

NRQCD based S- and P-wave bottomonium spectra at finite temperature from $48^3 \times 12$ lattices with $N_f = 2 + 1$ light HISQ flavors

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We study S-wave and P-wave bottomonium spectral functions at non-zero temperature in 2+1 flavor QCD using the NRQCD formulation for bottom quarks. We use a novel Bayesian approach to reconstruct the spectral functions and find that χ_{b1} survives up to $T = 249\text{MeV}$. We also study the effect of different temporal discretizations of the NRQCD formalism on the bottomonium correlation functions.

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1. Introduction

Quarkonium suppression has been suggested as the signal for the formation of a deconfined medium in heavy ion collisions by Matsui and Satz [1]. Since this seminal work the properties of quarkonium at non-zero temperature became a subject of intense theoretical studies (see e.g. Ref. [2] for a recent review). In recent years interesting experimental results appeared on bottomonium suppression in heavy ion collisions [3, 4, 5] making first principle lattice QCD studies of bottomonium properties at non-zero temperature timely. The study of bottomonium in lattice QCD is challenging due to the large bottom quark mass M_b . In standard lattice formulations discretization effects will be proportional to aM_b , and thus will be very large for typical values of the lattice spacing a available in today's calculations. Fortunately one can use the effective field theory approach and integrate out the physics related to the large bottom quark mass [6, 7]. This approach is known as non-relativistic QCD or NRQCD for short. It is widely used today to study bottomonium properties at zero temperature in lattice QCD (see e.g. Ref. [8]). NRQCD was first proposed to study quarkonium properties at non-zero temperature in Ref. [9] and recently it was used for bottomonium at non-zero temperature in 2-flavor and 2+1 flavor QCD [10, 11, 12, 13, 14] at un-physically large u/d quark mass corresponding to pion masses of about 400 MeV. In this contribution we will present a study of bottomonium correlation functions and spectral functions at non-zero temperature in 2+1 flavor QCD with nearly physical values of the strange and light quark masses using the $48^3 \times 12$ gauge configuration generated by HotQCD collaboration [15]. The chiral transition temperature corresponding to these lattices is about 159 MeV [15]. A more detailed account of this work can be found in Ref. [16], while preliminary results have been presented at Lattice 2013 conference [17].

2. Bottomonium in Lattice NRQCD

In order to investigate the properties of bottomonium in a thermal medium, we compute the correlators of heavy quarkonium using a lattice discretization of the $\mathcal{O}(v^4)$ NRQCD Lagrangian [7] for bottom quarks. In this approach the bottom quark is not part of the thermal medium and no temporal boundary conditions are imposed on the bottom quark. The bottom quark propagator is calculated as an initial value problem in the imaginary time direction with a step-size determined by the lattice spacing and the so-called Lepage parameter n (see Ref. [16] for a detailed discussion). We use the value $n = 2$ for the Lepage parameter which is suitable as long as $aM_b > 1.5$. We also consider $n = 3$ and 4 in our calculations and tested that our conclusions do not depend on the choice of n . The use of the NRQCD formulation in the study of quarkonium spectral functions has at least two advantages. First, the so-called zero mode contribution [18, 19] is absent in this case, making the analysis of the correlators easier. Second, because of the absence of periodic boundary conditions quarkonium correlators can be studied up to twice larger separations in Euclidean time, namely, $\tau_{max} = 1/T$ instead of $\tau_{max} = 1/(2T)$ in the usual (relativistic) formulation.

We start the discussion with presenting our numerical results at zero temperature. In Fig. 1 we show the results on the zero temperature Υ and χ_{b1} correlators for four values of the gauge coupling $\beta = 10/g^2 = 6.74, 6.80, 6.95$ and 7.28 in terms of the effective masses $am_{eff}(\tau) = \ln(D(\tau/a)/D(\tau/a+1))$. These values of the gauge coupling correspond to temperatures $T =$

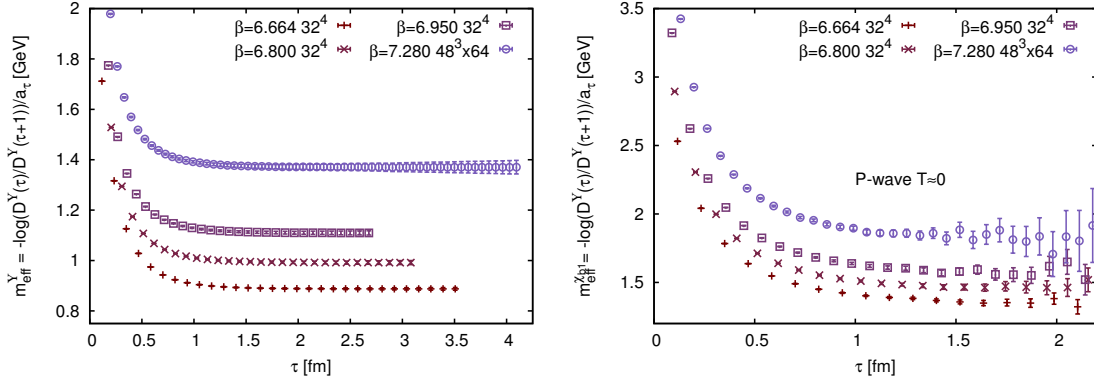


Figure 1: The effective masses $m_{\text{eff}}(\tau)$ in the S-wave channel (left) and P-wave channel (right) at $T \simeq 0$ for $\beta = 6.664, 6.800, 6.950,$ and 7.280

