Lattice NRQCD study of in-medium bottomonium states using $N_f = 2+1, 48^3 \times 12$ HotQCD configurations

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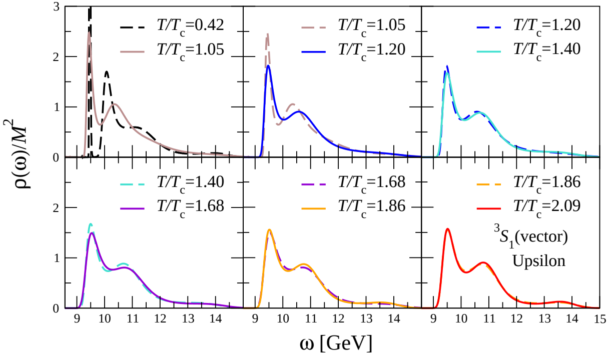
Outline

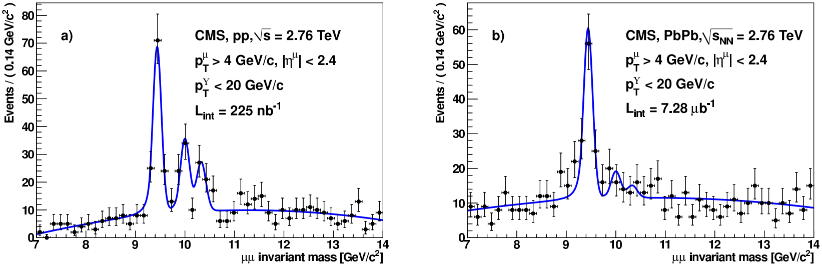
FASTSUM, JHEP 11 (2011) 103



- spectral function of Upsilon with lattice NRQCD kernel ($K(\tau) = e^{-\omega\tau}$)

- 1S peak survives, 2S and higher peaks merge and become a broad peak as T increases (melting)

CMS collaboration, PRL107 (2011) 052302



- In 2011, CMS collaboration observed disappearance of 2S and 3S upsilon state in Pb-Pb collisions
- sequential suppression

Motivation

- result obtained with non-zero temperature simulation with a fixed lattice spacing and anisotropic lattice
  - ☐ temperature can only be changed discretely by changing the number of time-slices since $T = \frac{1}{N_\tau a_\tau}$
  - ☐ difficult to investigate around T_c
  - ☐ coarse lattice $\rightarrow$ finite lattice spacing error
- Let's change T continuously by changing a_τ in $T = \frac{1}{N_\tau a_\tau}$
- caveats:
  - ☐ NRQCD has a unknown "energy shift"
  - ☐ lattice spacing (a_τ) change means that coupling constant (α_s) runs as well

- $\mathcal{O}(v^4)$ lattice NRQCD propagator for bottom quark

$$
\begin{aligned}
G(\vec{x},t=0) &= S(x) && (1)\\
G(\vec{x},t=1) &= \left[1+\frac{1}{2n}\,\frac{\vec{D}^2}{2m_b^0}\right]^n U_4^\dagger(\vec{x},t)\left[1+\frac{1}{2n}\,\frac{\vec{D}^2}{2m_b^0}\right]^n G(\vec{x},0) && (2)\\
G(\vec{x},t+1) &= \left[1+\frac{1}{2n}\,\frac{\vec{D}^2}{2m_b^0}\right]^n U_4^\dagger(\vec{x},t)\left[1+\frac{1}{2n}\,\frac{\vec{D}^2}{2m_b^0}\right]^n [1-\delta H]\,G(\vec{x},t)\\
\delta H &= -\frac{(\vec{D}^{(2)})^2}{8(m_b^0)^3}+\frac{ig}{8(m_b^0)^2}(\vec{D}\cdot\vec{E}-\vec{E}\cdot\vec{D})\\
&- \frac{g}{8(m_b^0)^2}\vec{\sigma}\cdot(\vec{D}\times\vec{E}-\vec{E}\times\vec{D})-\frac{g}{2m_b^0}\vec{\sigma}\cdot\vec{B}\\
&+ \frac{a^2\vec{D}^{(4)}}{24m_b^0}-\frac{a(\vec{D}^{(2)})^2}{16n(m_b^0)^2} && (3)
\end{aligned}
$$

• $M_b a$ for each a with $M_b = 4.65$ (GeV)

• HISQ action, $N_f = 2+1(m_{u,d}/m_s = 0.05)$ HotQCD configurations
(A. Bazavov et al, PRD85 (2012) 054503)

• improved Bayesian method with NRQCD kernel ($K(\tau) = e^{-\omega\tau}$)
(See A. Rothkopf's poster, and AR, Y. Burnier 1307.6106)

