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Quarkonium properties at non-zero temperature from lattice QCD

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HotQCD collaboration

In collaboration with Rasmus Larsen, Peter Petreczky, and Johannes H. Weber

2605.20034 [hep-lat]

PRELIMINARIES

HOW DOES THE MEDIUM MODIFY QUARKONIUM?

Quarkonium suppression is a key QGP signature: the heavy-quark potential is modified at a finite temperature.

$$V(r,T) = \mathrm{Re}\, V(r,T) + i\, \mathrm{Im}\, V(r,T)$$

MATSUI-SATZ PROPOSAL

$$\mathrm{Re} V(r,T) \sim \frac{e^{-m_D r}}{r}$$

Modifies the binding

THERMAL BROADENING

$$\mathrm{Im}\, V(r,T) \sim \Gamma(T)$$

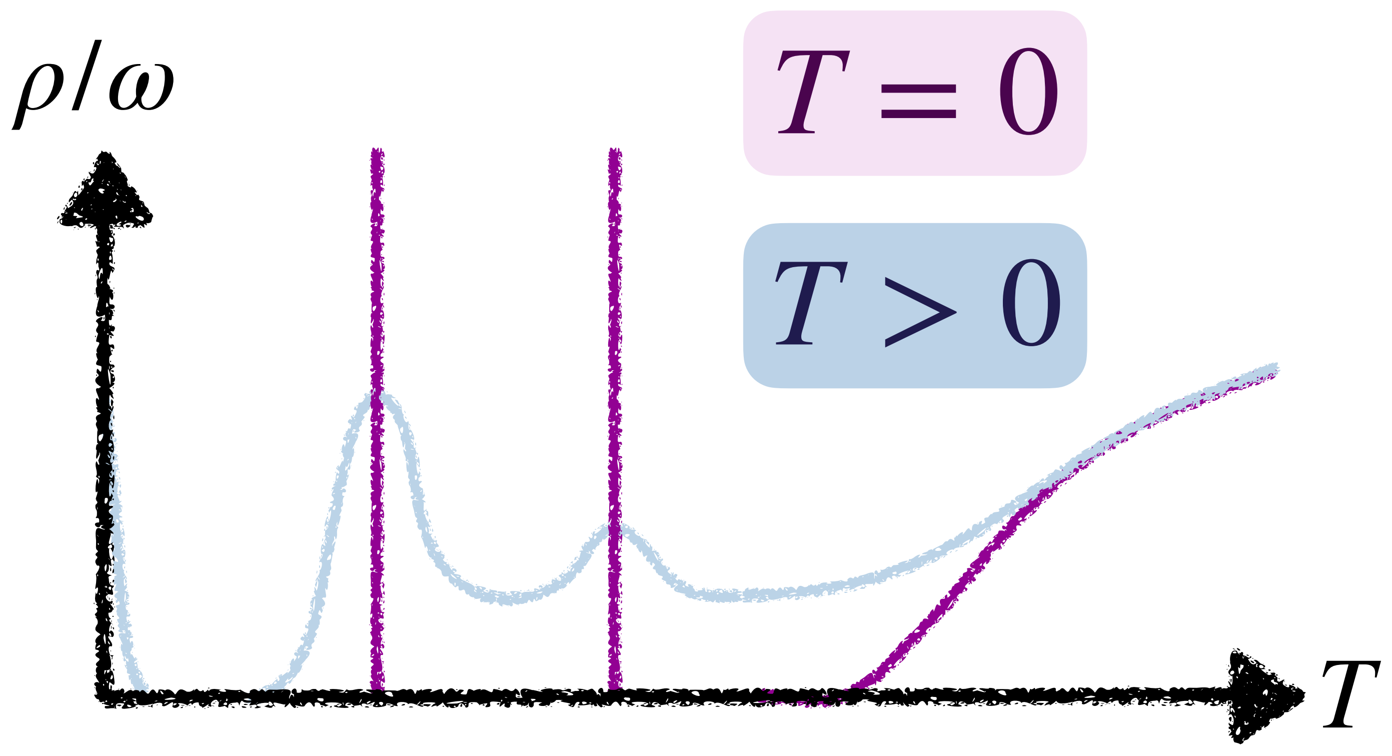
In-medium finite lifetime

All in-medium properties of quarkonia – masses, widths, dissolution – are encoded in **the spectral function**

A peak in the spectral function signals a surviving bound state.

IN-MEDIUM MASS $\longrightarrow M(T) \longrightarrow$ **Peak position**

THERMAL BROADENING $\longrightarrow \Gamma(T) \longrightarrow$ **Width**



CHARMONIA CORRELATORS

FROM SPECTRAL FUNCTIONS TO EUCLIDEAN CORRELATORS

The spectral function is not directly accessible, but it is related to the Euclidean-time correlation function $C_\alpha(\tau, T)$.

$$\boxed{C_\alpha(\tau, T)} = \int_0^\infty \frac{d\omega}{2\pi} \boxed{\rho(\omega, T)} K(\tau, \omega, T) \text{ with } K(\omega, \tau, T) = \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}$$

SPECTRAL FUNCTION

The correlation function is computable on the lattice

PROBLEM

Extracting $\rho(\omega, T)$ from $C_\alpha(\tau, T)$ is an inversion problem.

The kernel smooths information

$$\rho_1(\omega) \neq \rho_2(\omega) \quad \text{but} \quad C_1(\tau) \simeq C_2(\tau)$$

Only limited Euclidean time

$$0 \leq \tau \leq 1/2T$$

OPERATORS

To probe in-medium quarkonium properties directly from the lattice, the choice of meson operators is crucial.

The challenge: operator choice matters.

