Bottomonia in QGP from lattice QCD: Beyond the ground states

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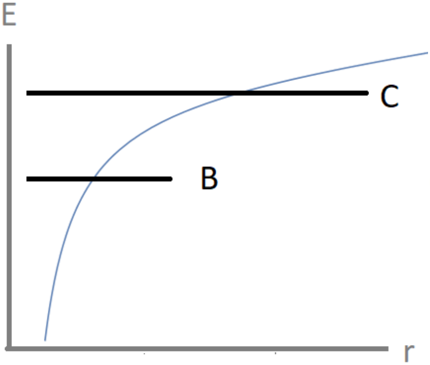
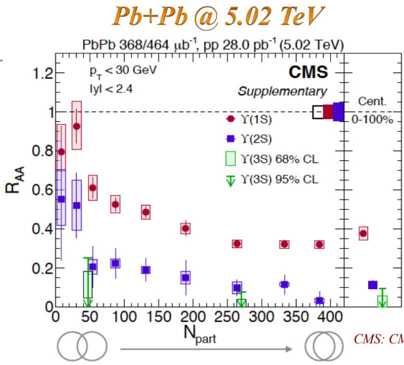
[Rasmus Larsen, Stefan Meinel, Swagato Mukherjee and Peter Petreczky, arXiv:1910.07374]

Motivation

- Motivation:
  - Use Bottomonium states as probe for change in color screening
  - Experimental results show suppression of Bottomonium states at finite temperature





CMS: CMS-HIN-16-023

Approach

- Approach
  - Non Relativistic QCD (NRQCD) on lattice
    - with $O(v^4)$ corrections, plus $O(v^6)$ spin corrections
  - 2+1 flavor HotQCD configurations from $T = 151MeV$ to $T = 334MeV$
  - Pion mass 160MeV, Kaon mass physical
  - Explore Υ, χ_b
- Main observable: Correlation function $C(\tau)$
  - $C(\tau)$ is the zero momentum of the state of interest

$$\int d^3x < O(\tau, x) O^\dagger(0,0) > \; = \; C(\tau) \; = \; \int_0^\infty \rho(\omega) \exp(-\omega\tau) d\omega \qquad (1)$$

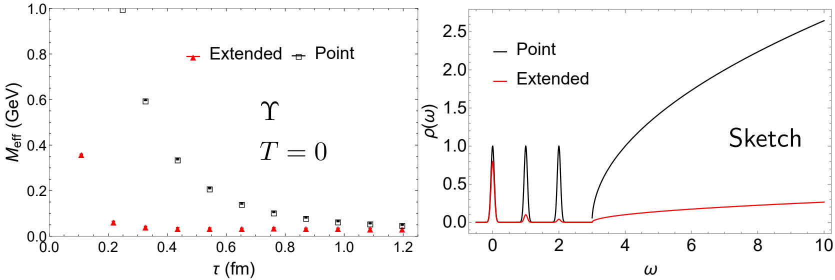
- Invert equation to find spectral function $\rho(\omega)$

Spectral Function

- Plateaus of the effective mass M_{eff} $->$ Mass state exists in $\rho(\omega)$

$$M_{eff} = \frac{1}{a} \log[C(t)/C(t+a)] \quad (2)$$

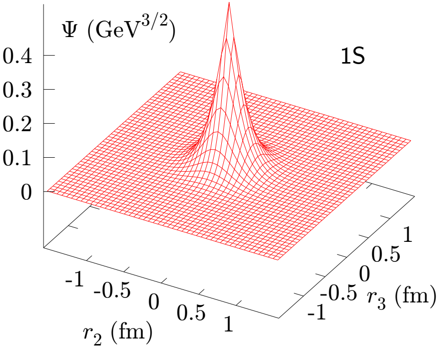
- Continuum in $\rho(\omega)$ with point sources dominates contribution to correlation function
- Solution:
  - Use sources with finite (extended) size $\rightarrow$ project onto specific region in ω