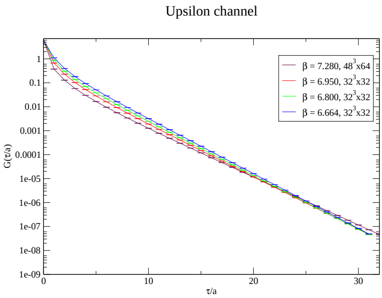
N_s	N_t	β	T(MeV)	T/T_c	a_τ^{-1} (fm)	No. of Conf.(analyzed)
		6.664	140.40	0.911	0.1169	100
		6.700	145.32	0.944	0.1130	100
		6.740	150.97	0.980	0.1087	100
		6.770	155.33	1.008	0.1057	100
		6.800	159.33	1.038	0.1027	100
		6.840	165.95	1.078	0.09893	100
		6.880	172.30	1.119	0.09528	100
48	12	6.910	177.21	1.151	0.09264	100
		6.950	183.94	1.194	0.08925	100
		6.990	190.89	1.240	0.08600	100
		7.030	198.08	1.286	0.08288	100
		7.100	211.23	1.371	0.07772	100
		7.150	221.08	1.436	0.07426	100
		7.280	248.63	1.614	0.06603	100

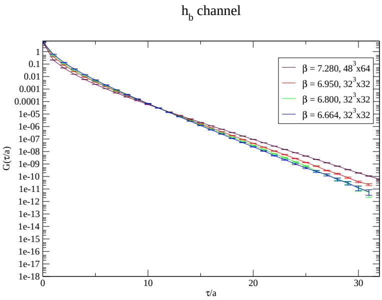
Table: summary for the $T \neq 0$ lattice data set

N_s	N_t	β	T(MeV)	T/T_c	a_τ^{-1} (fm)	No. of Conf.(analyzed)
32	32	6.664	52.65	0.342	0.1169	100
32	32	6.800	59.93	0.389	0.1027	100
32	32	6.950	68.98	0.448	0.08925	100
48	64	7.280	46.62	0.302	0.06603	100

Table: summary for the $T = 0$ lattice data set

Zero Temperature

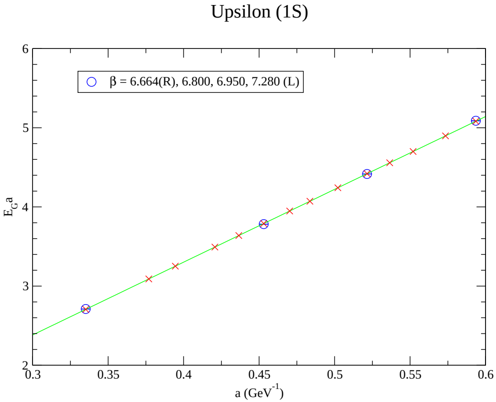




- Upsilon and P-wave(h_b) correlator at zero temperature for $\beta = 6.664, 6.800, 6.950, 7.280$ from lattice NRQCD heavy quark correlator

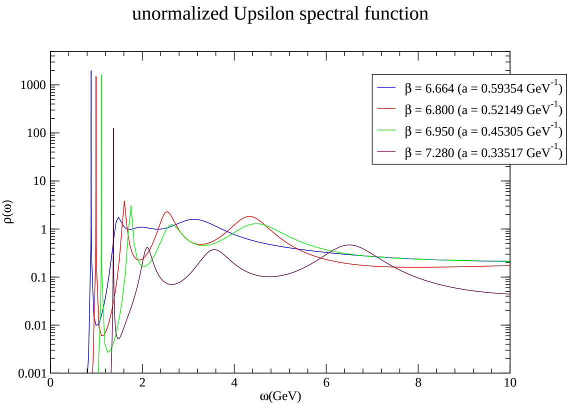
- behaves as an exponential fall-off ($G(\tau/a) \sim e^{-\Delta Ea \cdot \tau/a}$)

Zero Temperature



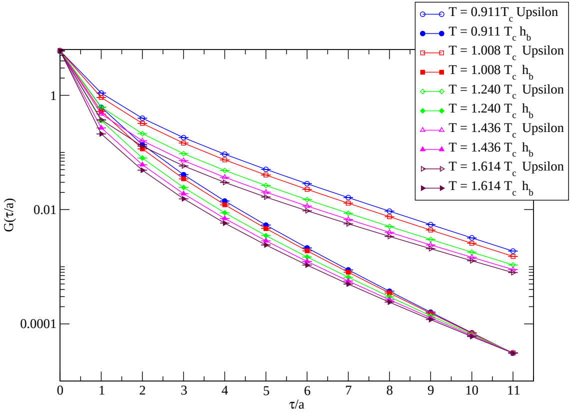
- "energy offset constant" for each β. The green line is a fit using the energy of Upsilon (1S) state at $\beta = 6.664, 6.800, 6.950, 7.280$ obtained from exponential function fit to Upsilon correlator (blue points)
- red crosses are the energy offset constant which will be used for the spectral function of non-zero T quarkonium correlators

Zero Temperature



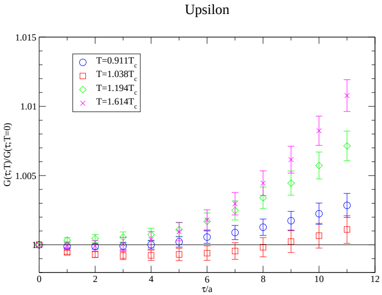
- unnormalized spectral functions calculated by improved method for $\beta = 6.664, 6.800, 6.950, 7.280$

