Bottomonium in thermal medium from NRQCD on $N_f = 2+1$ light flavor lattices

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Outline

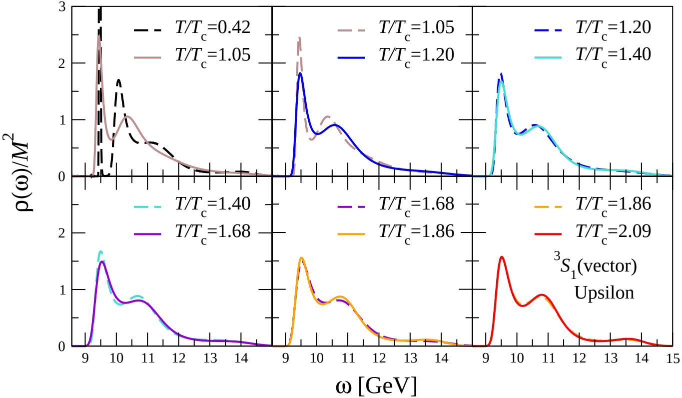
Goal

study how bottomonium behaves

in thermal medium

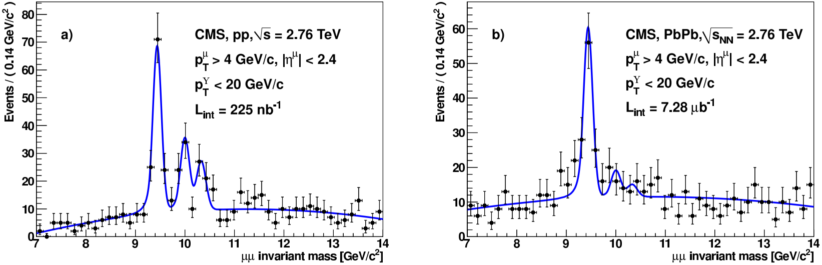
(around the deconfinement temperature)

T-dependence of the Υ spectral function



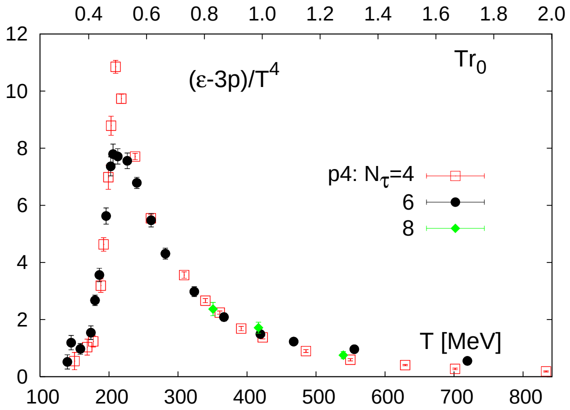
G. Aarts et al, PRL106 (2011) 061602, JHEP1111 (2011) 103

CMS collaboration, PRL107 (2011) 052302



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

Why lattice NRQCD?



• M.Cheng et al, (Columbia-BNL-RBC-Bielefeld) PRD 77 (2008) 014511, $N_f = 2 + 1$, $m_\pi = 220$ MeV

• strongly interacting QGP and absence of scale symmetry

Lattice NRQCD

- Thermodynamic QCD can be investigated using

$$\langle \mathcal{O} \rangle = \frac{\mathrm{Tr}\,\mathcal{O}e^{-\beta H}}{\mathrm{Tr}e^{-\beta H}} \rightarrow \frac{\int D\phi\, \mathcal{O} e^{-\int d^4x\, \mathcal{L}_E}}{\int D\phi\, e^{-\int d^4x\, \mathcal{L}_E}} \tag{1}$$

- Lattice QCD allows systematic study of non-perturbative physics using first principles of quantum field theory by numerically evaluating this integral

- Lattice QCD is defined on discrete space-time lattices
  $\rightarrow$ various scales $(a_\tau, N_s a_s, N_\tau a_\tau = \frac{1}{T}, \frac{1}{M_q})$

- Temperature can be changed
  by changing a (by changing lattice coupling) or N_τ

