Quarkonium in Thermal Environment

Seyong Kim

Sejong University

JLab related

- Frascati-Argonne-Swansea-Trinity-Sejong-Utah-Maynooth (FASTSUM):
  - ☐ M.-P. Lombardo, D.K. Sinclair, G. Aarts, C. Allton, S. Ryan, SK, B. Oktay, J.-I. Skullerud + many others
  - ☐ anisotropic lattices, $T = 0$ HadSpec parameters
  - ☐ PRL106(2011)061602, JHEP111(2011)103, JHEP1303(2013)084, JHEP1312(2013)064, JHEP1407(2014)097
- SK (Sejong), P. Petreczky (BNL), A. Rothkopf (Heidelberg)
  - ☐ JLab clusters via USQCD
  - ☐ PRD91(2015)054511

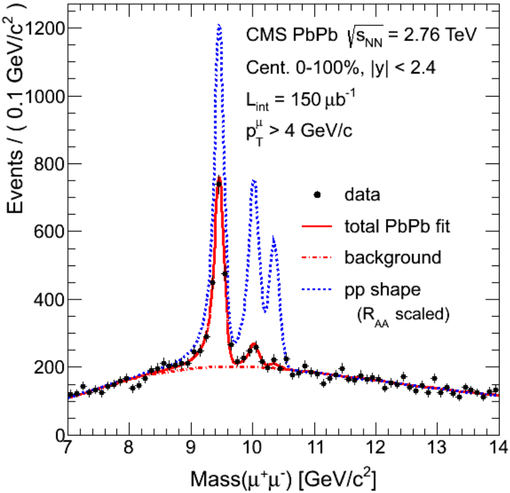
Outline

Heavy Quarkonium

modification in the spectral behavior of

quarkonium at $T \neq 0$

Heavy Quarkonium



- sequential suppression of $\Upsilon(1S, 2S, 3S)$: CMS, PRL109 (2012) 222301

Heavy Quarkonium

• Investigation of QGP properties requires comparison between the baseline (p, p) and relativistic heavy ion collisions

• heavy quark system is one of better understood hadronic systems

• heavy quark mass scale(M) is large and the strong coupling at the mass scale is “small”

$\rightarrow$ separation of bound state dynamics from short distance perturbative dynamics

Heavy Quarkonium

•effective field theory descriptions : NRQCD (pNRQCD), HQET (cf. G.T.Bodwin, E. Braaten, G.P. Legage, PRD51 (1995) 1125, N. Brambilla, A. Pineda, J. Soto, and A. Vairo, Rev. Mod. Phys 77 (2005) 1423, N. Isgur and M. Wise, PLB 237 (1990) 527)

• NRQCD is an effective field theory: separation of perturbative UV physics ($> M_b$) and non-perturbative IR physics

• inclusive decay rates = partonic decay rate $\times$ the probability for heavy quark to meet anti-heavy quark (cf. E.Braaten, G.T.Bodwin, G.P.Lepage, PRD51 (1995) 1125)

• allows accurrate measurements (e.g., lattice calculation of α_S using quarkonium spectrum)

• long distance matrix elements can be calculated by lattice method (e.g, G.T.Bodwin, D.K.Sinclair, SK, PRL77 (1996) 2376)

Quarkonium in dense medium

- T. Matsui and H. Satz, PLB178 (1986) 416.

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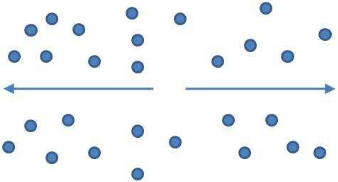
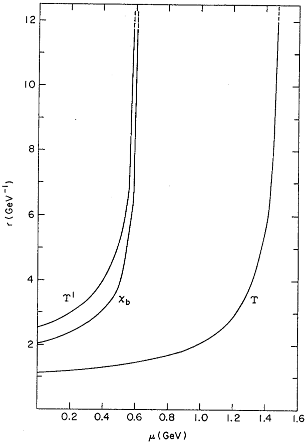
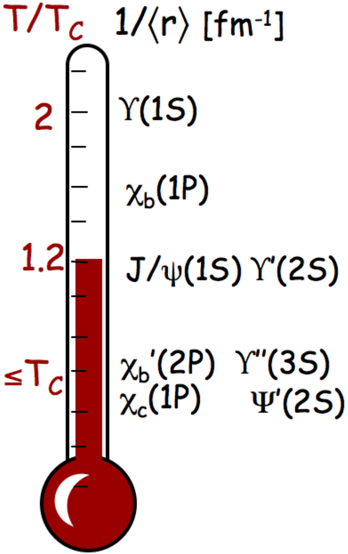