POINT OPERATORS

$$O_\Gamma(\mathbf{x},\tau) = \bar{\Psi}(\mathbf{x},\tau)\,\Gamma\,\Psi(\mathbf{x},\tau)$$

Quark and antiquark at the same spatial point

Large overlap with UV continuum states

Weak overlap with physical quarkonium states

Consequence:

Correlators dominated by continuum contributions

Reduced sensitivity to in-medium modifications

EXTENDED OPERATORS

$$\tilde{O}_\alpha(\mathbf{x},\tau) = \sum_{\mathbf{y}} \phi_\alpha(\mathbf{y})\,\bar{\Psi}(\mathbf{x}+\mathbf{y},\tau)\,\Gamma\,\Psi(\mathbf{x},\tau)$$

Spatially extended quarkonium-like operators

Wavefunction-inspired smearing

Optimized overlap with 1S, 2S, 1P

Advantage:

Suppress continuum contamination

Enhanced sensitivity: widths and mass shifts

Ding, Kaczmarek, Karsch, Satz, Jakovac, Petreczky, Velytsky, Datta, etc

PHYSICAL STATES

We construct the optimized operators:

$$\tilde{C}_{\alpha,\beta}(\tau) = \sum_{\mathbf{x}} \left\langle \tilde{O}^{\dagger}_{\alpha}(\mathbf{x},\tau)\tilde{O}_{\beta}(\mathbf{0},0) \right\rangle$$

$$\tilde{C}_{\alpha,\beta}(\tau) = \begin{pmatrix} \boxed{\delta\delta} & & \text{Cross terms} & \\ & \boxed{\text{1S 1S}} & & \\ & & \boxed{\text{2S 2S}} & \\ \text{Cross terms} & & & \boxed{\text{3S 3S}} \end{pmatrix}$$

We then approximately diagonalize the correlator matrix using a GEVP:

$$C_{\alpha,\beta}(\tau) = \sum_{\mathbf{x}} \left\langle O^{\dagger}_{\alpha}(\mathbf{x},\tau)O_{\beta}(\mathbf{0},0) \right\rangle = \delta_{\alpha,\beta}\, C_{\alpha}(\tau) \text{ with } \tilde{C}_{\alpha'\beta'}(\tau)\,\Omega_{\alpha\alpha'} = \lambda_{\alpha}(\tau,\tau_0)\,\tilde{C}_{\alpha'\beta'}(\tau_0)\,\Omega_{\alpha\alpha'}$$

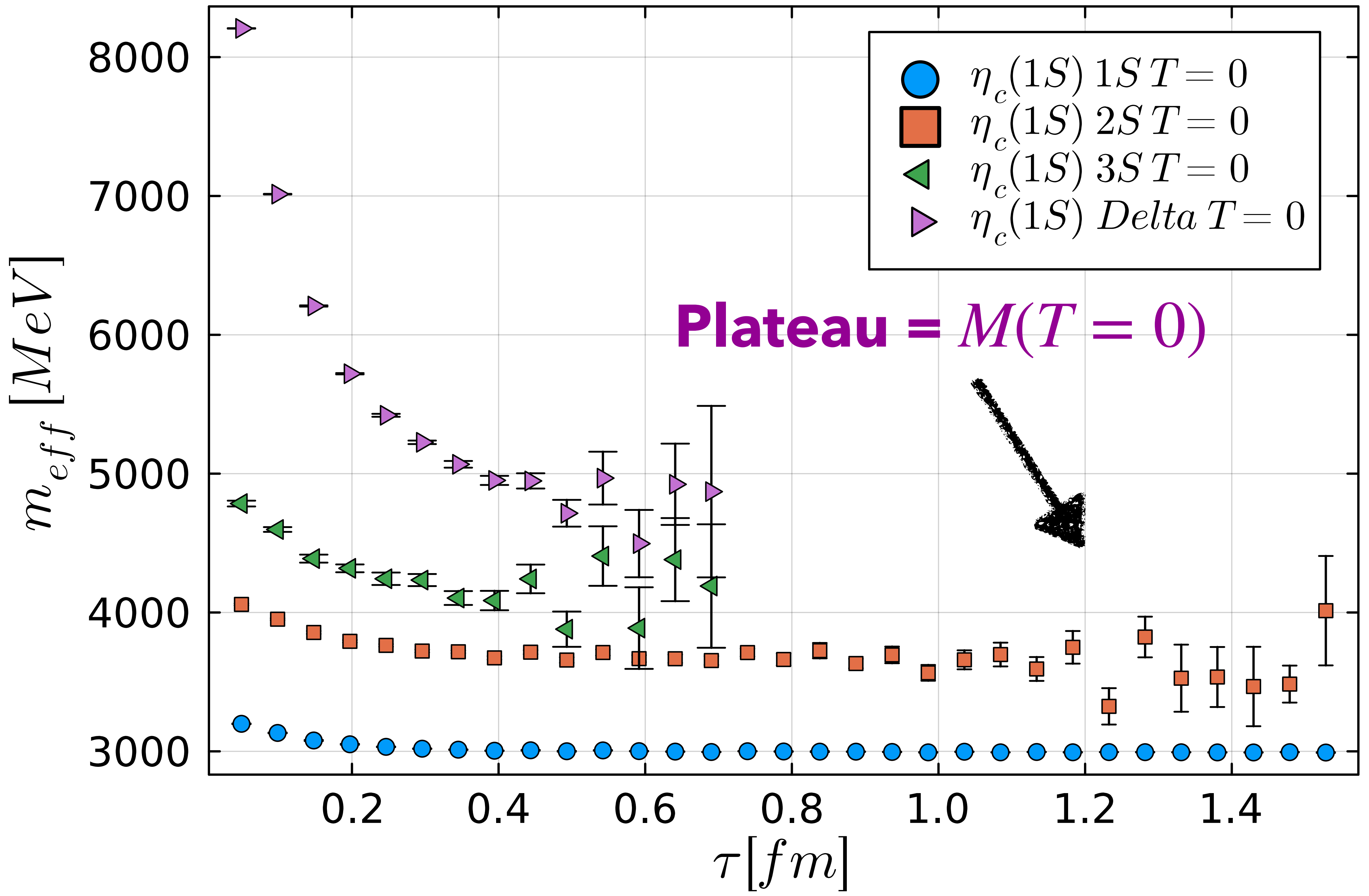
On a finite-temperature lattice with periodic Euclidean time, we use the following definition:

