In-medium Bottomonium Properties from Lattice NRQCD Calculations with Extended Meson Operators

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based on JHEP 05 (2025) 149,

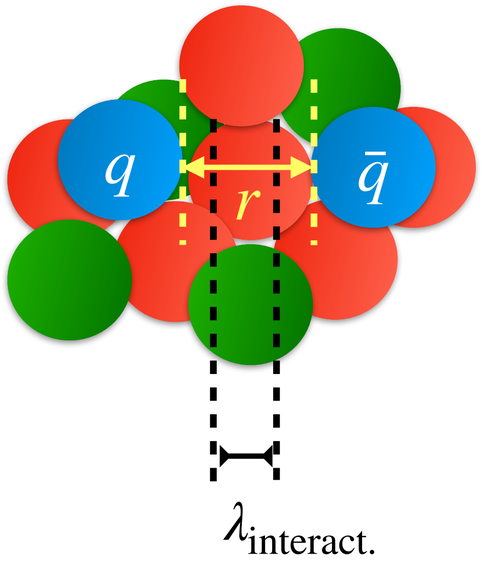
in collaboration with Heng-Tong Ding, Rasmus Larsen, Stefan Meinel, Swagato Mukherjee, Peter Petreczky and Zhanduo Tang

The 25th Zimányi School Winter Workshop on Heavy Ion Physics, Dec. 1 - 5, 2025 @ Budapest

Quarkonium as a probe

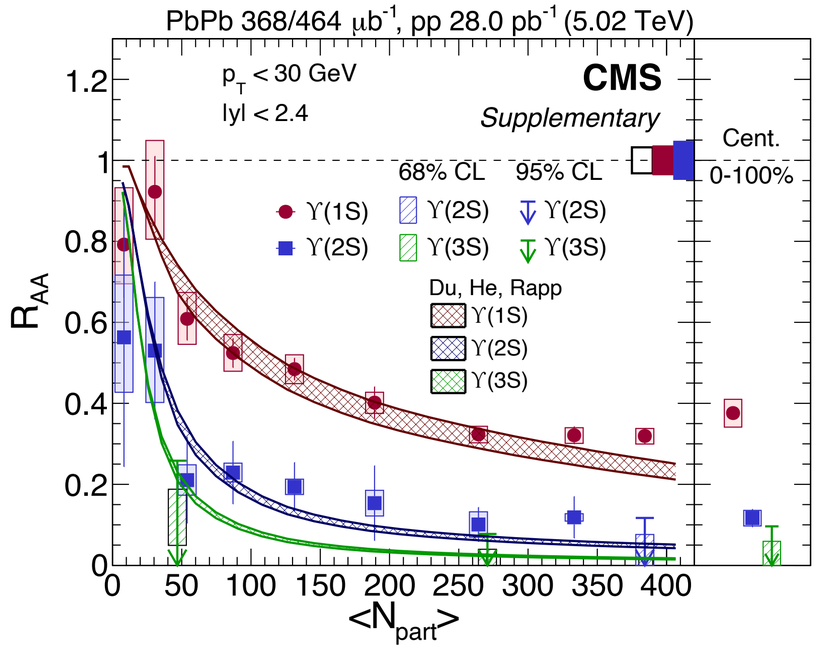
Quarkonium suppression via color screening in Quark-Gluon Plasma

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



Hints for sequential in-medium modification

CMS collab., PLB790 (2019) 270



How to understand these in-medium bottomonium behaviors from the first principle ?

Correlators from lattice NRQCD & extended source

$$C(\tau,T)=\int_{-\infty}^{+\infty}\mathrm{d}\omega\ \rho(\omega,T)K(\tau,\omega,T)$$

$C(\tau,T)$: correlators is calculable on lattice

$\rho(\omega,T)$: spectral function includes all in-medium infos

$C(\tau,T)$ from relativistic QCD & point source

☹ Limited sensitivity in $C(\tau,T)$: $\tau_{\max}=1/(2T)$

A. Mocsy, P. Petreczky, PRD 77, 014501(2008)

P. Petreczky, EPJC 62, 85 (2009)

☹ Large discretization effect

☹ Non-optimal overlap with states of interest

$C(\tau,T)$ from NRQCD & extended source

😀 Pair creation is not allowed $\Rightarrow \tau_{\max}=1/T$

N. Brambilla, J. Ghiglieri, et.al., PRD 78, 014017(2008)

😀 Well-controlled discretization error

😀 Optimized projection onto particular states

Gaussian-smeared source — R. Larsen, et.al., PRD 100, 074506 (2019)

Wave-function optimized source — R. Larsen, et.al., PLB 800, 135119 (2020)

Simulation details

- Bottom quark on the lattice:
  - Tree-level tadpole-improved NRQCD action, with $\mathcal{O}(v^6)$ corrections
  - Bare bottom mass tuning: matching kinetic mass M_{kin,η_b} to its PDG value

S. Meinel, PRD 82, 114502 (2010)

R. Larsen, et.al., PRD 100, 074506 (2019)

R. Larsen, et.al., PLB 800, 135119 (2020)

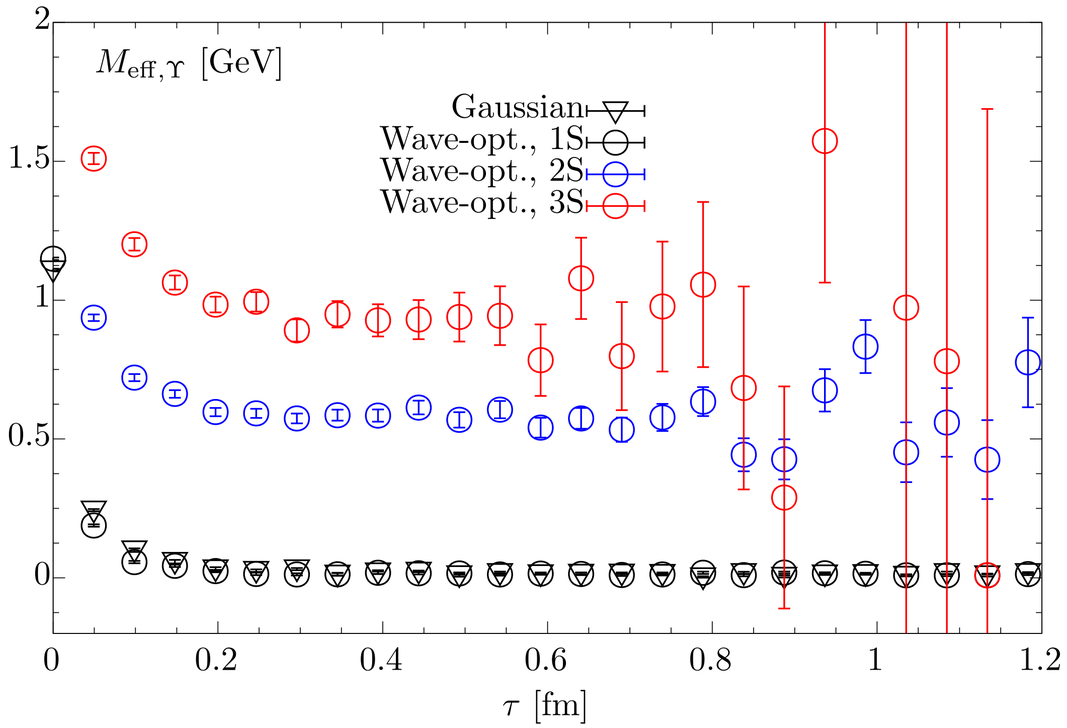
- Background gauge fields with (2+1)-flavor dynamical sea quarks:
  - HISQ/tree action
  - Quark mass: $m_s^{\mathrm{phy}}/m_l = 20$ $(m_\pi \approx 160\ \mathrm{MeV})$
  - Two fine lattice spacings used: $a = 0.0493$ fm and 0.0602 fm
  - Temperature is increased by reducing the temporal extent: $N_\tau \in [16,\ 30]$, $T \in (133,\ 250)$ MeV