140, 160, 184 and 249 MeV, respectively on $N_\tau = 12$ lattices. At large τ the effective mass reaches a plateau which corresponds to the mass of the bottomonium state. The meson masses in NRQCD are related to the physical meson masses by a β dependent constant $C(\beta)$, e.g.

$$M_{\Upsilon(1S)}^{\text{exp}} = E_{\Upsilon(1S)}^{\text{sim}} + C(\beta), \quad (2.1)$$

where $E_{\Upsilon(1S)}^{\text{sim}}$ is the $(1S)$ energy computed in the Υ channel in NRQCD and $M_{\Upsilon}^{\text{exp}}$ refers to the experimental value for the mass of the Υ state. Therefore, the effective masses in Fig. 1 depend on β . We reconstruct the spectral function of S-wave and P-wave quarkonia using the novel Bayesian approach described in Ref. [20]. More precisely we consider Υ and χ_{b1} states which corresponds to the vector and axial-vector channels in relativistic QCD. The results are shown in Fig. 2. The $\Upsilon(1S)$ state is very well determined from the reconstruction. The second bump corresponds to excited states, mostly $\Upsilon(2S)$. In the case of P-wave spectral function the first peak corresponding to the $\chi_{b1}(1P)$ state is broader and the statistical errors on the spectral functions are larger. This is due to at least two effects. First, the mass of the $\chi_{b1}(1P)$ state is larger than the mass of $\Upsilon(1S)$, so the signal-to-noise ratio is smaller. Second, the relative contribution of the bound state peak to the correlator compared to the continuum contribution is smaller than in the S-wave. To get the spectral functions in terms of the physical energy the curves in Fig. 2 should be shifted by the constant $C(\beta)$ defined above.

The reconstruction of the spectral function at non-zero temperature is more difficult. Therefore, as the first step it is worth to discuss the temperature dependence of the correlation functions. In Fig. 3 we show the ratio of the correlators for S-wave and P-wave bottomonia to the corresponding zero temperature result. Below or at the transition the changes in the correlators are quite small, only marginally larger than the statistical errors. At the two temperatures above the transition we see much larger changes, although the total size of the temperature dependence does not exceed 1% for the S-wave correlator and 5% for the P-wave correlator. The difference of the medium modification of the S-wave and P-wave correlators is expected. The larger and more loosely bound χ_{b1} state experiences larger in-medium modification than the smaller and more tightly bound $\Upsilon(1S)$ state. The reconstruction of the spectral function at non-zero temperature is more difficult for two reasons. First, the Euclidean time being limited to $\tau_{\text{max}} = 1/T$, is short. Second the number of

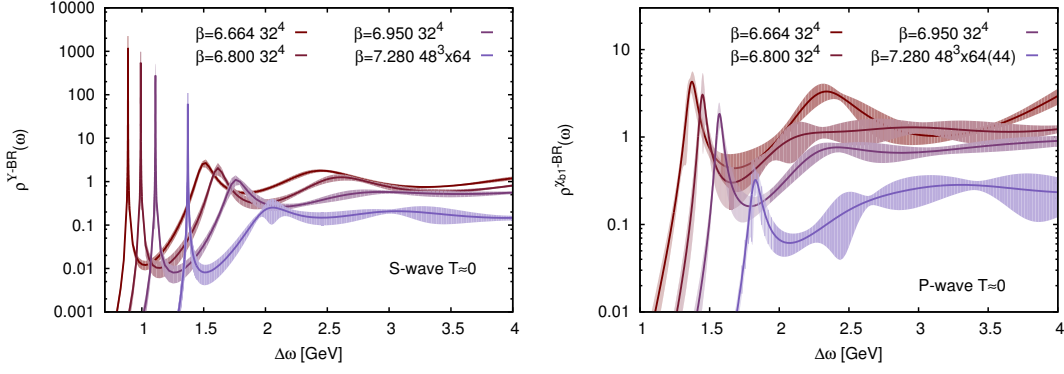


Figure 2: Bayesian reconstruction of the non shifted spectra in the S-wave channel (left) and P-wave channel (right) at $T \simeq 0$ temperature for $\beta = 6.664, 6.800, 6.950,$ and 7.280 . Note that at $\beta = 7.280$ we only use the first 44 data points there the signal is not yet lost to round-off-errors.