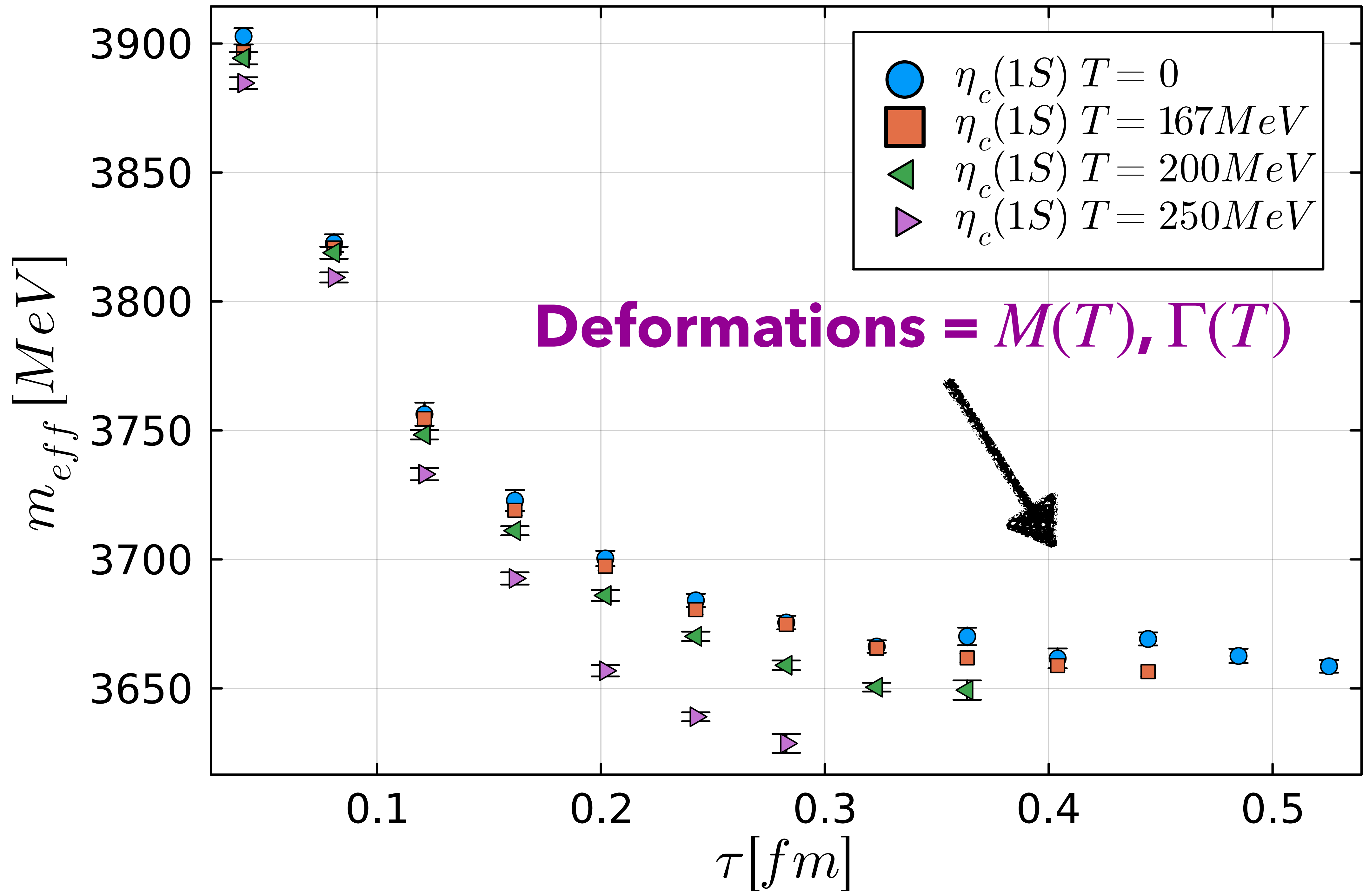
Forward and backward

$$\frac{C_{\alpha}(\tau + a_{\tau})}{C_{\alpha}(\tau)} = \frac{\cosh\left[m_{\text{eff}}(\tau)\left(\tau + a_{\tau} - \frac{N_{\tau}a_{\tau}}{2}\right)\right]}{\cosh\left[m_{\text{eff}}(\tau)\left(\tau - \frac{N_{\tau}a_{\tau}}{2}\right)\right]}$$

EFFECTIVE MASS m_{eff}

EFFECTIVE MASSES





ZERO TEMPERATURE EFFECTIVE MASS

FINITE TEMPERATURE EFFECTIVE MASS

The plateaus on the effective mass m_{eff} represents the masses of the state that exists in $\rho(\omega, T)$.

At finite temperature, there is a slight difference in effective mass with respect to the zero temperature plateau.

To isolate the in-medium peak, we must remove the high-energy contribution

ISOLATING THE IN-MEDIUM PEAK

We estimate the approximately temperature-independent high-energy contribution from the $T = 0$ correlator.