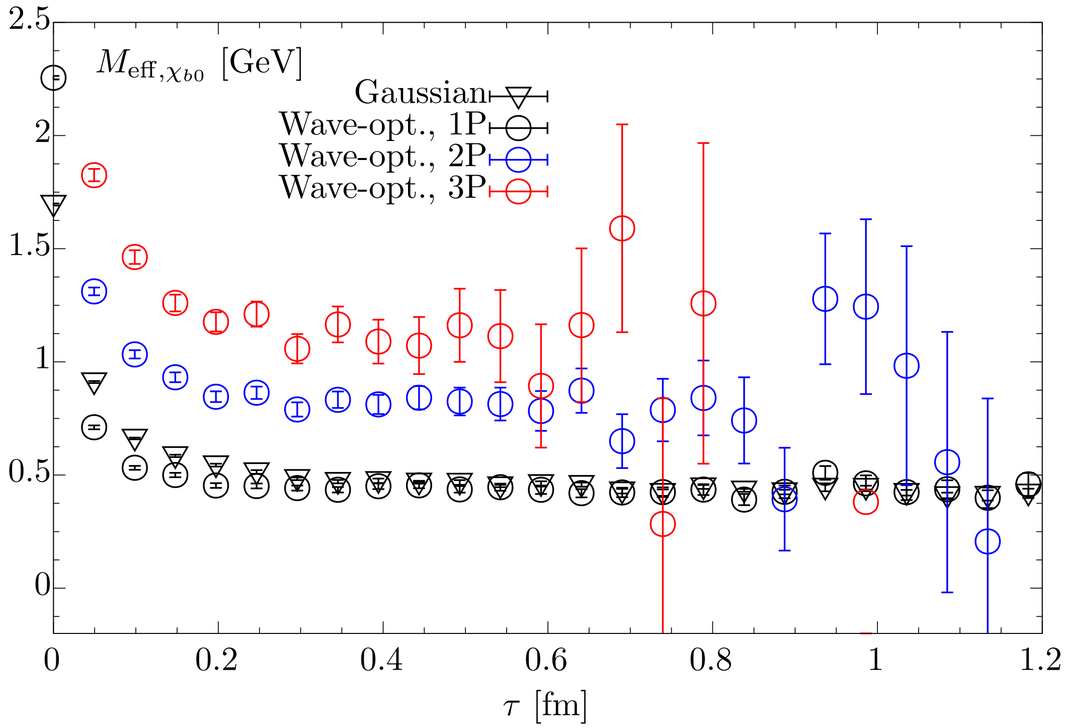
Nuclear Science Computing Center at CCNU

Effective mass in vacuum

$$M_{\text{eff}}(\tau) = \frac{1}{a} \log \left[\frac{C(\tau, T)}{C(\tau + a, T)} \right]$$

All vertical scales are calibrated with the spin-averaged mass of 1S bottomonium hereafter