Extended Sources

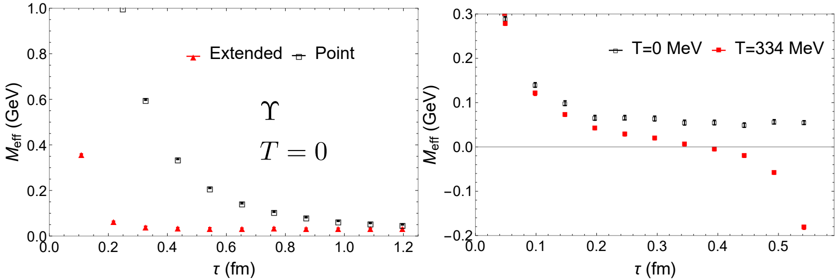
- Source calculated from discretized schroedinger equation with confining potential that reproduces zero temperature spectrum

$$O_i(\mathbf{x},t) = \sum_{\mathbf{r}} \Psi_i(\mathbf{r}) \bar{q}(\mathbf{x}+\mathbf{r},t)\Gamma q(\mathbf{x},t) \quad (3)$$



Continuum Subtracted S-wave

- Extended sources greatly reduces continuum contribution

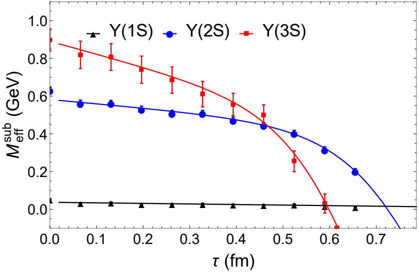


- Small τ behavior similar at $T = 0$ and $T \neq 0$
- Extract continuum $C_{high}(\tau)$ from $T = 0$ results
- 0 Corresponds to energy of η_b at $T = 0MeV$.

$$
\begin{aligned}
C(\tau) &= Ae^{-M\tau} + C_{high}(\tau) \\
C_{sub}(\tau, T) &= C(\tau, T) - C_{high}(\tau)
\end{aligned} \quad (4)
$$

Finite Temperature Subtracted Effective Mass

- Drop in effective mass as $\tau \to 1/T$
- Linear behavior at small to mid range τ

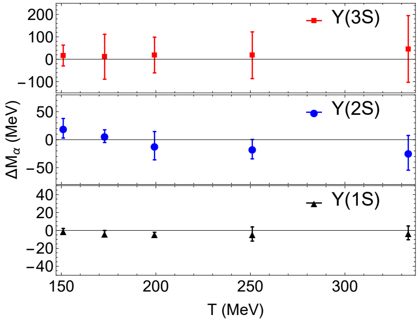


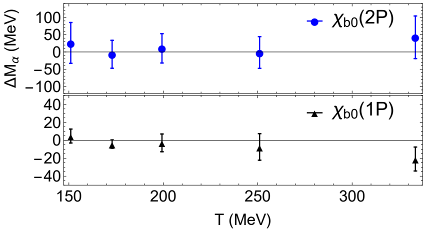
- Information in correlation function is thus

$$C_{sub}(\tau, T) \sim \exp(-M_\alpha \tau + \frac{1}{2}\Gamma_\alpha^2 \tau^2 + O(\tau^3)) \quad (5)$$

$$\rho_\alpha(\omega, T) = A_\alpha(T) \exp\left(-\frac{[\omega - M_\alpha(T)]^2}{2\Gamma_\alpha^2(T)}\right) + A_\alpha^{\rm cut}(T)\,\delta\left(\omega - \omega_\alpha^{\rm cut}(T)\right)$$

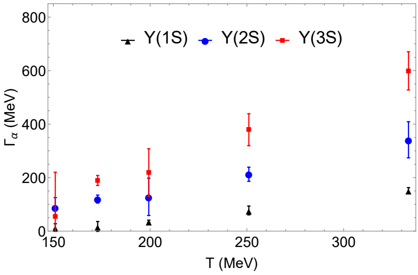
- The mass is found to be consistent with zero temperature results [R. Larsen et al., arXiv:1910.07374]
- $\Delta M_\alpha = M_\alpha(T) - M_\alpha(0)$

