Beauty in the QGP from the lattice

J. I. SKULLERUD
Department of Mathematical Physics, NUI Maynooth, Co Kildare, Ireland
FASTSUM COLLABORATION
G. Aarts, C.R. Allton, A. Kelly, S. Kim, M.P. Lombardo, M.B. Oktay, S.M. Ryan, D.K. Sinclair

NUI MAYNOOTH
Ollscoil na hÉireann Má Nuad

science foundation ireland
fondúireacht eolaíochta éireann

ABSTRACT

We study the temperature dependence of bottomonium for temperatures in the range $0.4T_c < T < 2.1T_c$, using nonrelativistic dynamics for the bottom quark and full relativistic lattice QCD simulations for $N_f = 2$ light flavors on a highly anisotropic lattice. We find that the Υ is insensitive to the temperature in this range, while the χ_b propagators show a crossover from the exponential decay characterizing the hadronic phase to a power-law behaviour consistent with nearly-free dynamics at $T \simeq 2T_c$ [1]

1 Introduction

Heavy quark bound states are important probes of the dynamics in the Quark Gluon Plasma. Charmonium suppression has been observed at a variety of energies at SPS and RHIC, but different, even competing, effects make it difficult to interpret charmonium suppression patterns. Such effects should be less significant for bottomonium. Since at LHC energies bottomonium will be produced copiously precision studies of the suppression pattern and its unambiguous link with the spectrum of bound states should be possible. The advent of the LHC calls therefore for precision studies of bottomonium at high temperature.

2 Effective field theories at nonzero T

At zero temperature it is possible to define a series effective field theories for heavy quarks, given a clear separation of scales between the heavy quark mass M, the typical distance r between heavy quarks, and the kinetic energy $E \sim Mv^2$. Starting from QCD and integrating out the hard degrees of freedom yields the effective theories outlined below.

Heavy quark mass	Quarkonium radius	Kinetic energy
M	$1/r \sim g^2M$	$mv^2 \sim g^4M$
QCD	NRQCD	pNRQCD

The introduction of the temperature scale T gives rise to several possible hierarchies and associated effective theories, eg

$$M \gg T > g^2M > gT \gg g^4M\,.$$

The effective theories combine features of (potential)NRQCD and hard thermal loop (HTL) effective theories [2].

2.1 NRQCD: advantages and disadvantages

Advantages

1. NRQCD relies only on the scale separation $M \gg T \gtrsim Mv$. Its use is fully justified for beauty quarks up to $2T_c \simeq 400$ MeV.
2. Beauty quarks can be simulated directly on the lattice, since the $\mathcal{O}(aM)$ discretisation errors are absent from the effective theory.
3. There are no thermal boundary conditions, ie the meson correlators are not periodic $G(\tau+\beta) \neq G(\tau)$. For a given lattice extent N_τ this doubles the effective number of points in the temporal direction, as there is no symmetry around $\tau = N_\tau/2$.
4. Because of this, there is no constant contribution to the correlator. This contribution complicates the reconstruction of spectral functions from euclidean correlators.

Disadvantages

1. NRQCD is not renormalisable, and it is not possible to take the continuum limit in lattice NRQCD: one must keep $a_\tau M \gtrsim 1$.
2. There is no absolute energy scale: only energy differences can be determined, and the spectral function extends to negative frequencies.

2.2 Free NRQCD correlators

To study what to expect when quarks are no longer bound, consider free quarks in continuum NRQCD with energy $E_\mathbf{p} = \mathbf{p}^2/2M$. The correlators for the S and P waves are then of the form [3]

$$G_S(\tau) \sim \int \frac{d^3p}{(2\pi)^3} \exp(-2E_\mathbf{p}\tau) \sim \tau^{-3/2}, \qquad (1)$$

$$G_P(\tau) \sim \int \frac{d^3p}{(2\pi)^3}\, \mathbf{p}^2 \exp(-2E_\mathbf{p}\tau) \sim \tau^{-5/2}, \qquad (2)$$

i.e., they decay as a power for large euclidean time. Interactions and finite lattice spacing and volume effects will modify this in the realistic case.

3 Results

We use the two-plaquette Symanzik improved gauge action [4] with the fine-Wilson coarse-Hamber–Wu fermion action [5] for the sea quarks. The parameters, given below, are the same as were previously used in studies of charmonium at high temperature [6, 7]. We computed NRQCD propagators on these configurations using a mean-field improved action with tree-level coefficients, including terms up to and including $\mathcal{O}(v^4)$.