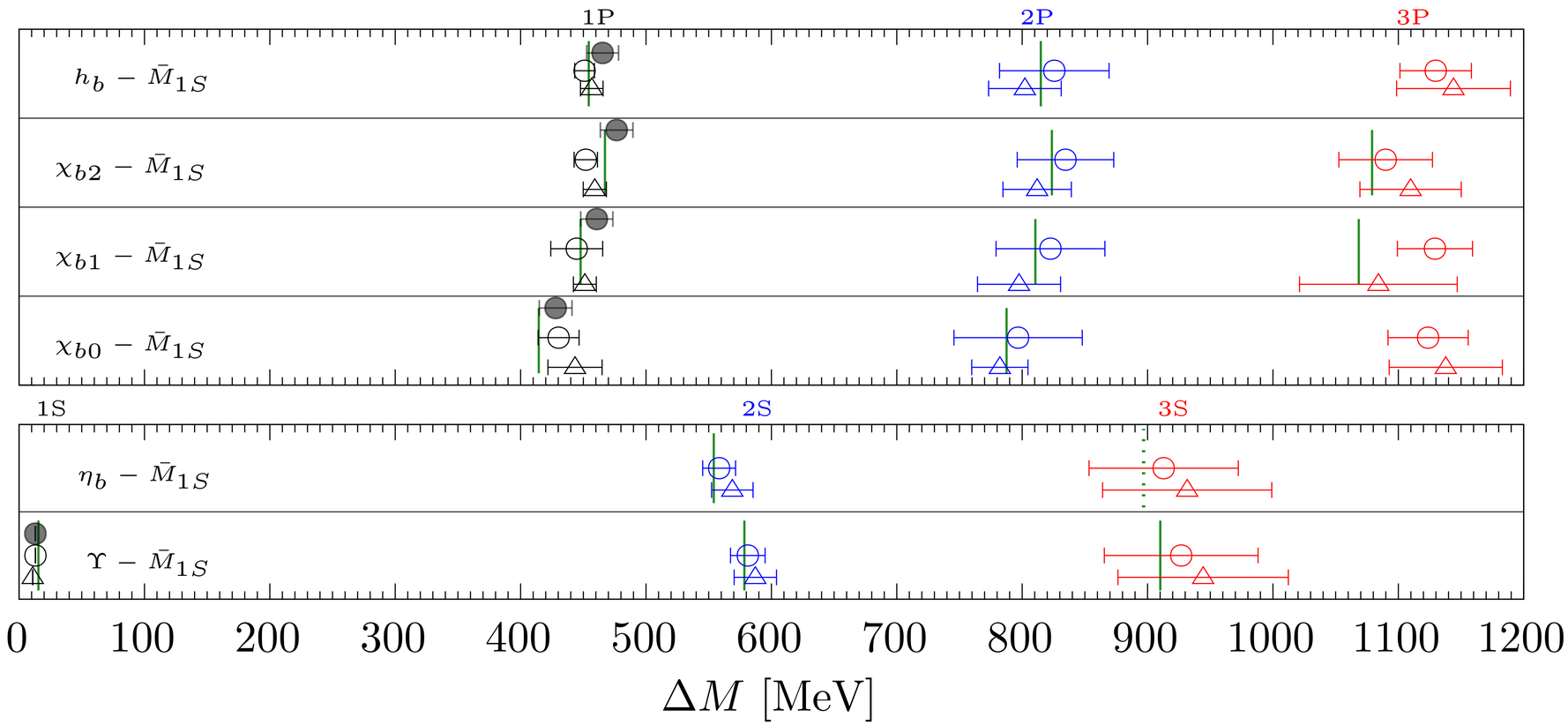




- Mild effects arise from different extended sources for ground states at $T = 0$
- Plateau starts from $\tau \sim 0.25$ fm, but shorter for excited states with worse signal

Mass spectra in vacuum

Mass difference: $\Delta M = M - (M_{\eta_b} - 3M_{\Upsilon})/4$ → Spin-averaged mass of 1S bottomonium