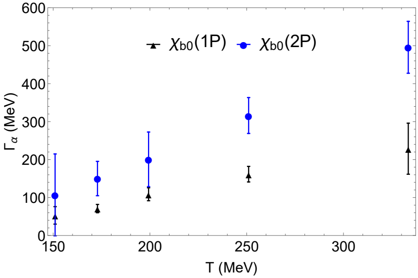




Spectral Width

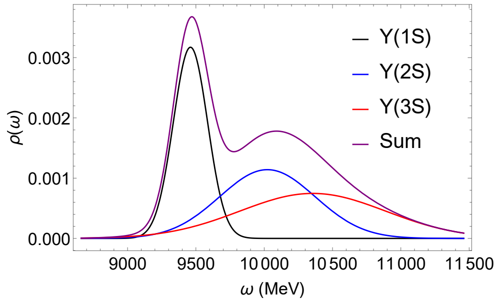
- Spectral width grows with temperature like T^2 [R. Larsen et al., arXiv:1910.07374]
- The higher the energy of the state, the wider the spectral function becomes



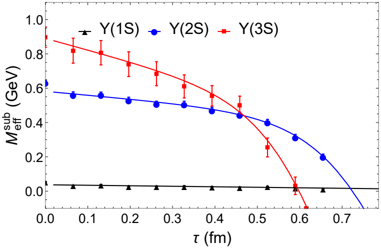


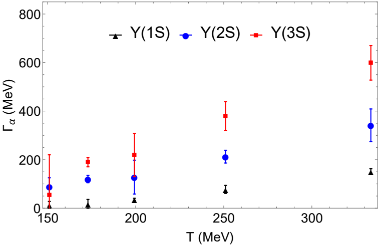
Picture at finite temperature

- Our results indicate the following picture
  - No significant change in energy/mass of states
  - Large spectral width, such that states start to overlap
  - Spectral function with equal weight at $T = 334 MeV$ shown below

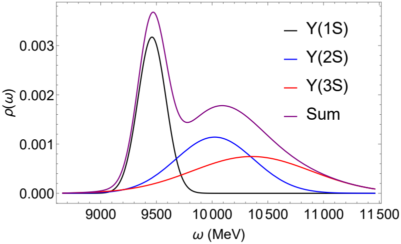


Conclusion





- Novel techniques allow us to explore excited state bottomonia in QGP
- Linear behavior in effective mass observed
- Behavior explained by large spectral width $\sim 160 - 600 MeV$
- 2S and 3S, 1P and 2P spectral functions overlap strongly above $T = 200 MeV$



Backup

Wilson Lines Correlator

- Same procedure works for Wilson lines Correlator
- Almost no change in energy, but increasing width

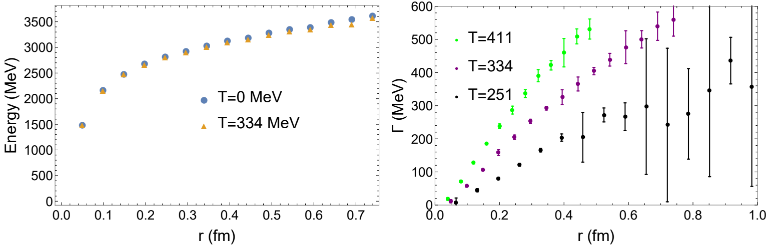
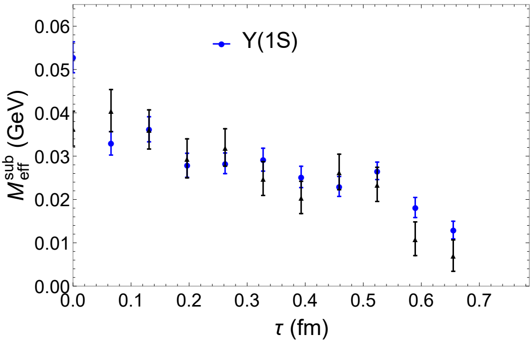


Figure: (Left) Energy obtained for $T = 334 MeV$. (Right) Width at several temperatures around 300 MeV.

- Width obtained from Wilson lines correlator consistent with width of Υ when looking at distance of Υ 's average radius.