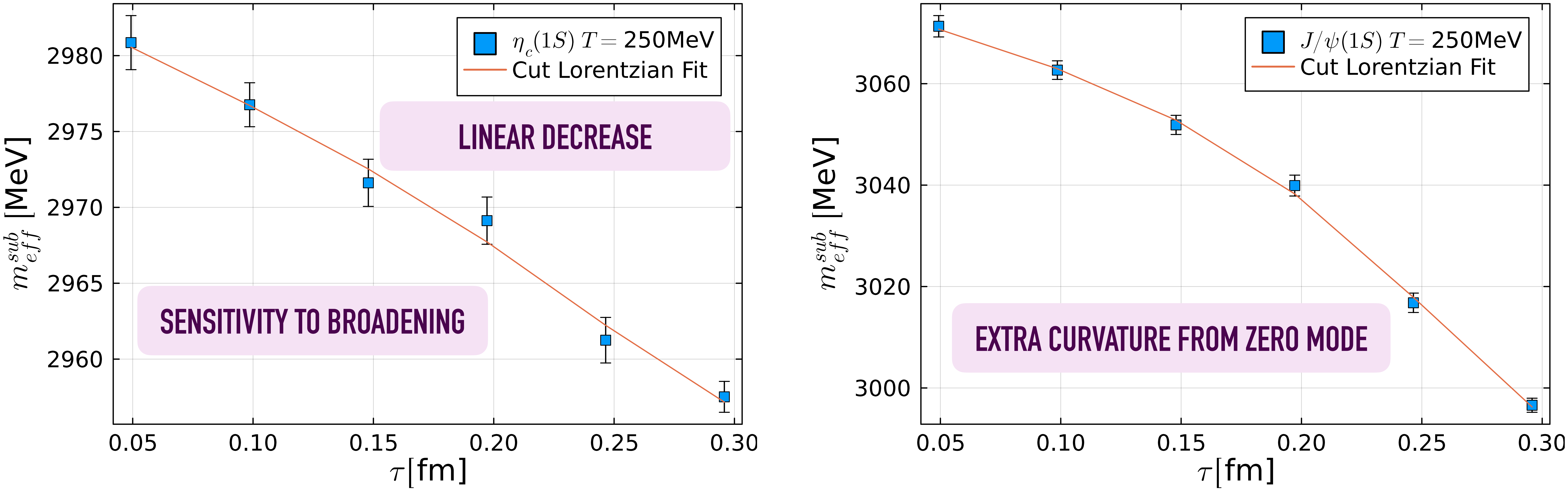
$$\sigma_\alpha(\omega, T) = \sigma_\alpha^{\text{med}}(\omega, T) + \sigma_\alpha^{\text{high}}(\omega)$$

SUBTRACTED CORRELATORS

$$C_\alpha^{\text{high}}(\tau, 0) = C_\alpha(\tau, 0) - A_\alpha^0 e^{-M_\alpha^0 \tau}$$

$$C_\alpha^{\text{sub}}(\tau, T) = C_\alpha(\tau, T) - C_\alpha^{\text{high}}(\tau, 0) - C_\alpha^{\text{high}}\left(\frac{1}{T} - \tau, 0\right)$$

Larsen, Meinel, Mukherjee, Petreczky (2020)



MODELING THE IN-MEDIUM PEAK

Ding, Huang, Petreczky, Larsen, Meinel, Mukherjee, Tang (2025)

We model the remaining in-medium contribution with a broadened peak:

$$\sigma_\alpha^{\mathrm{med}}(\omega, T) = \frac{A_\alpha(T)}{\pi} \frac{\Gamma_\alpha(\omega, T)}{\left[\omega - M_\alpha(T)\right]^2 + \Gamma_\alpha^2(\omega, T)} + z_\alpha\, \omega\, \delta(\omega)$$

LORENTZIAN CUT ANSATZ

with the frequency-dependent width $\Gamma_\alpha(\omega, T) = \Gamma_\alpha^0(T)\,\Theta\Big(\mathrm{cut}_\alpha - \big|\omega - M_\alpha(T)\big|\Big)$ and $\mathrm{cut}_\alpha = 4\Gamma_\alpha^0$.

$M_\alpha(T)$ IS IN-MEDIUM MASS

Robust

$\Gamma_\alpha^0(T)$ IS A THERMAL WIDTH

Ansatz dependent

The zero-mode term is included where relevant, especially in vector and P-wave channels.