○△ : wave-function optimized results at two lattice spacings

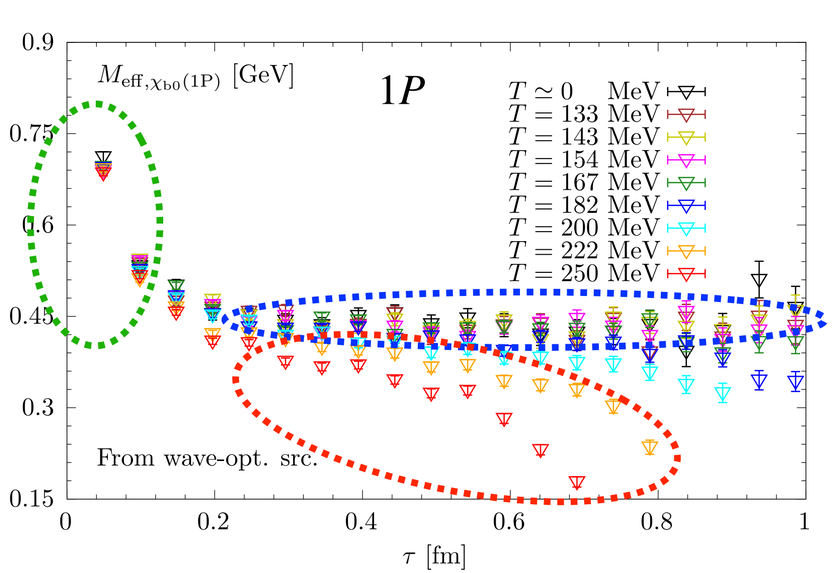
● : Gaussian-smeared results

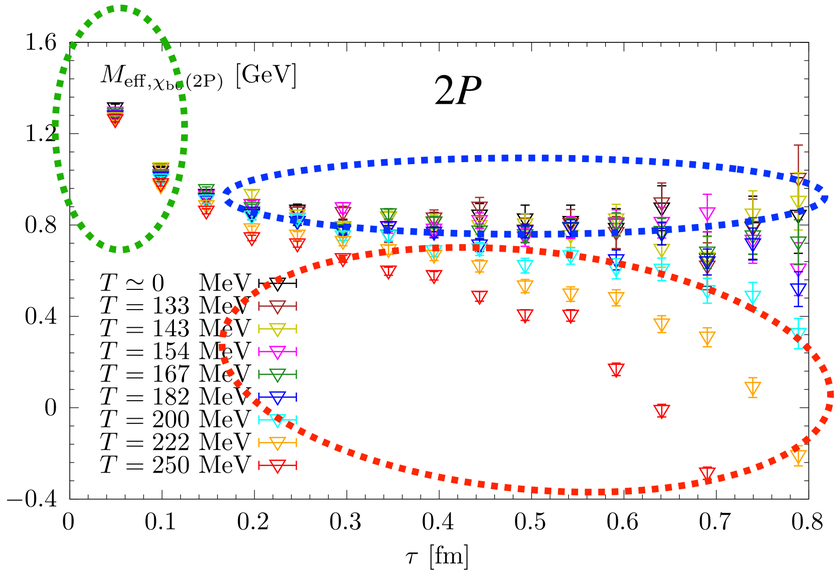
| : PDG values

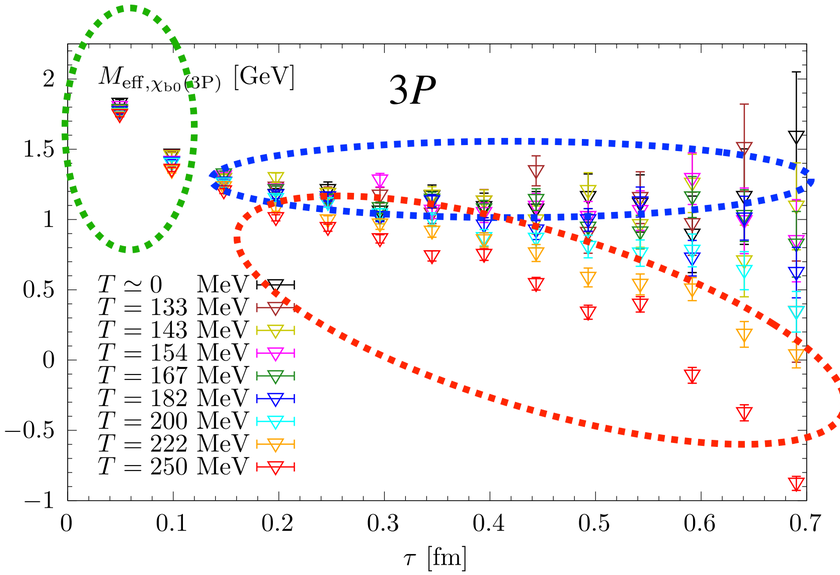
⋮ : lattice-predicted $M_{\eta_b(3S)}$

R. Larsen, et.al., PLB 800, 135119 (2020)

Effective mass at finite temperatures

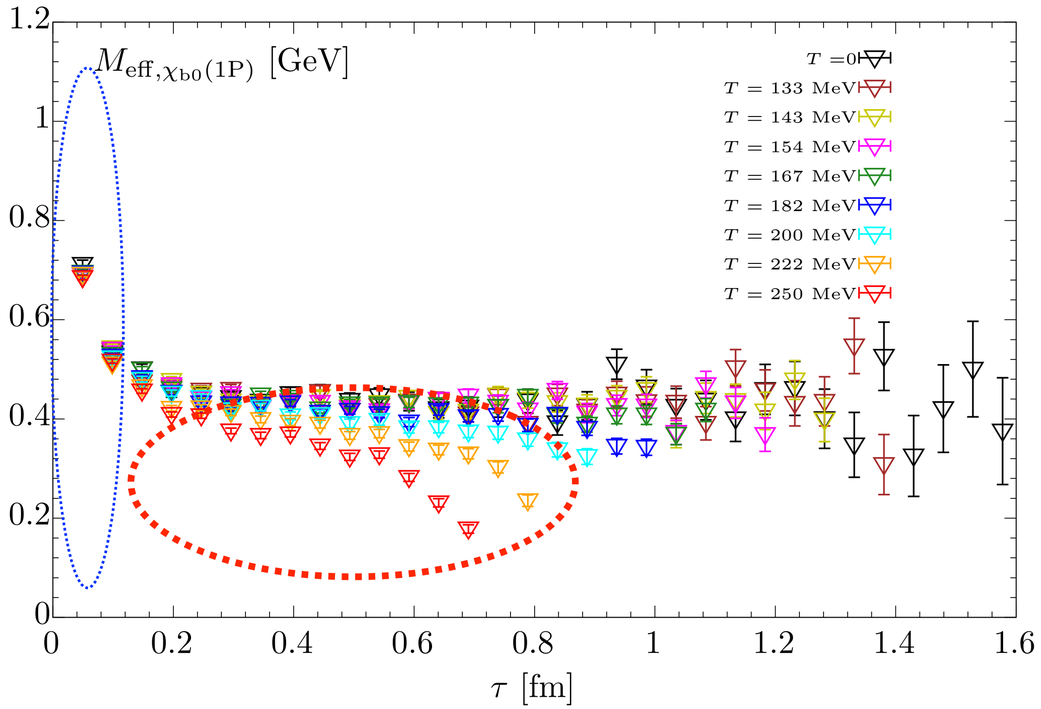






- Overlap within small τ region : temperature-independent behavior
- Approach to vacuum plateau at $T \lesssim 170$ MeV : weak in-medium modification
- Shorter plateau ends with faster drop for higher T : clear in-medium effect, prominent for higher excited state

Defining continuum-subtracted correlator



$$C_{\mathrm{sub}}(\tau, T) \equiv C(\tau, T) - C_{\mathrm{cont}}(\tau)$$

Sensitive to thermal effect

Temperature independent

To be extracted at $T = 0$:

$$C_{\mathrm{cont}}(\tau) = C(\tau, T = 0) - Ae^{-M\tau}$$

$$C_{\mathrm{sub}} = \int_{-\infty}^{+\infty} \rho_{\mathrm{med}}\, e^{-\tau\omega}\, \mathrm{d}\omega$$

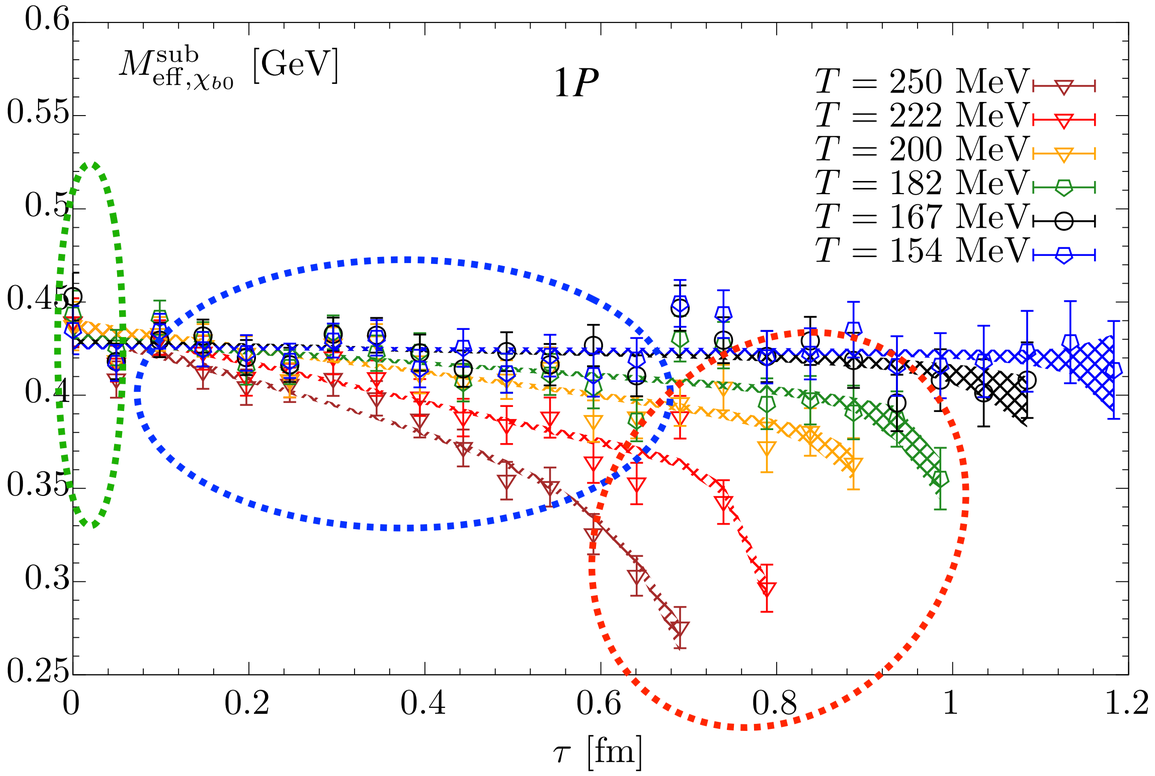
$$\rho_{\mathrm{med}}(\omega, T) \equiv \rho(\omega, T) - \rho_{\mathrm{cont}}(\omega)$$

