathbf{p}} = \frac{p^2}{2M}$

$$G_S(\tau) \sim \int d^3p\, e^{-2E_{\mathbf{p}}\tau} \sim \frac{1}{\tau^{3/2}}$$
$$G_P(\tau) \sim \int d^3p\, \mathbf{p}^2 e^{-2E_{\mathbf{p}}\tau} \sim \frac{1}{\tau^{5/2}}$$

- power decay at large euclidean times

P waves at finite temperature

- power decay at large euclidean times



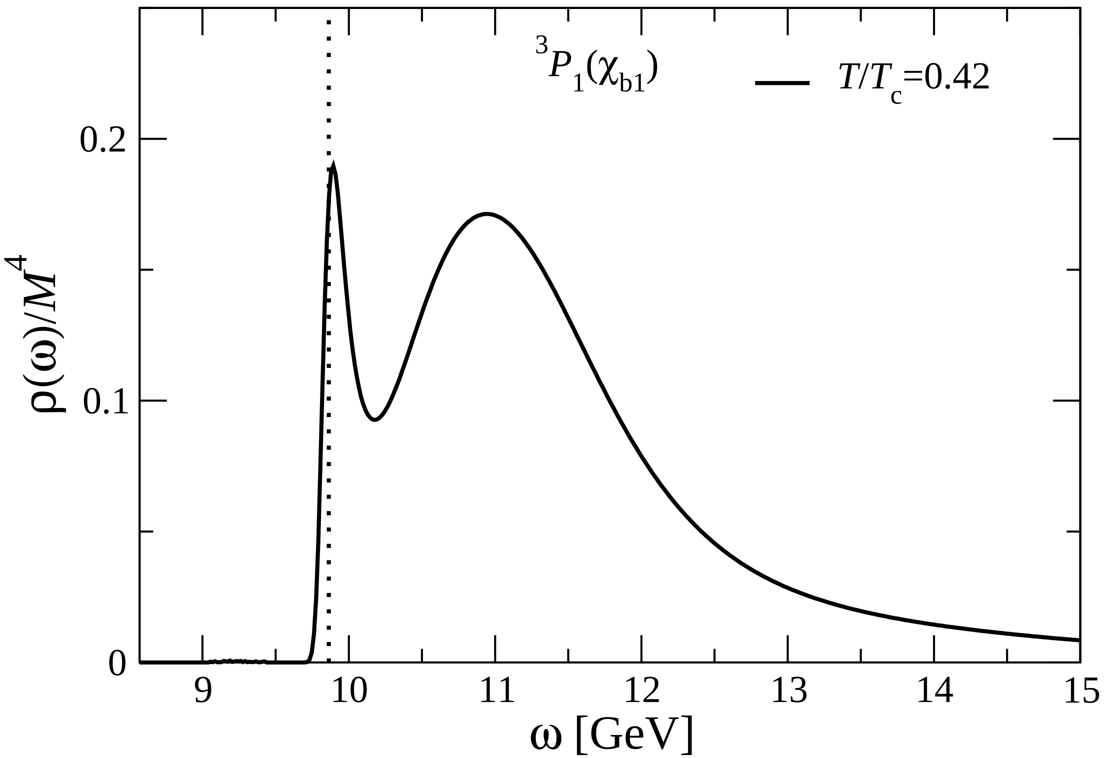
- fit: $G(\tau) \sim 1/\tau^\gamma$, $\gamma = 2.605(1)$

  without interactions: $\gamma = 5/2$

- spectral analysis?