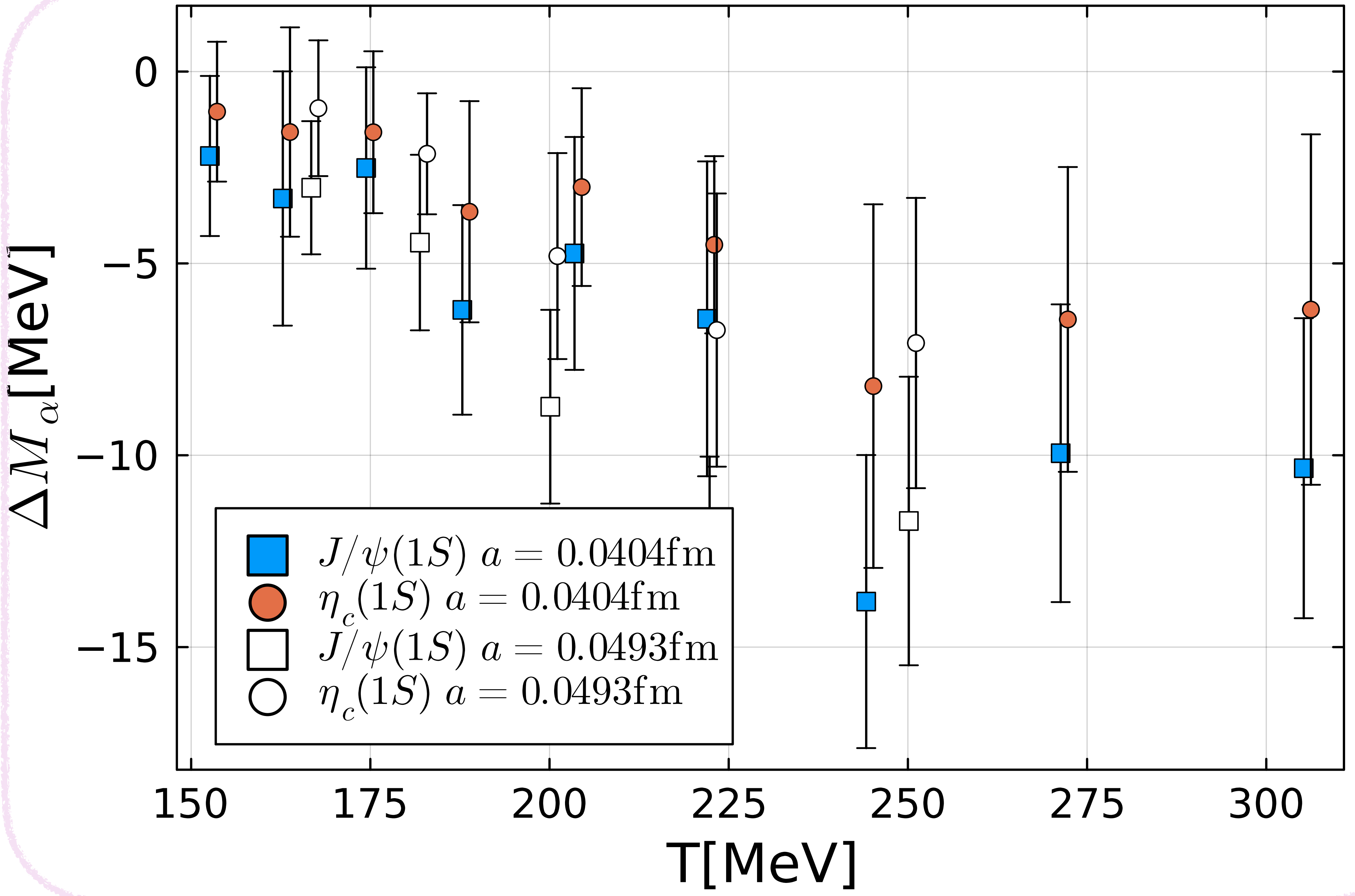
η_c **Pseudoscalar:** no zero mode expected

J/ψ **Vector:** zero mode related to heavy-flavor transport

χ_{c0} **and** χ_{c1} **P states:** large zero-mode contribution; removed using the derivative correlator