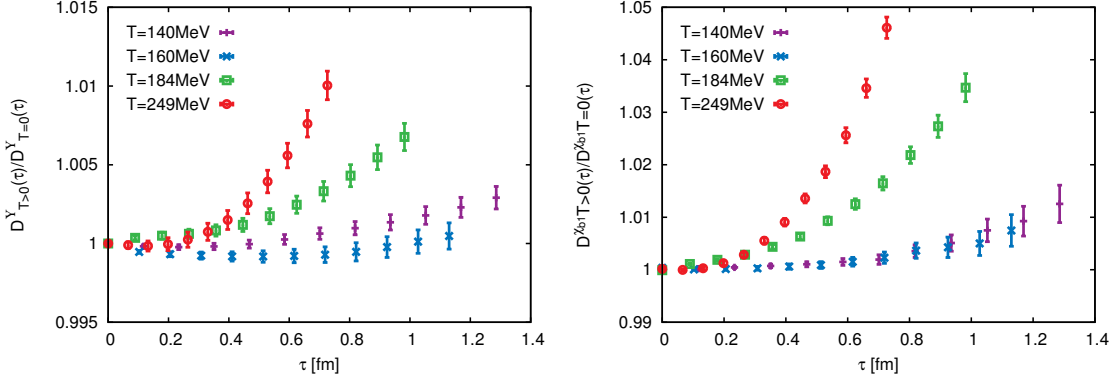


Figure 3: Ratios of the Euclidean correlator at finite temperature and close to $T = 0$ for the Υ (left) and χ_{b1} channel at the lattice spacings, where $T \simeq 0$ measurements were carried out.

available data points is also smaller. Therefore when comparing spectral functions at non-zero temperature with the corresponding zero temperature result it is important to take into account these systematic effects and distinguish them from the true medium effects. For this reason we reconstruct the zero temperature spectral functions for S-wave and P-wave bottomonium using only the first twelve data points. We then compare the zero temperature spectral functions reconstructed this way with the finite temperature case, where only twelve data points are available. This comparison is shown in Fig. 4 for $\beta = 7.28$, corresponding to $T = 249$ MeV. The ω -axis in Fig.4 was shifted by $C(\beta)$ defined above. The ground state peak in the zero temperature spectral functions is significantly broadened when only the first twelve data points are used in the analysis. The difference between the zero temperature and the finite temperature spectral functions remains small up to this temperature. Furthermore, at low ω the spectral function are very different from the free spectral functions. Thus we conclude that 1S and 1P bottomonium states do not melt up to temperatures $T = 249$ MeV.

So far we presented our numerical results only for $n = 2$. It is important to check if and to what extent our conclusions depend on the temporal discretization controlled by the Lepage parameter n . We performed calculations of bottomonium correlators also for $n = 3$ and 4. In Fig. 5 we show

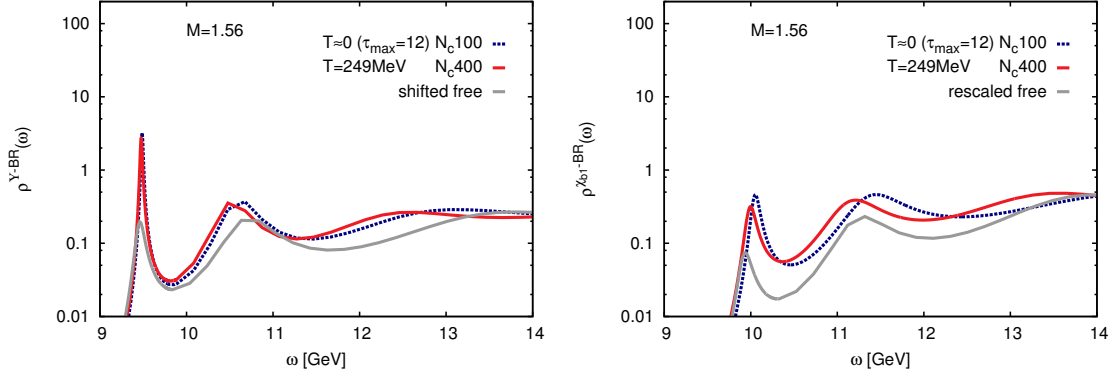


Figure 4: The S-wave (left) and P-wave (right) bottomonium spectral functions at $T = 0$ and $T = 249$ MeV. The zero temperature spectral functions have been reconstructed using only the first twelve data points. Also shown are the free spectral functions.