Encodes in-medium properties

The continuum at large ω

Continuum-subtracted effective mass

$$M_{\mathrm{eff}}^{\mathrm{sub}}(\tau) = \frac{1}{a}\log\left[\frac{C_{\mathrm{sub}}(\tau,T)}{C_{\mathrm{sub}}(\tau+a,T)}\right]$$



Small τ region:
close to bottomonium masses in vacuum

Middle τ region:
nearly linear decrease;
steeper slope for higher T

Tail around $\tau \sim 1/T$:
sharp drop, prominent for higher T

$$\rho_{\mathrm{med}}(\omega,T) = \rho^{\mathrm{peak}}(\omega,T) + A_{\mathrm{low}}(T)\delta\left(\omega - \omega_{\mathrm{low}}(T)\right)$$

Dominant peak structure,
related to linear behavior of $M_{\mathrm{eff}}^{\mathrm{sub}}$ in middle τ

Small, medium-dependent contribution below the main peak,
related to $M_{\mathrm{eff}}^{\mathrm{sub}}$ at large τ around $1/T$

Next: Extract in-medium parameters from $C^{\mathrm{sub}}(\tau,T)$ via physically-motivated parameterization of $\rho^{\mathrm{peak}}(\omega,T)$

Parameterization of $\rho^{\mathrm{peak}}(\omega, T)$

$$\rho_{\mathrm{med}}(\omega,T) = A_{\mathrm{low}}(T)\delta\left(\omega-\omega_{\mathrm{low}}(T)\right) + A_{\mathrm{med}}(T)\frac{\Gamma(\omega,T)}{\left(\omega-M_{\mathrm{med}}(T)\right)^2+\Gamma^2(\omega,T)}$$

Cut-Lorentzian type:

A. Bazavov, et.al., PRD 109, 074504 (2024)

$$\Gamma(\omega,T) = \Gamma_0\Theta(cut - |\omega - M_{\mathrm{med}}|)$$

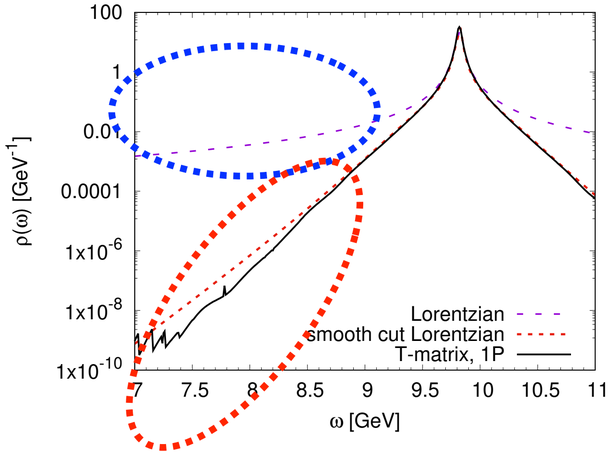
Smooth cut-Lorentzian type:

$$\Gamma(\omega) = \Gamma_0\Theta_\delta(cut-(\omega-M))\Theta_\delta(cut+(\omega-M))$$

$$\text{with } \Theta_\delta(x) = \frac{1}{2}[1+\mathrm{sgn}(x)\tanh(\frac{x}{\delta})]$$

☹ Only valid closely around the main peak

☹ Tail behavior is badly described around *cut*



😀 Incorporate feature of main peak from T-matrix

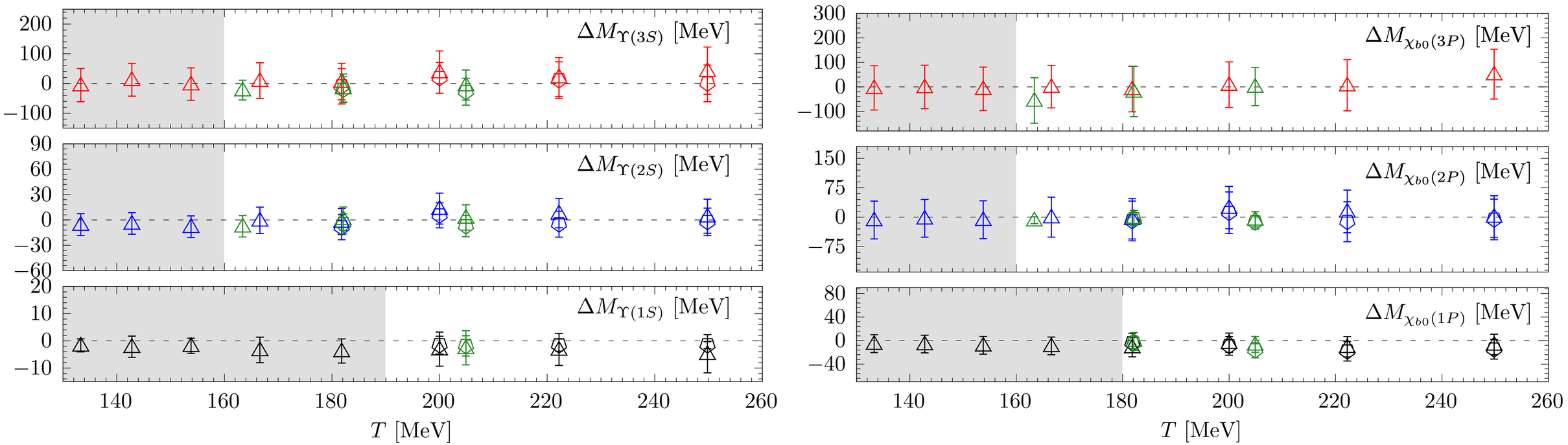
S. Y. F. Liu&R. Rapp, PRC 97, 034918 (2018)

Z. D. Tang, et.al., arXiv:2411.09132

😀 Better described tail of main peak

In-medium mass shift

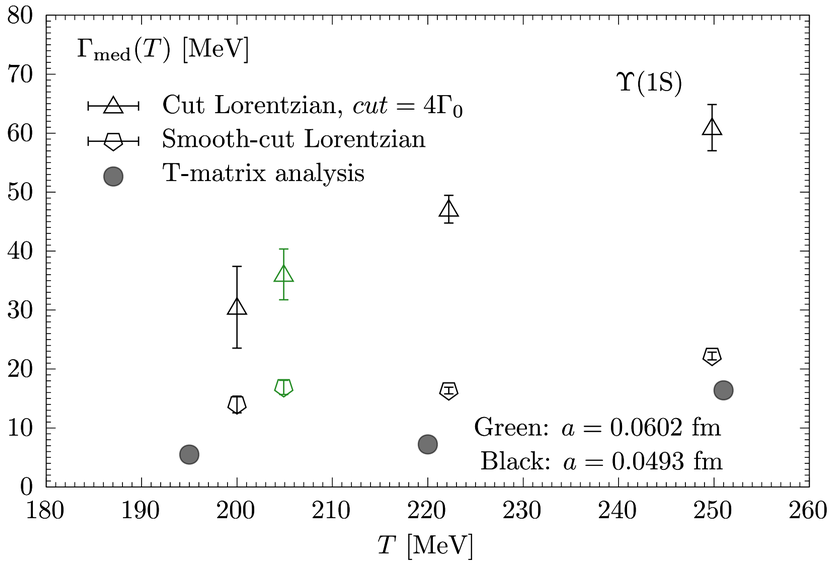
$$\Delta M = M_{\mathrm{med}}(T) - M(T=0)$$