Quarkonium in dense medium

F. Karsch, M.T. Mehr, and H. Satz, Z.Phys.C37 (1988) 617



Quarkonium in dense medium



cf. A. Mocsy, 0811.0337

Quarkonium in dense medium

- qualitatively, melting of quarkonium at $T \neq 0$ can be understood in terms of screening potential and imaginary part

$$V(r) = -\alpha_s C_F \left[m_D + \frac{\exp(-m_D r)}{r} \right] - i\alpha_S C_F T \phi(m_D r) \qquad (1)$$

(cf. M. Laine, O. Philipsen, P. Romatschke, M. Tassler, JHEP0703(2007)054)

- however quantitative study requires first principle calculation
  $\rightarrow$ lattice gauge theory method

Quarkonium in dense medium

- use lattice version of NRQCD for quarkonium at $T \neq 0$

- to keep NRQCD remain valid as an effective field theory, $T << M_b$

- for the study of in-medium bottomonium, study bottomonium correlator using lattice NRQCD

$$G(\tau) = \sum_{\vec{x}} \langle \phi^{\dagger}(\vec{x}, \tau; \vec{0}, 0) \phi(\vec{x}, \tau; \vec{0}, 0) \rangle \qquad (1)$$

Quarkonium in dense medium

- at $T = 0$,

$$G(\tau) = \sum_n e^{-E_n\tau} |\langle 0|\phi(0)|n\rangle|^2 \tag{1}$$

- if the states are well defined stationary states ($T = 0$),

$$\rightarrow G(\tau) \sim a_0 e^{-E_0\tau} + a_1 e^{-E_1\tau} + a_2 e^{-E_2\tau} + \cdots \tag{2}$$

usual χ^2 fitting is sufficient

- for in-medium bottomonium, the states are no longer narrow

  $\rightarrow$ spectral information is needed unless the functional form at $T \neq 0$ is known

Quarkonium in dense medium

- spectral representation

$$G_\Lambda(\tau) = \sum_{\vec{x}} \langle \overline{\psi}(\tau,\vec{x})\Lambda\psi(\tau,\vec{x})\overline{\psi}(0,\vec{0})\Lambda\psi(0,\vec{0})\rangle \quad (1)$$

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

and

$$K(\tau,\omega) = \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}. \quad (3)$$

- 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)

Quarkonium in dense medium

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• 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

Quarkonium in dense medium

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

$$G(\tau) = \int_{-2M}^{\infty} \frac{d\omega'}{2\pi} \exp(-\omega'\tau)\rho(\omega') \tag{1}$$

- inverse Laplace transform problem

- Maximum Entropy Method (G. Aarts et al, JHEP1111 (2011) 103)

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

Bayesian methods

- given $G(\tau)$ which is calculated on lattice, what is the spectral function, $\rho(\omega)$?

- Bayes theorm

$$P[X|Y] = P[Y|X]P[X]/P[Y]$$

- in other words

$$P[\rho|D,H] \propto P[D|\rho,H]P[\rho|H]$$

- systematic inclusion of prior knowledge (H)

$$P[D|\rho,H] = e^{-L}, \quad L = \frac{1}{2}\sum_i (D_i - D_i^{\rho})^2/\sigma_i^2$$

and

$$P[\rho|H] = e^{-S}, \quad S = S[\rho(\omega), m(\omega)]$$

where S is the prior and $m(\omega)$ is default model

Bayesian methods

• Shannon-Jaynes entropy for S (cf. Asakwa, Hatsuda, Nakahara, Prog. Part.Nucl.Phys. 45 (2001) 459)

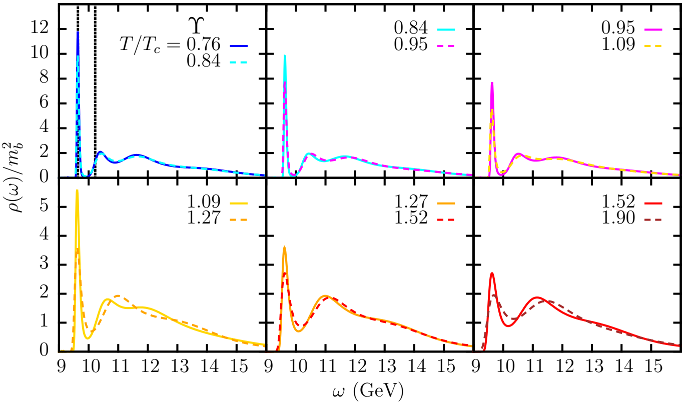
$$S_{SJ} = \alpha \int d\omega \left(\rho - m - \rho \log(\frac{\rho}{m})\right)$$