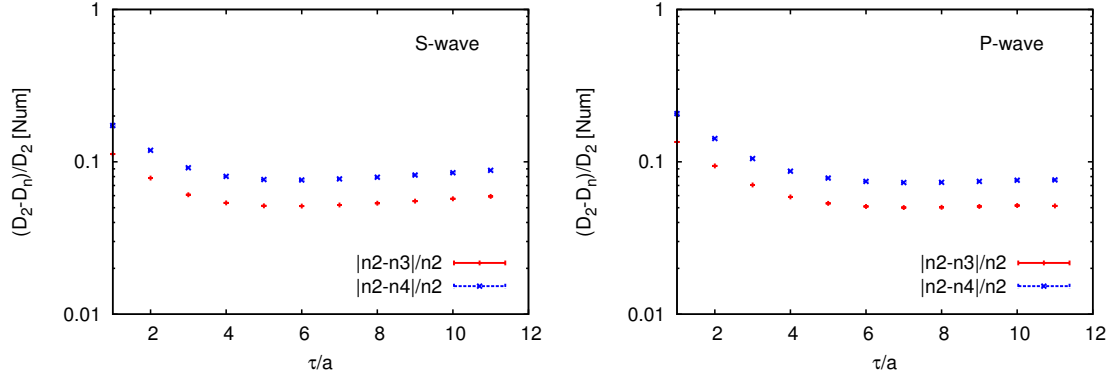


Figure 5: The relative difference between correlators calculated with $n = 3$ and 4 and the correlators calculated with $n = 2$ for $T = 249$ MeV for S-wave (left) and P-wave (right) bottomonia.

the difference between the bottomonium correlation function calculated with $n = 3, 4$ and $n = 2$ for our highest temperature $T = 249$ MeV. Since this corresponds also to the finest lattice used in our study the choice of n is expected to have the largest effect here. Changing n from 2 to 3 and 4 has the biggest effect at small τ , where it reaches about 10% for $n = 3$ and 20% for $n = 4$ for S-wave. For P-wave it can reach 30%. For larger τ the dependence on n becomes smaller. We observe similar dependence on n in the free theory. In the free theory the dominant effect of increasing n is the reduction of the high ω range, where the NRQCD spectral function has a support [16]. This is the reason why the effect of changing n is most prominent at small τ . We are mostly interested in the temperature dependence of the bottomonium spectral properties, and to what extent this temperature dependence is effected by the choice of n . Therefore, we consider the ratio of the bottomonium correlators calculated for $T = 249$ MeV to the corresponding zero temperature correlators for $n = 2, 3$ and 4. Our results are shown in Fig. 6 for S-wave and P-wave correlators. As one can see from the figure no dependence on n is visible in the ratios within the statistical errors, implying that the temperature dependence of the bottomonium spectral functions

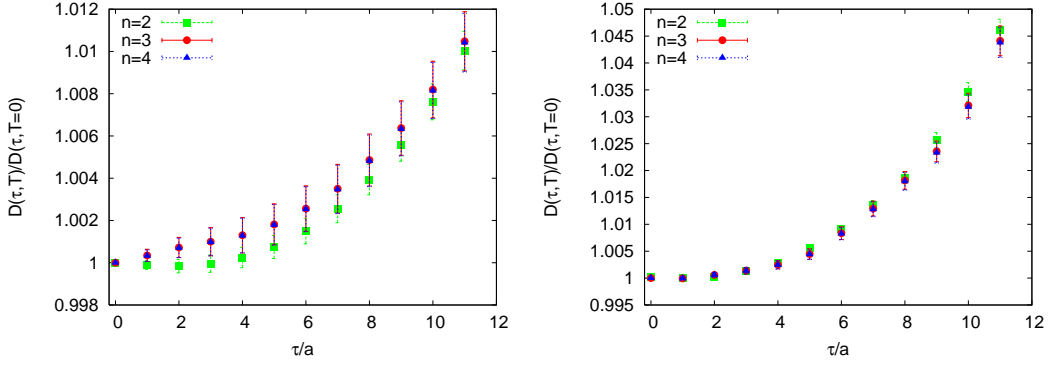


Figure 6: The ratio of the S-wave (left) and P-wave (right) correlators at $T = 249$ MeV to the corresponding zero temperature correlators for the values $n = 2, 3$ and 4 of the Lepage parameter.

is not affected by the choice of n .

3. Conclusion

In this contribution we studied bottomonium properties at non-zero temperature using NRQCD and gauge configurations generated by HotQCD on $48^3 \times 12$ lattices. We used a novel Bayesian approach to reconstruct the bottomonium spectral functions, which works reasonably well even for lattices with temporal extent $N_\tau = 12$. We see small but statistically significant temperature dependence in the bottomonium correlators which are larger for the P-wave than for the S-wave, as expected. The analysis of the spectral function shows that both Υ and χ_{b1} states survive in the deconfined phase up to the highest temperature of 249 MeV considered in this study.

Acknowledgments

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