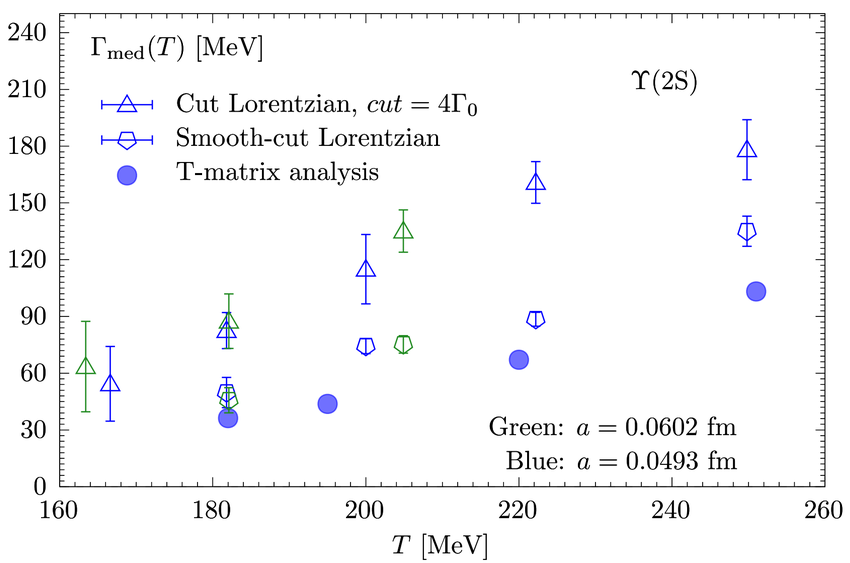


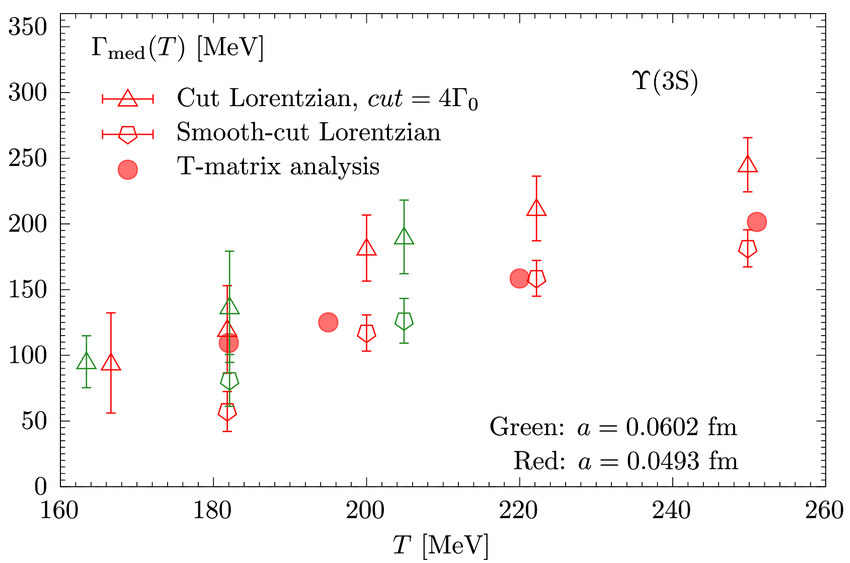
Cut Lorentzian ansatz : 0.0493 fm 0.0602 fm Smooth-cut Lorentzian ansatz : 0.0493 fm 0.0602 fm

- ΔM consistent with zero: almost no change in the in-medium masses
- Unscreened real part of heavy quark-antiquark potential is supported up to $T \sim 250$ MeV

Thermal width





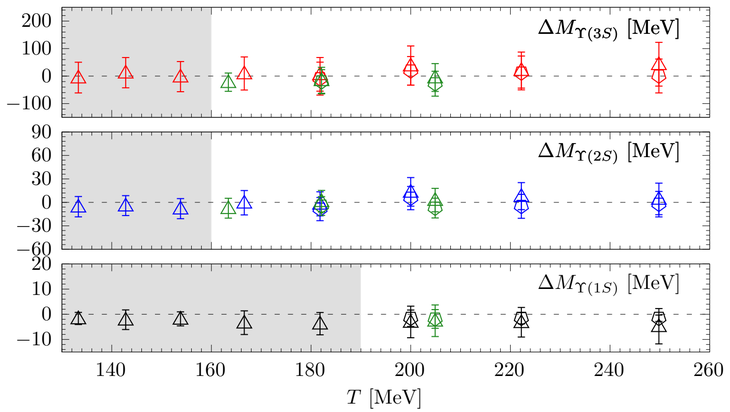


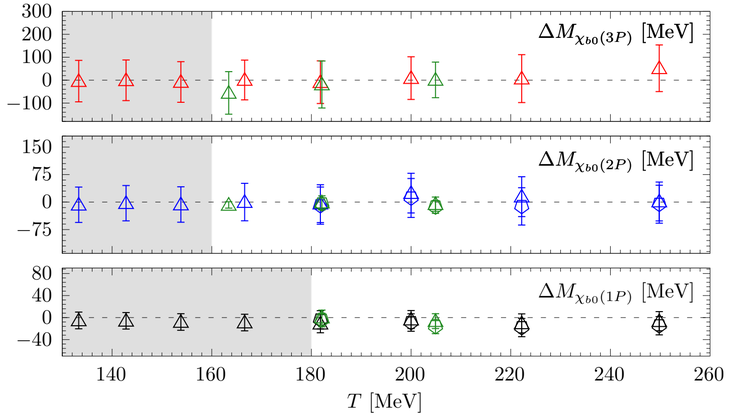
- Significant increase with rising temperatures
- Sequential hierarchy appears in the magnitudes of the thermal widths
- Modeling tail of main peak matters