• new prior (cf. Y.Burnier, A. Rothkopf, PRL111 (2013) 182003)

$$S_{BR} = \alpha \int d\omega \left(1 - \frac{\rho}{m} + \log(\frac{\rho}{m})\right)$$

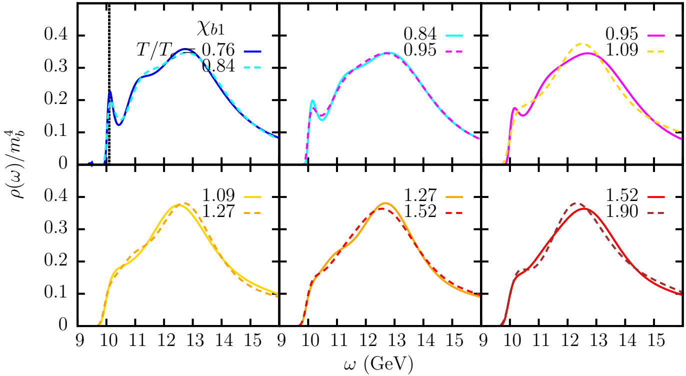
Using MEM

- FASTSUM, JHEP1407 (2014) 097 : S-wave



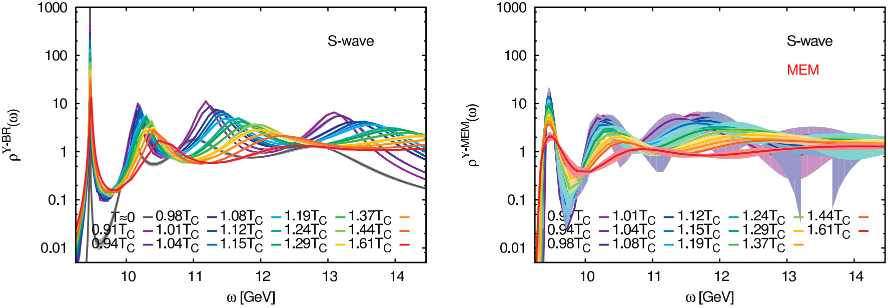
Using MEM

- FASTSUM, JHEP1407 (2014) 097 : P-wave



Different Bayesian Method

- S.K. A. Rothkopf, P. Petreczky, PRD 91 (2015) 054511



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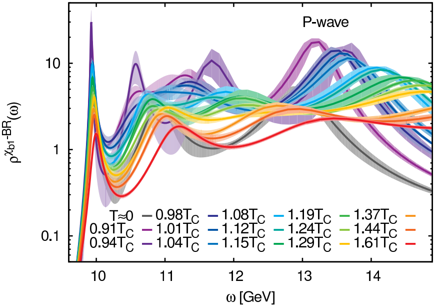
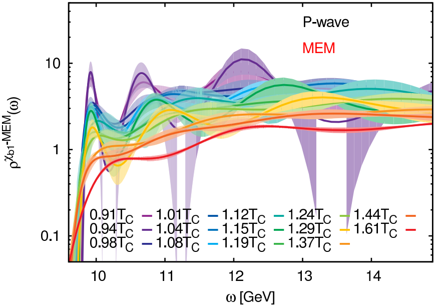
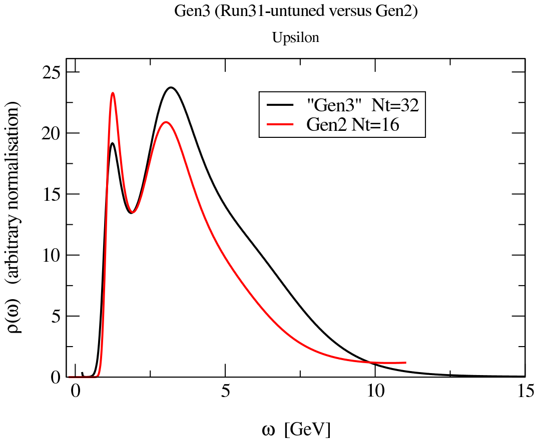




Current efforts

- FASTSUM runs simulations which increase N_τ while fixing all the other parameters



Current efforts

- KPR experiments with modifying Bayesian regulator