P waves at finite temperature

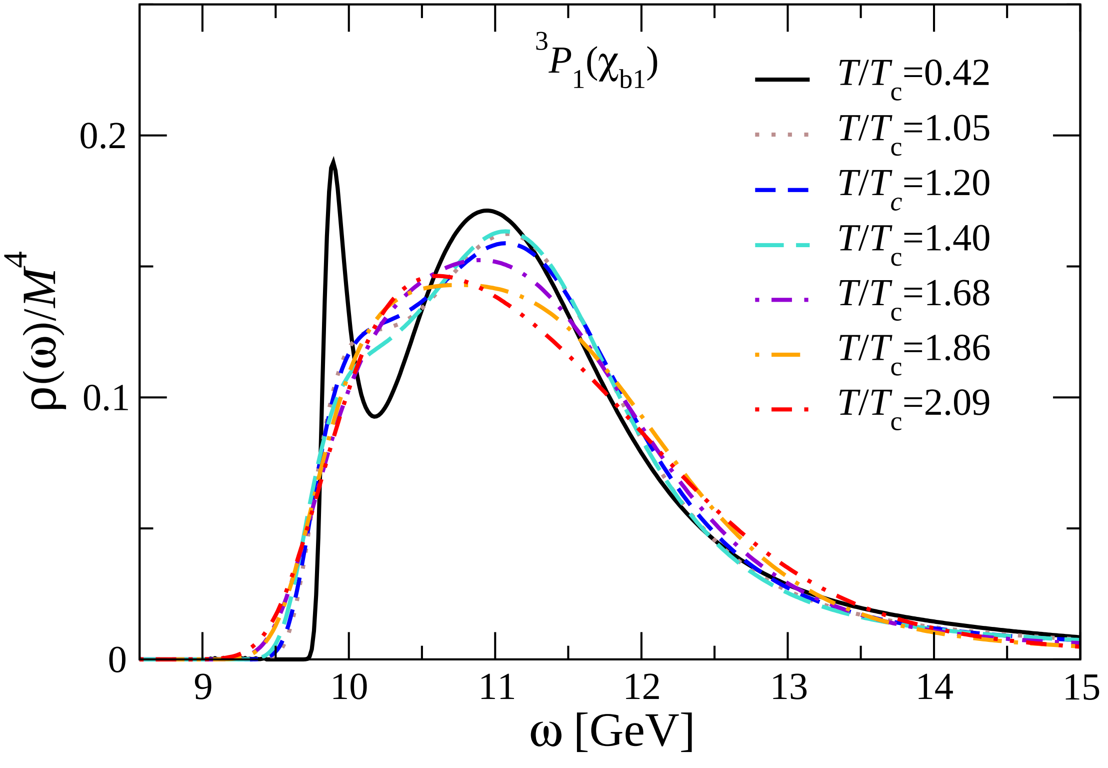
- χ_{b1} axial-vector channel (preliminary)



- groundstate below T_c, agreement with exp. fit

P waves at finite temperature

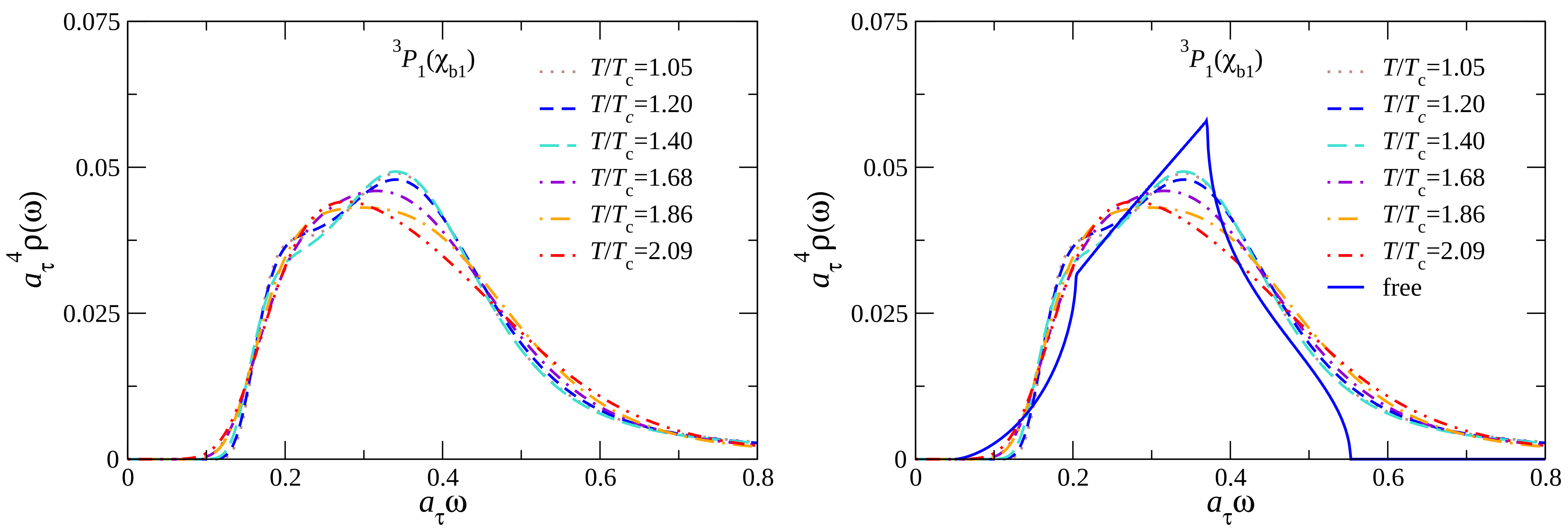
- χ_{b1} axial-vector channel (preliminary)



- melting immediately above T_c

P waves at finite temperature

- χ_{b1} axial-vector channel (preliminary)



- melting above T_c: a featureless blob ?
- shape similar to free lattice spectral function ?
- in progress

Summary

- bottomonium: NRQCD on QGP background
- S wave ground states survive, at rest and moving
  excited states appear suppressed
- P wave states melt immediately above T_c
- use of NRQCD greatly improves reliability of MEM
- in progress: extension to $N_f = 2 + 1$ on a finer lattice

EMMI workshop:

SIGN 2014

3rd international workshop on the sign problem
in QCD and related theories

18-21 February 2014

GSI, Darmstadt, Germany

organisers: Owe Philipsen and GA