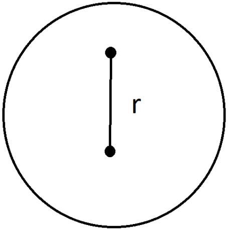
Dependence on Source

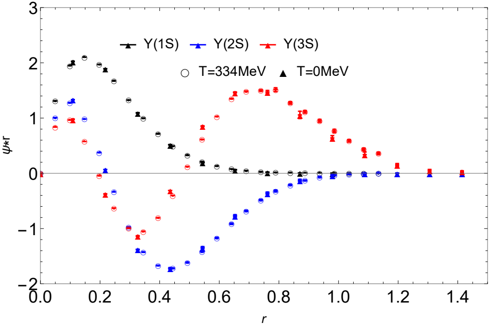
- Slope consistent between smeared sources and wavefunction sources
- Drop off at $\tau \sim 1/T$ smaller for wavefunctions



Spatial Localization of States

- Look at the change in shape using the Bethe-Saltpeter wavefunction
- Shows the distribution of the state as a function of distance r

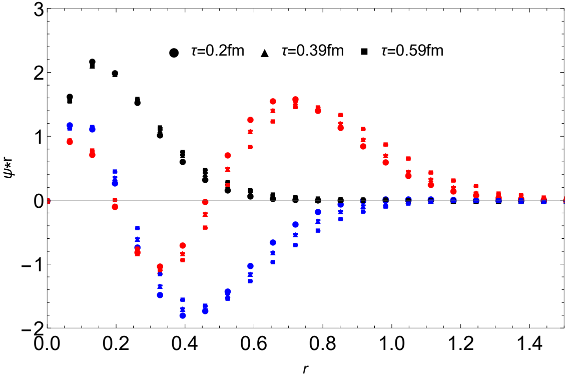




- No significant difference in shape is seen at $\tau \sim 0.4 fm$

Bethe-Saltpeter Wavefunction 2

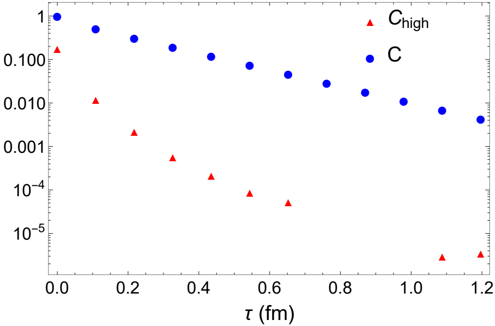
- For large temperature BS wavefunction is seen to move out slightly to larger distances as τ increases
- T=251MeV



Continuum Subtracted

- Small τ behavior same at $T = 0$ and $T \neq 0$
- Extract difference from groundstate at $T = 0$

$$C(\tau) \quad = \quad Ae^{-M\tau} + C_{high}(\tau)$$

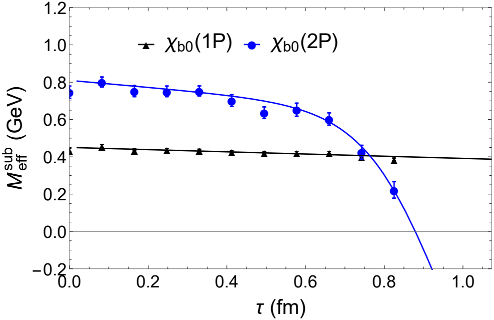


- Subtract result from finite temperature result

$$C_{sub}(\tau, T) = C(\tau, T) - C_{high}(\tau). \tag{6}$$

Continuum Subtracted P-wave

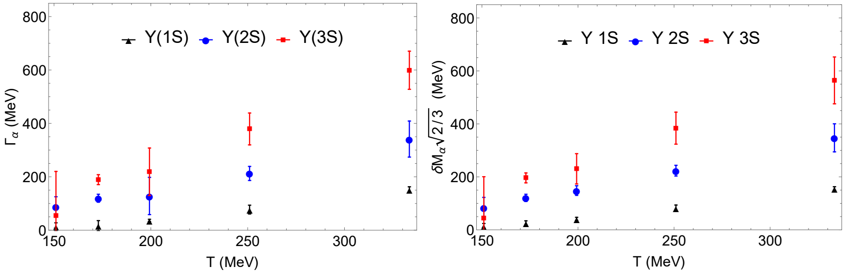
- Same procedure works for χ_b
- Figure below is for $T = 199 MV$



- M_{eff}^{sub} goes to energy of the $T = 0$ result when extrapolated to $\tau = 0$

Ansatz Comparison

- Ansatz with Gaussian spectral function (left) and 3 delta functions representing a width (right) are consistent
- δM_α is difference between middle delta function and the two other delta functions



- Width $\sqrt{\langle\omega^2\rangle - \langle\omega\rangle^2}$ is equal to:
  - Γ_α for Gaussian ansatz
  - $\delta M_\alpha\sqrt{2/3}$ for 3 delta functions ansatz