Summary

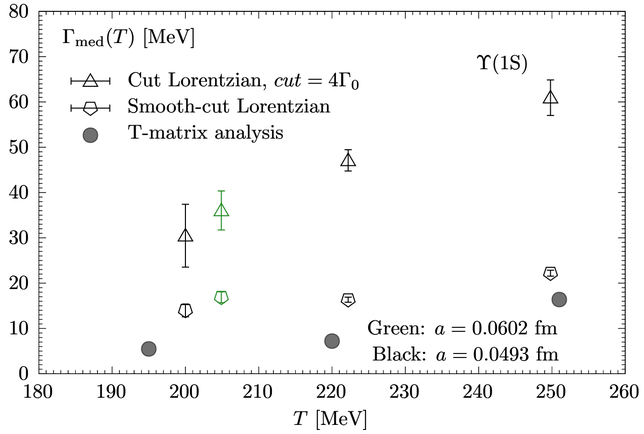
Lattice NRQCD calculations of bottomonium correlators are performed within $T \in (133, 250)$ MeV :

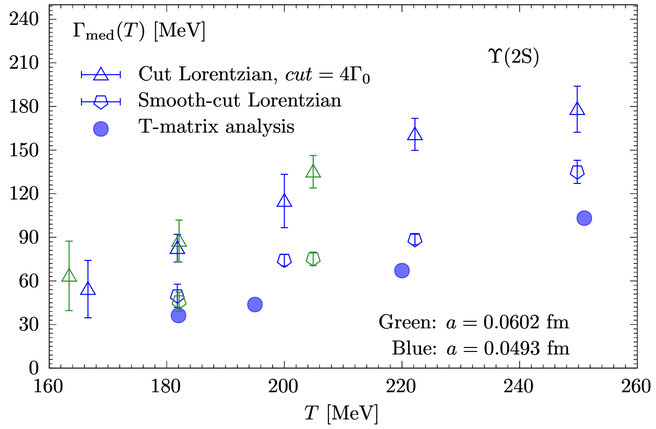
☑ No significant changes in in-medium masses

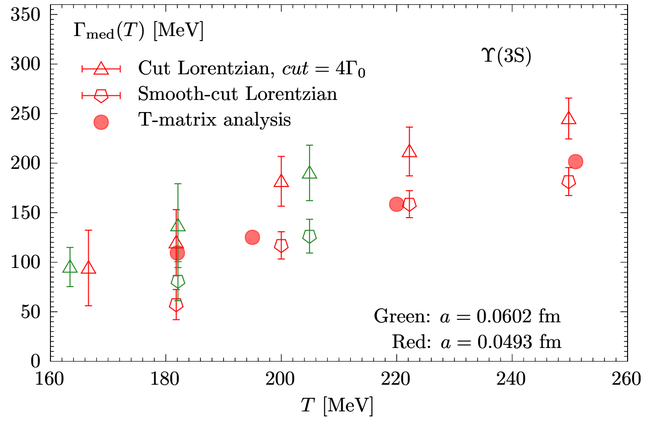




☑ Sequential thermal broadening



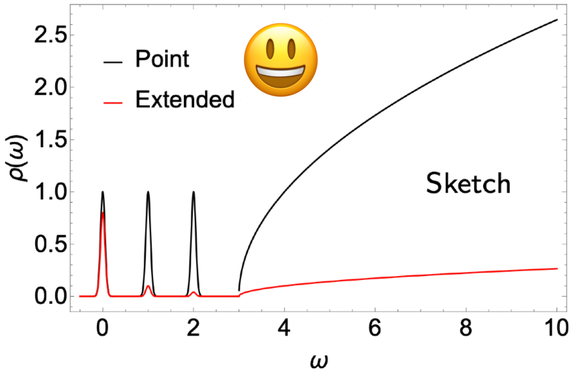




Bottomonia under consideration exist as well-defined quasi-particle excitations
up to $T \sim 250$ MeV, with unchanged vacuum masses, but large thermal widths observed.

Backup

Correlators with extended sources



Correlator: $C(\tau) = \sum_{\mathbf{x}} \langle O(\mathbf{x}, \tau) O^{\dagger}(\mathbf{0}, 0) \rangle$

Gaussian-smeared source

R. Larsen, et.al., PRD 100, 074506 (2019)

$$O(\mathbf{x}, \tau) = \tilde{\bar{q}}(\mathbf{x}, \tau) \Gamma \tilde{q}(\mathbf{x}, \tau)$$

Bottomonium interpolators

Smeared quark and antiquark fields: $\tilde{q} = Wq$

Gaussian-shaped factor

Wave-function optimized source

R. Larsen, et.al., PLB 800, 135119 (2020)

$$O_{\alpha}(\mathbf{x}, \tau) = \sum_{\mathbf{r}} \Psi_{\alpha}(\mathbf{r}) \bar{q}(\mathbf{x} + \mathbf{r}, \tau) \Gamma q(\mathbf{x}, \tau)$$

From the discretized 3-d Schrodinger equation:

$$\left[-\frac{\Delta}{m_b} + V(\mathbf{r}) \right] \Psi(\mathbf{r}) = E \Psi(\mathbf{r})$$