- Note that $a_\tau << \frac{1}{M_q}$ and $N_s a_s \gtrsim$ typical hadron size

Lattice NRQCD

• For the bottom quark, it is difficult to satisfy this condition with the current state of computing powers

$\rightarrow$ simulate effective field theory, NRQCD

• bottomon quark velocity $v = \frac{p}{M}$ is small (non-relativistic) in the bottomonium rest frame and momentum scale $> M_q$ is “integrated away” (Bodwin et al, PRD51 (1995) 1125)

• Foldy-Wouthuysen-Tani transform gives non-relativistic QCD lagrangian from QCD lagrangian

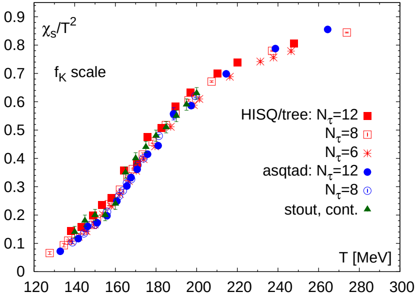
$$\mathcal{L}_q = \psi^\dagger \left(D_t - \frac{\mathbf{D}^2}{2M_q} \right) \psi + \mathcal{O}(v^4) \quad (1)$$

• gauge field ensemble has thermal effect and bottom quark moves under this background gauge field

• construct bottomonium correlators out of NRQCD bottom quark correlator

Lattice NRQCD

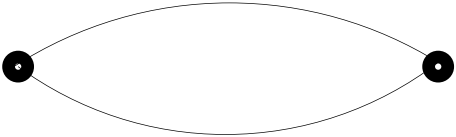
- gauge field in thermal environment is from HotQCD (PRD85 (2012) 054503)



strange quark number susceptibility ($m_l = 0.05 m_s$)

Lattice NRQCD

bottomonium correlator, $G(\tau, \mathbf{x})$



- NRQCD dispersion relation has undetermined zero point energy

$$E_q = \sqrt{M_q^2 + \mathbf{p}^2} \sim M_q + \frac{\mathbf{p}^2}{2M_q} - \frac{\mathbf{p}^4}{8M_q^3} + \cdots \tag{1}$$

- simulation at zero temperature is required to determine the zero point energy

Lattice NRQCD

- consistent lattice NRQCD requires $M_q a_\tau \sim 1$
- To keep NRQCD as an effective field theory remain valid, $T << M_q$
- In summary, a consistent lattice NRQCD for bottomonium ($M_b = 4.65$ GeV) requires

$$a_\tau \gtrsim \frac{1}{4.65}(\mathrm{GeV}^{-1}) \tag{1}$$

and

$$T = \frac{1}{N_\tau a_\tau} \leq \frac{4.65\mathrm{GeV}^{-1}}{N_\tau} \tag{2}$$

- If we are interested in a few MeV temperature, $N_\tau \sim \mathcal{O}(10)$

spectral function in NRQCD

In QCD,

$$G_\Gamma(\tau) = \sum_{\vec{x}} \langle \overline{\psi}(\tau,\vec{x})\Gamma\psi(\tau,\vec{x})\overline{\psi}(0,\vec{0})\Gamma\psi(0,\vec{0})\rangle \tag{3}$$

$$= \int \frac{d^3p}{(2\pi)^3} \int_0^\infty \frac{d\omega}{2\pi} K(\tau,\omega)\rho_\Gamma(\omega,\vec{p}) \tag{4}$$

and

$$K(\tau,\omega) = \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}. \tag{5}$$

- the spectral function of Euclidean correlator has all the information on the finite temperature behavior of a propagator
- numerically ill-posed problem
- Maximum Entropy Method is used (cf. M. Asakawa, T. Hatsuda, Y. Nakahara, PPNP46 (2001) 459)

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and

$$K(\tau,\omega) = \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}. \quad (5)$$

• known to have problems (cf. T. Umeda, PRD75 (2007) 094502 and A. Mocsy and P. Petreczky, PRD77 (2008) 014501)