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

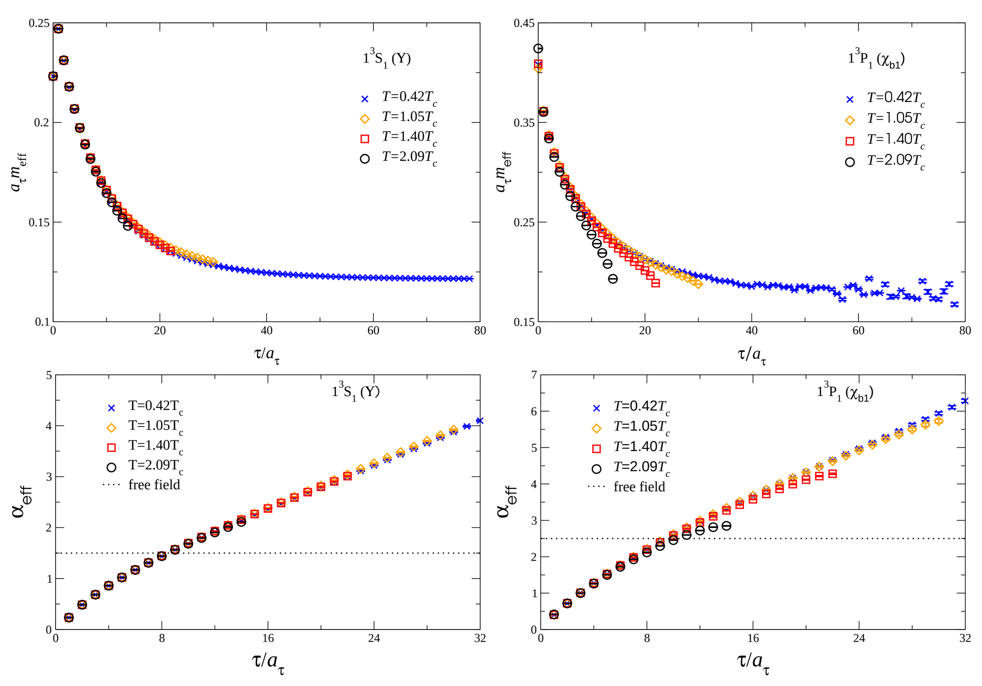
3.1 Υ and χ_b correlators in the plasma

To distinguish between bound states and free correlators, we constructed two quantities from the euclidean correlators:

Effective mass $$m_{\rm eff}(\tau) = -\log\frac{G(\tau)}{G(\tau-a_\tau)} \qquad (3)$$

Effective power $$\gamma_{\rm eff}(\tau) = -\tau\frac{G(\tau+a_\tau)-G(\tau-a_\tau)}{2a_\tau G(\tau)}, \qquad (4)$$

In the hadronic phase, with exponential decay characteristic of bound states, $m_{\rm eff}$ goes to a constant at large τ. When the quarks are unbound, the correlators will show power-law behaviour consistent with (1, 2), and $\gamma_{\rm eff}$ will go to a constant.

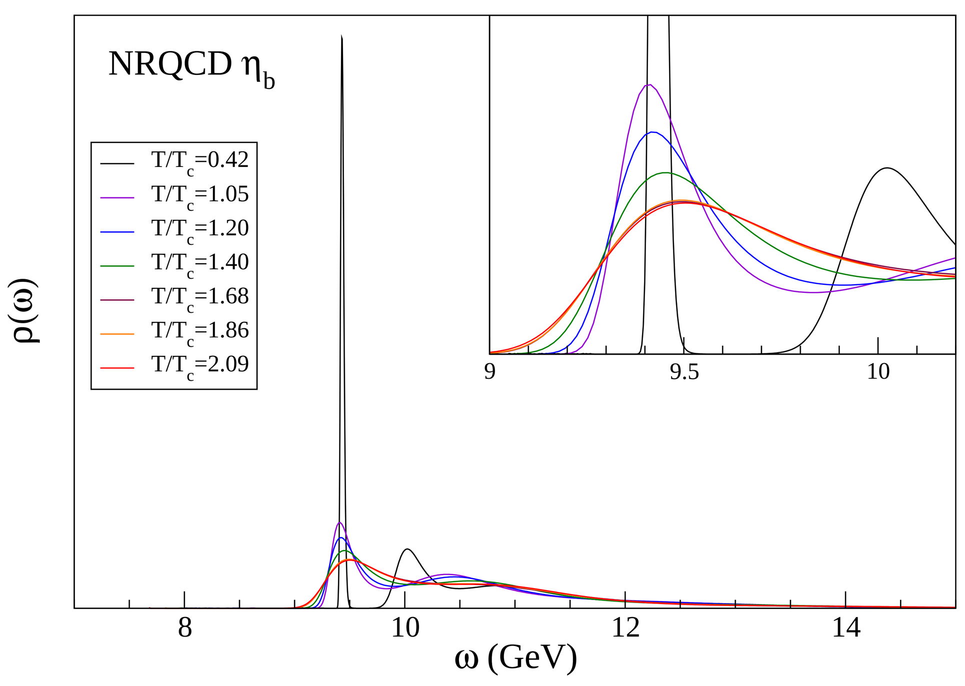


In both S- and P-wave channels we see the expected bound state behaviour at low T. For the Υ (S-wave), the correlator is nearly temperature-independent, while for the χ_b (P-wave) we see an approach to the noninteracting power-law behaviour at $T \approx 2T_c$.