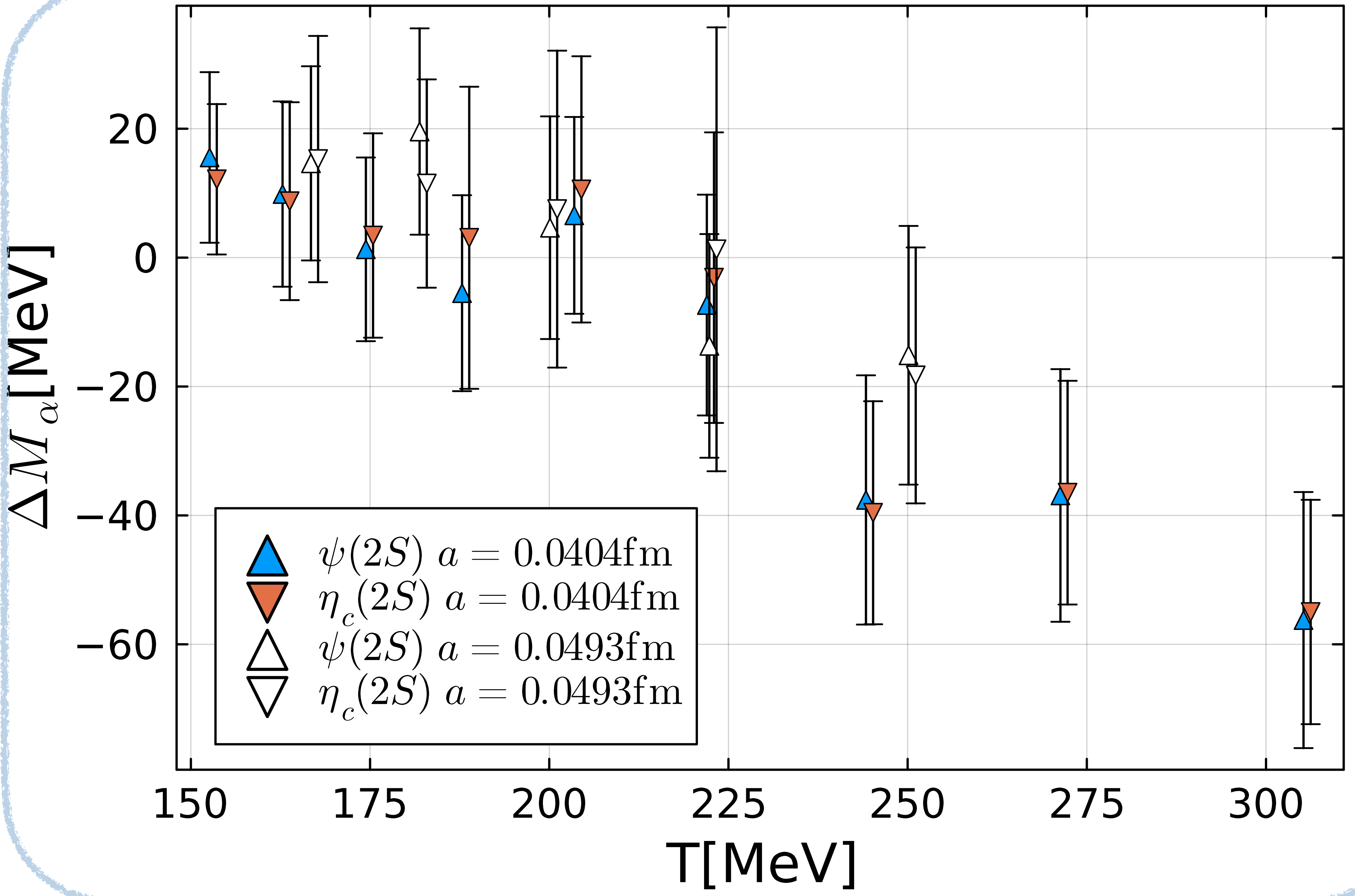
MODELING THE IN-MEDIUM PEAK

1S



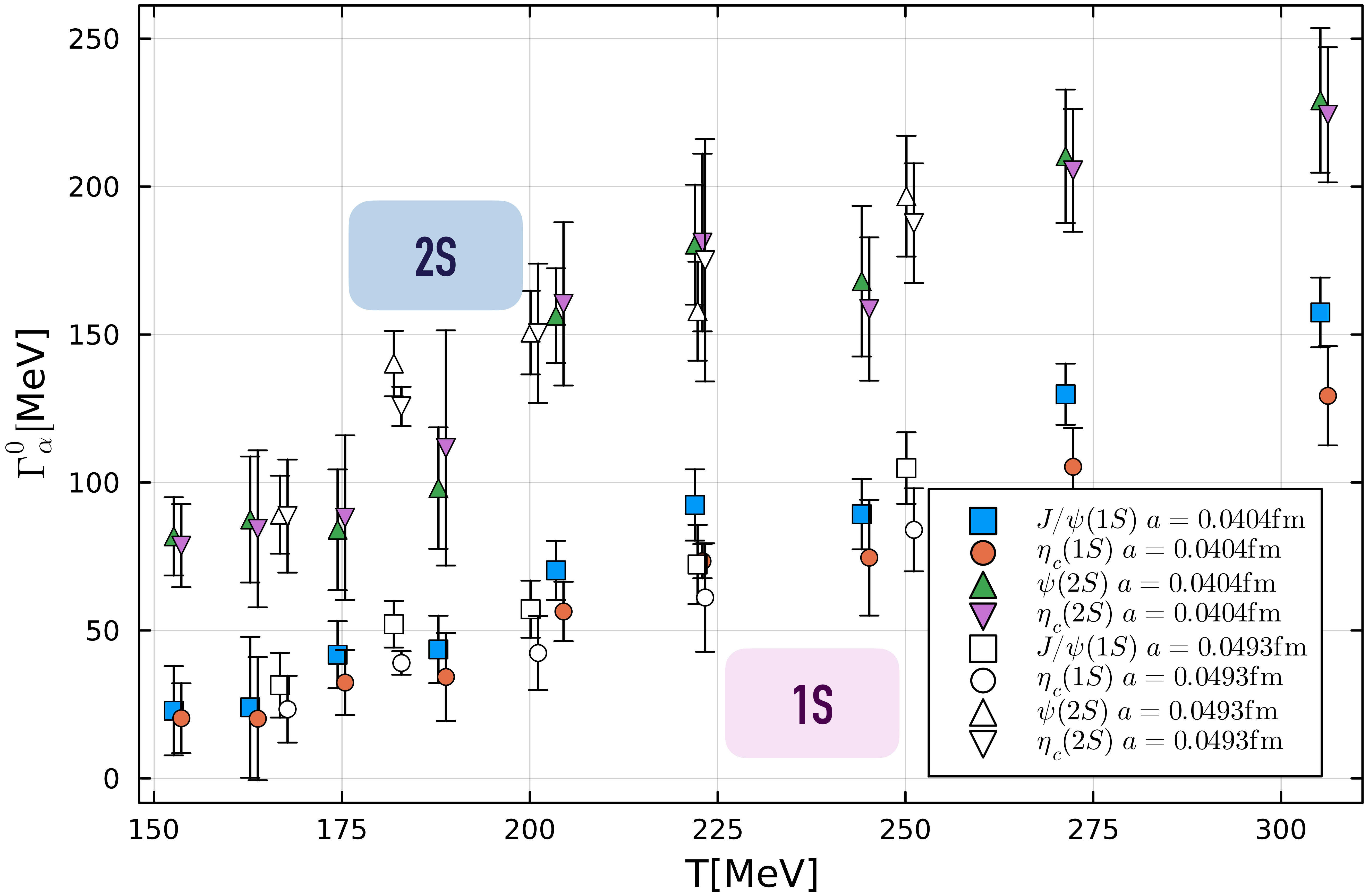
Small downward mass shifts

2S



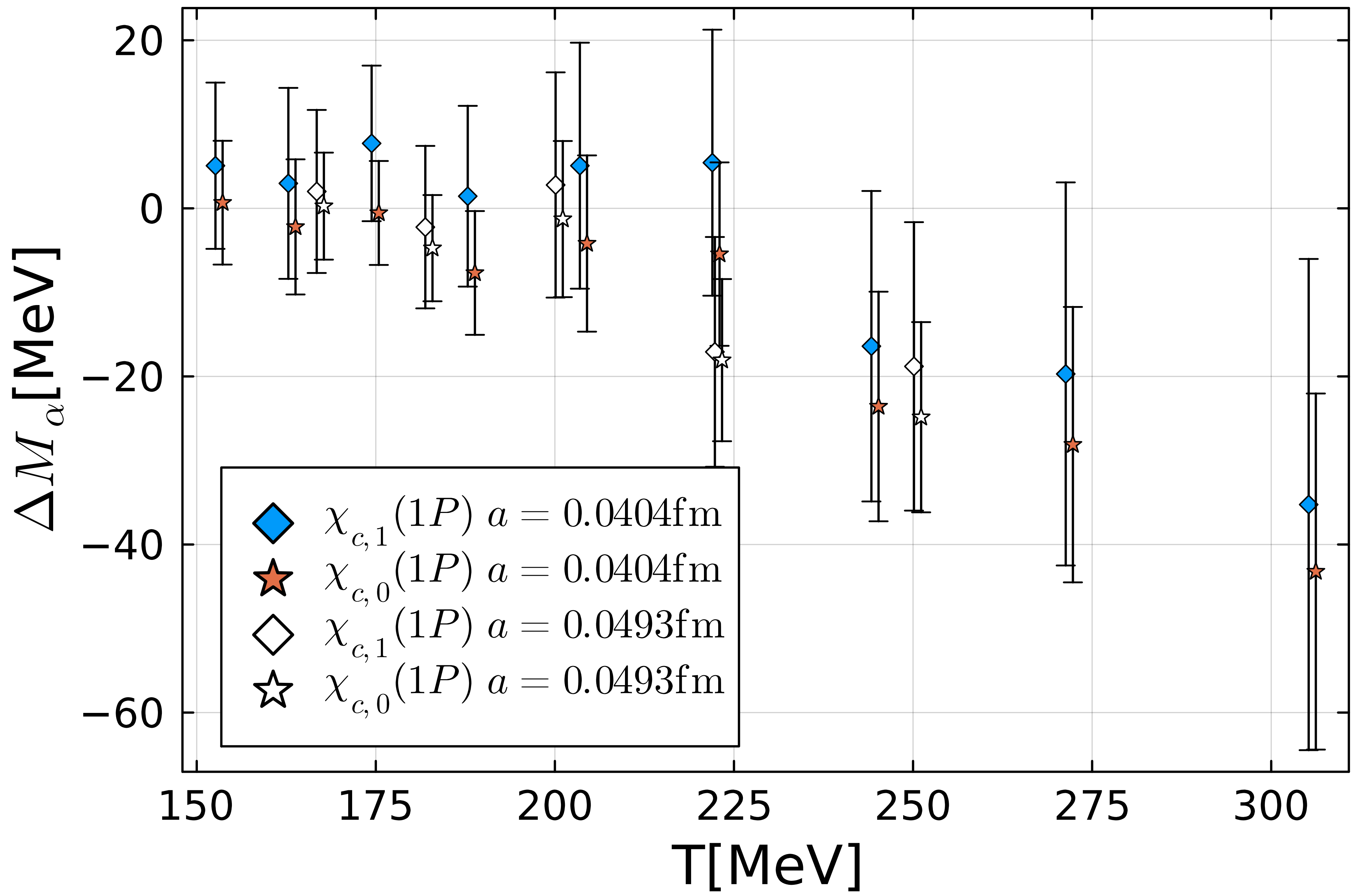
Visible above $T \simeq 200$ MeV

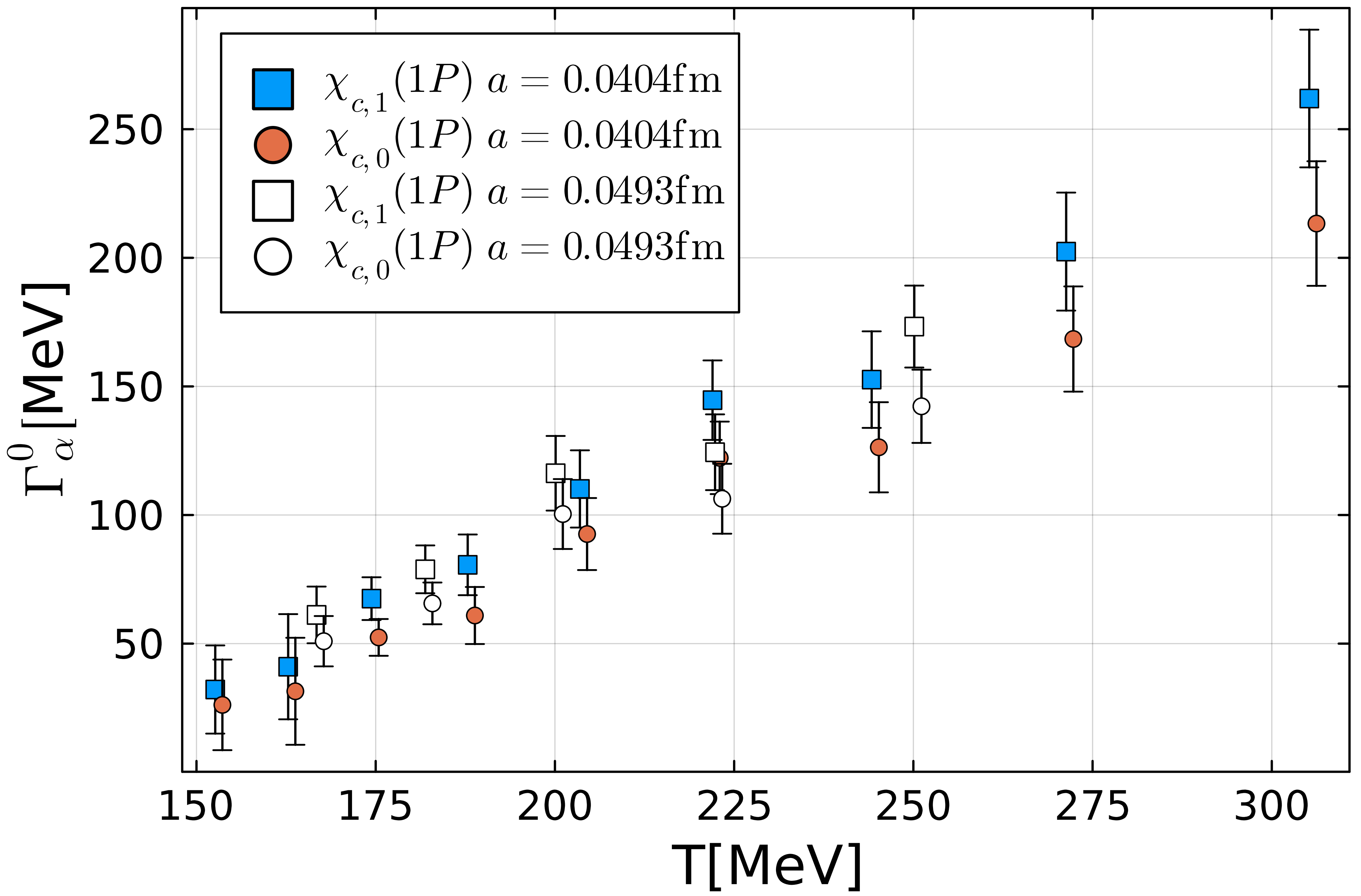