• both the kernel($K(\tau,\omega)$) and the spectral density($\rho_\Gamma(\omega,\vec{p})$) depend on temperature

• constant contribution

spectral function in NRQCD

- In NRQCD, with $\omega = 2M + \omega'$ and $T/M << 1$, $K(\tau, \omega) \rightarrow e^{-\omega\tau}$

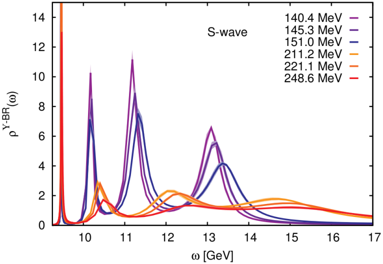
$$G(\tau) = \int_{-2M}^{\infty} \frac{d\omega'}{2\pi} \exp(-\omega'\tau)\rho(\omega') \quad (3)$$

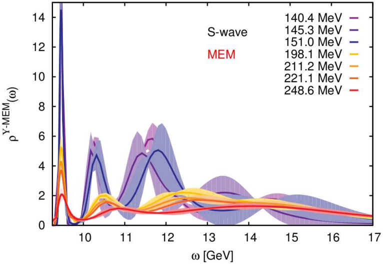
- inverse Laplace transform problem

- new improved Bayesian method (Burnier-Rothkopf, PRL111 (2013) 182003, next talk)

Spectral functions

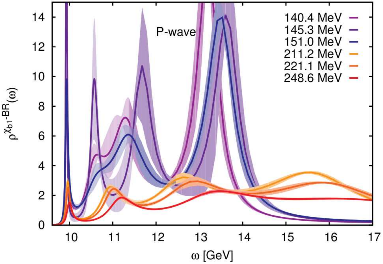
ϒ channel spectral function

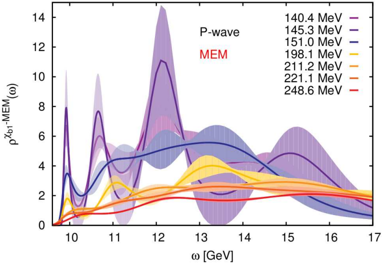




Spectral functions

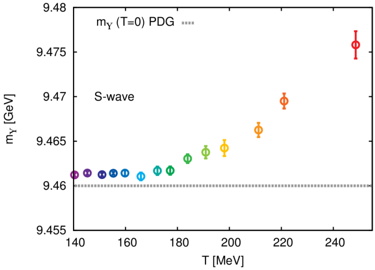
χ_{b1} channel spectral function





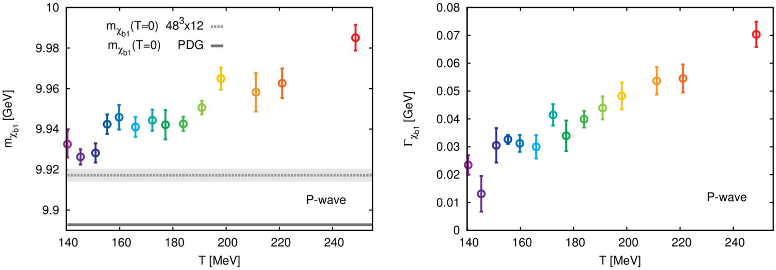
Spectral functions

temperature dependence of $\Upsilon(1S)$ mass and it width



Spectral functions

temperature dependence of $\chi_{b1}(1P)$ mass and it width



Conclusion

• On $T = 0$ and $T \neq 0$, lattice NRQCD + new Baysesian Reconstruction (BR) of spectral function on bottomonium, which is systematically improvable and is based on the first principel of quantum field theory (not a model)

• free from known problem in QCD (constant contribution problem) and improvement from MEM

• from both BR and MEM, the ground state of Υ survives but the excited states are suppressed as the temperature increases above T_c

• 1S peak of Υ channgel starts to increase at $T \gtrsim 1.14T_c$ and its width increases monotonically in T

• From BR, the ground state of χ_{b1} retains peak structure even at $1.6T_c$ but from MEM, χ_b (P-wave) melts around $1.3T_c$