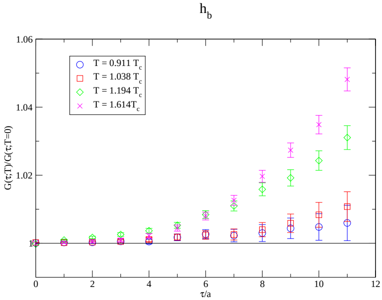
Non-Zero Temperature



- sample of $48^3 \times 12$ lattice Upsilon correlator (empty symbol) and P-wave(h_b) correlator (filled symbol) for $T/T_c = 0.911, 1.008, 1.240, 1.436, 1.614$

Non-Zero Temperature



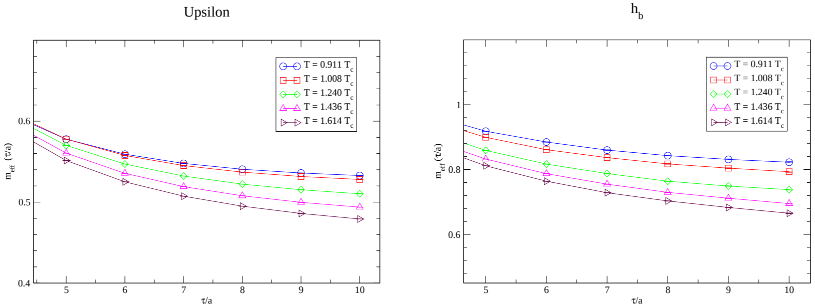


- correlator ratio: non-zero T $G(\tau/a)$ ($48^3 \times 12$ at $\beta = 6.664, 6.800, 6.950, 7.280$) divided by zero T $G(\tau/a)$ ($32^3 \times 32$ at $\beta = 6.664, 6.800, 6.950$ and $48^3 \times 64$ at $\beta = 7.280$)

- "energy offset constant" effect is removed (ratio is taken at the same β)

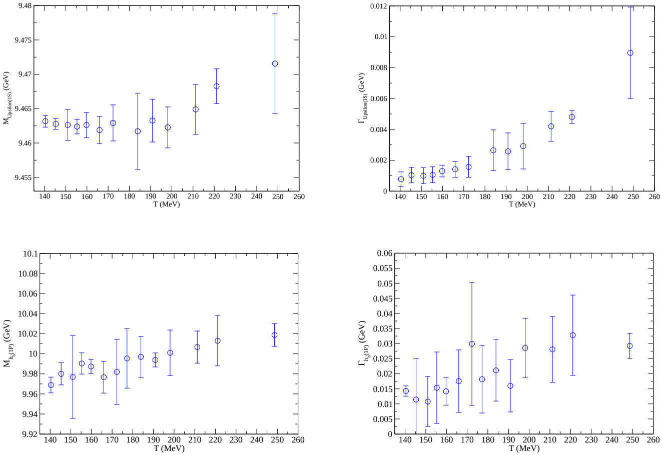
- note that for Upsilon, the ratio at $T/T_c = 0.911$ is larger than that at $T/T_c = 1.008$

Non-Zero Temperature



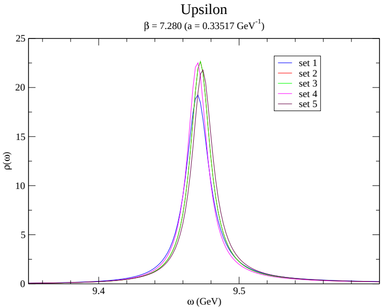
- “effective mass” from non-zero T $G(\tau/a)$
- “energy offset constant” effect is removed (ratio is taken at the same β)
- note that Upsilon effective mass below T_c is clustered but above T_c is spread but P-wave (h_b) effective mass is equally spaced.

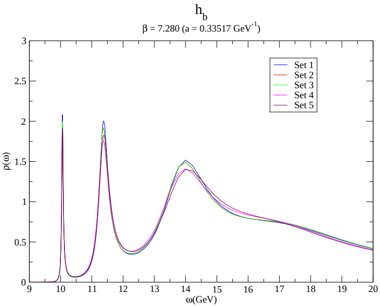
Non-Zero Temperature



- for the first peak, position vs. T (left) and width vs. T (right) for S-wave (Upsilon) (top) and P-wave (h_b) (bottom) from spectral functions

Non-Zero Temperature





- comparison of spectral functions from 5-Jackknife set

Conclusion

- Non-zero temperature behavior of S-wave and P-wave bottomonium with light dynamical quarks $(N_f = 2+1, m_{u,d}/m_s = 0.005)$ with HiSQ action is studied using lattice NRQCD method

- Bottomonia around the deconfinement temperature, 140.4(MeV) $\leq T \leq$ 221 (MeV) are investigated

- We found that behaviors of S-wave (Upsilon and η_b state) and P-wave (h_b state) are distinctly different

- The first peak position of S-wave bottominum stays more or less the same below T_c and starts to increase above T_c

- On the other hand, the first peak position of P-wave bottominum appears to be proportional to T across T_c