3.2 Spectral functions

We have computed spectral functions from the NRQCD correlators with the maximum entropy method, using the relation

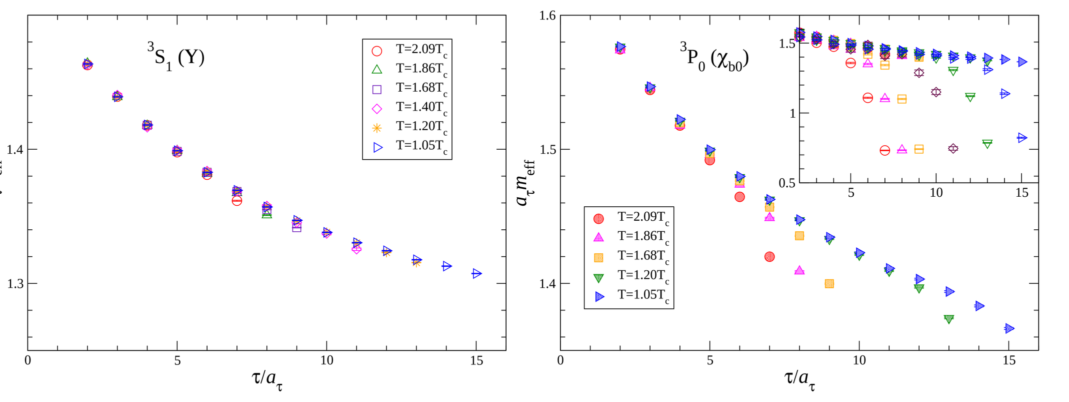
$$G(\tau) = \int_{-2M}^{\infty} \frac{d\omega'}{\pi}\, e^{-\omega'\tau}\rho(\omega')\,. \qquad (5)$$



At low temperature we can clearly identify the ground and first excited state peaks in the pseudoscalar (η_b) channel. At $T > T_c$ the excited state peak is absent, while the ground state remains until at least $1.4-1.6T_c$. The broadening of the peaks needs to be investigated further, since both finite volume and artefacts of the MEM algorithm may influence the apparent peak width However, the broadening is not due to finite statistics.

3.3 Relativistic beauty

Using the same relativistic action as for the sea quarks (and the charm quarks in [6, 7]) we have computed correlators in all S- and P-wave channels. For the P-waves both point and derivative operators were used.



In the S-wave channel (Υ) the correlator shows no significant temperature-dependence. For the P-wave χ_{b0} there is a significant trend in qualitative agreement with the NRQCD data, although the magnitude of the deviations from the low-temperature correlator is smaller when using a derivative operator (filled symbols). Correlators of point operators (open symbols) have a large constant mode due to the thermal boundary conditions, and as a result $m_{\rm eff}$ goes to 0 at large τ.

Preliminary results from a MEM analysis suggests that the S-wave η_b survives at least up to $T \gtrsim 1.4T_c$. Lattice artefacts and thermal boundary effects make it hard to draw any further conclusions at this stage.

4 Conclusions and outlook

- S-wave correlators are almost independent of T up to $T \approx 2T_c$.
- P-wave correlators are significantly modified for $T \gtrsim 1.4T_c$, and approach their noninteracting form at $T \approx 2T_c$.
- The maximum entropy analysis suggests that S-waves acquire a large thermal width Γ above T_c, with $\Gamma \gtrsim T$ for $T \gtrsim 1.4T_c$. This requires further investigation.
- Our results indicate that a large Υ suppression may be observed at the LHC: the feed-down from χ_b and Υ' is likely to be gone, and it is possible that even direct Υs may be suppressed above $1.4T_c$.
- We are in the process of extending the MEM analysis to all S- and P-wave channels, including a thorough investigation of systematic uncertainties. Comparing results from the relativistic and the nonrelativistic formulation will allow us to assess the systematic uncertainties inherent in both approaches.
- This study will shortly be extended using gauge configurations with a realistic ($N_f = 2+1$) light flavour content and a smaller spatial lattice spacing. An investigation of possible finite volume effects will also be carried out on these configurations.

References

[1] G. Aarts *et al.*, Phys. Rev. Lett. **106**, 061602 (2011) [arXiv:1010.3725].

[2] N. Brambilla, J. Ghiglieri, A. Vairo and P. Petreczky, Phys.Rev. **D78**, 014017 (2008) [arXiv:0804.0993].

[3] Y. Burnier, M. Laine and M. Vepsalainen, JHEP **0801**, 043 (2008) [arXiv:0711.1743].

[4] C. Morningstar and M. J. Peardon, Nucl. Phys. Proc. Suppl. **83**, 887 (2000) [hep-lat/9911003].

[5] TrinLat, J. Foley, A. Ó Cais, M. Peardon and S. M. Ryan, Phys. Rev. **D73**, 014514 (2006) [hep-lat/0405030].

[6] G. Aarts, C. Allton, M. B. Oktay, M. Peardon and J.-I. Skullerud, Phys. Rev. **D76**, 094513 (2007), [arXiv:0705.2198].

[7] M. B. Oktay and J. I. Skullerud, arXiv:1005.1209.

Acknowledgments

This work was supported by Science Foundation Ireland grant number RFP–08–PHY1462, using computing resources from the Trinity Centre for High Performance Computing.