$O(a^4)$-improved discretized Laplacian

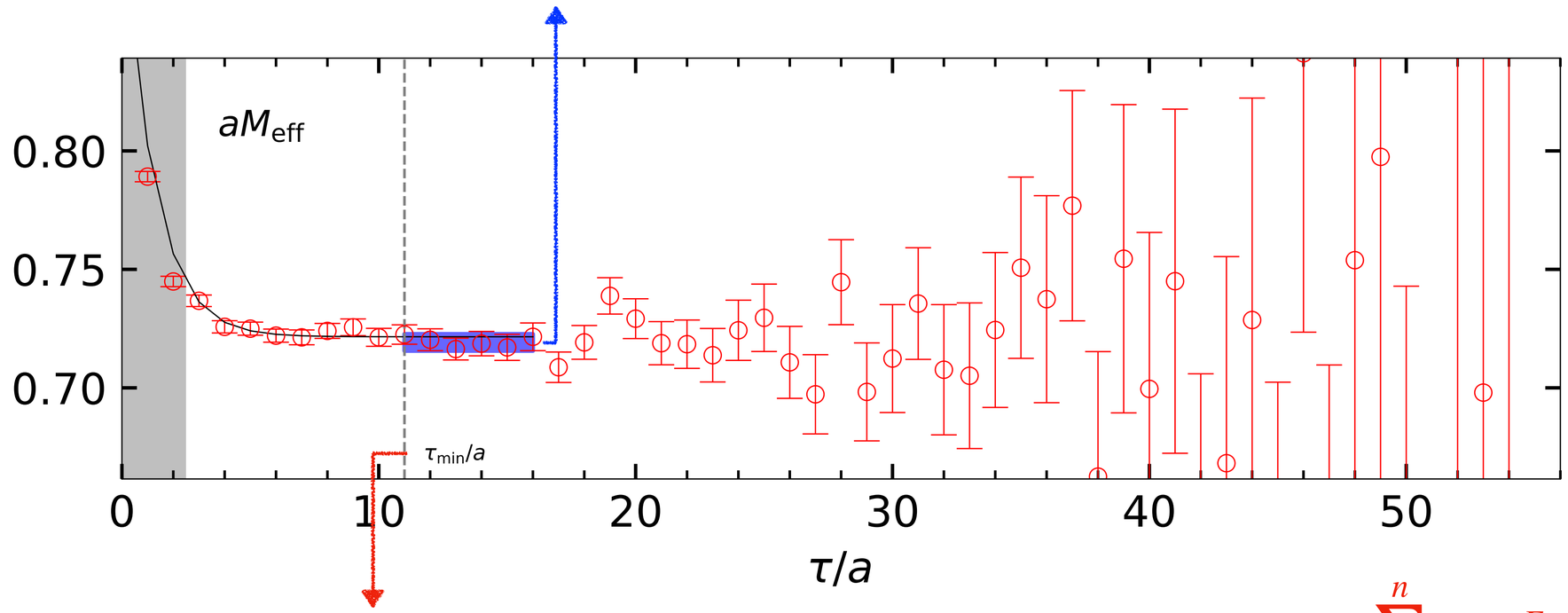
Cornell potential

S. Meinel, PRD 82, 114502 (2010)

Ground state extraction

Ground states are extracted by 1-state fits on correlators within $[\tau_{\min}, \tau_{\max}]$

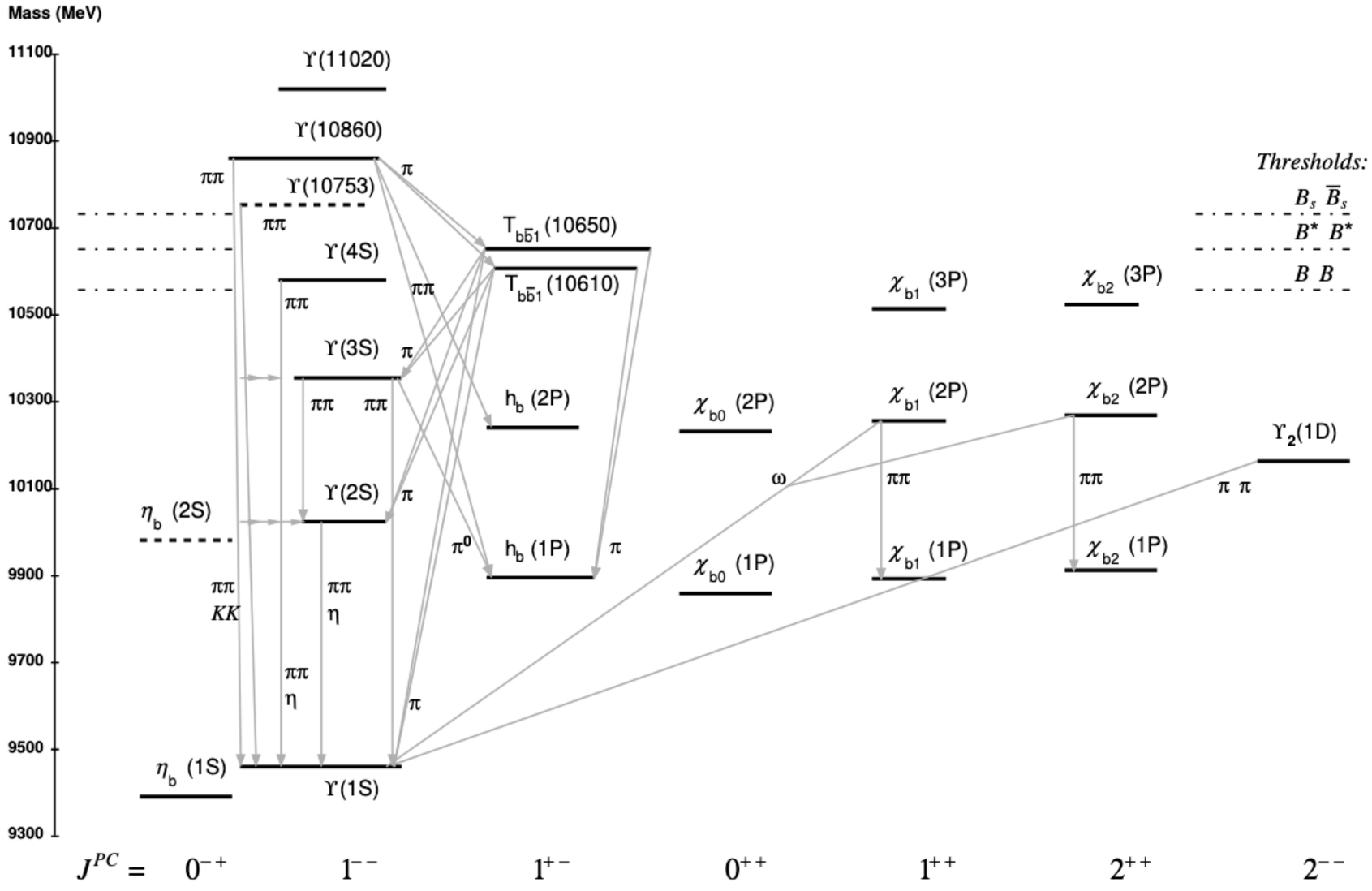
$\tau_{\max}$: Signal-to-noise ratio reaches to 1% (Gaussian) and 8% (wave-opt.)



$\tau_{\min}$: 1. Two-state exponential fit to estimate high state contribution via $f_n(\tau) = \sum_{i=0}^{n} A_i e^{-E_i \tau}, n = 1$

2. Excited-state contribution to the effective mass is under statistical uncertainty:

$$\frac{\log[f_1(\tau)/f_1(\tau+a)] - \log[f_0(\tau)/f_0(\tau+a)]}{E_0} < 25\% \times \frac{\delta_{M_{\text{eff}}}(\tau)}{M_{\text{eff}}(\tau)}$$

P. Fritzsch, et.al., NPB 865, 397(2012)

Bottomonium system from PDG