MODELING THE IN-MEDIUM PEAK



Thermal widths increase clearly with temperature → Clear broadening of the spectral peak

MODELING THE IN-MEDIUM PEAK





The larger, less tightly bound 2S and 1P states are more strongly affected than the compact 1S states

THERMAL MODIFICATIONS FOLLOW THE STATE-SIZE HIERARCHY

BOTTOMONIA CORRELATORS

NRQCD RESULTS

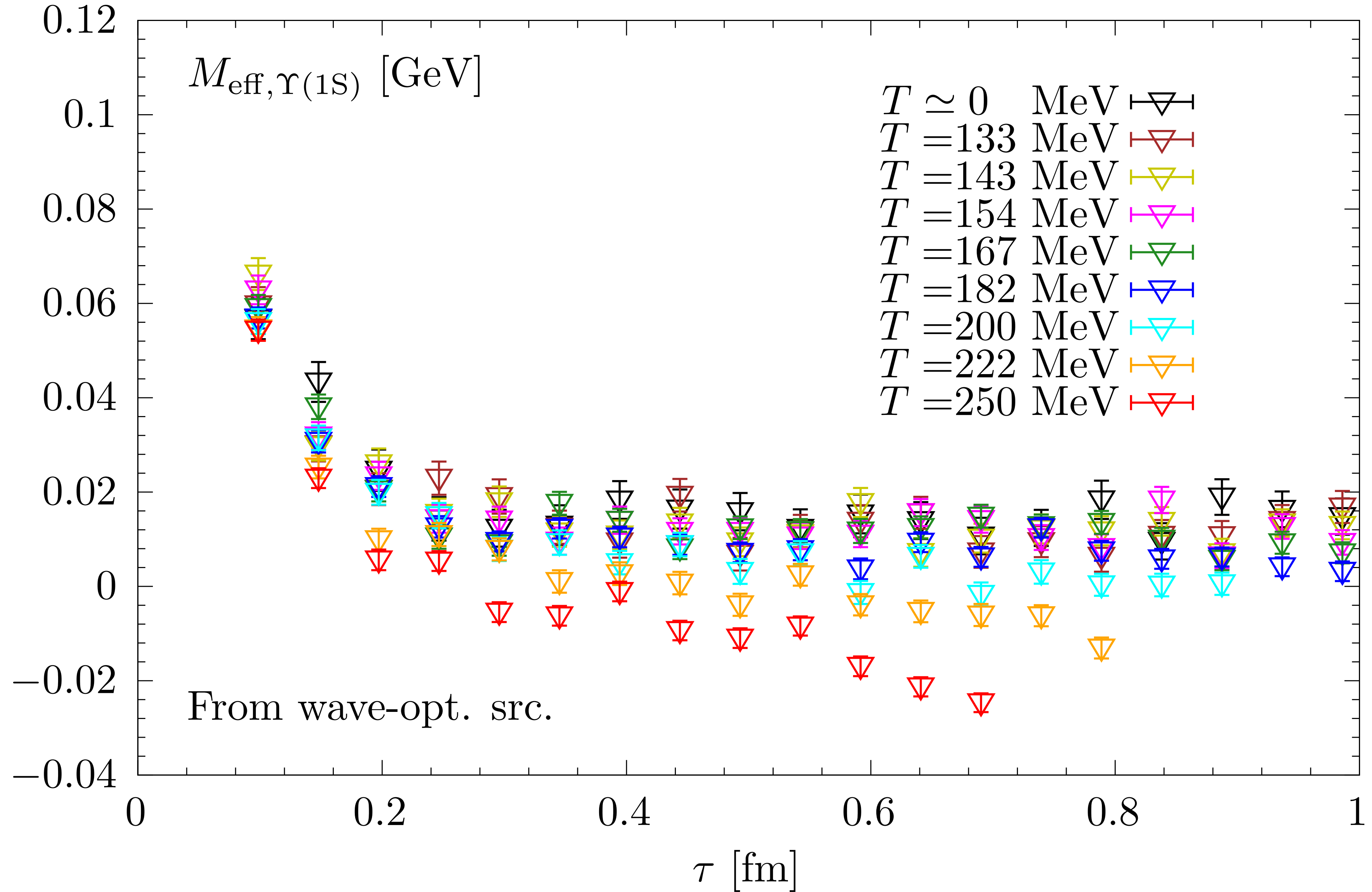
Bottom quarks are sufficiently heavy for a lattice non-relativistic QCD (NRQCD) description.

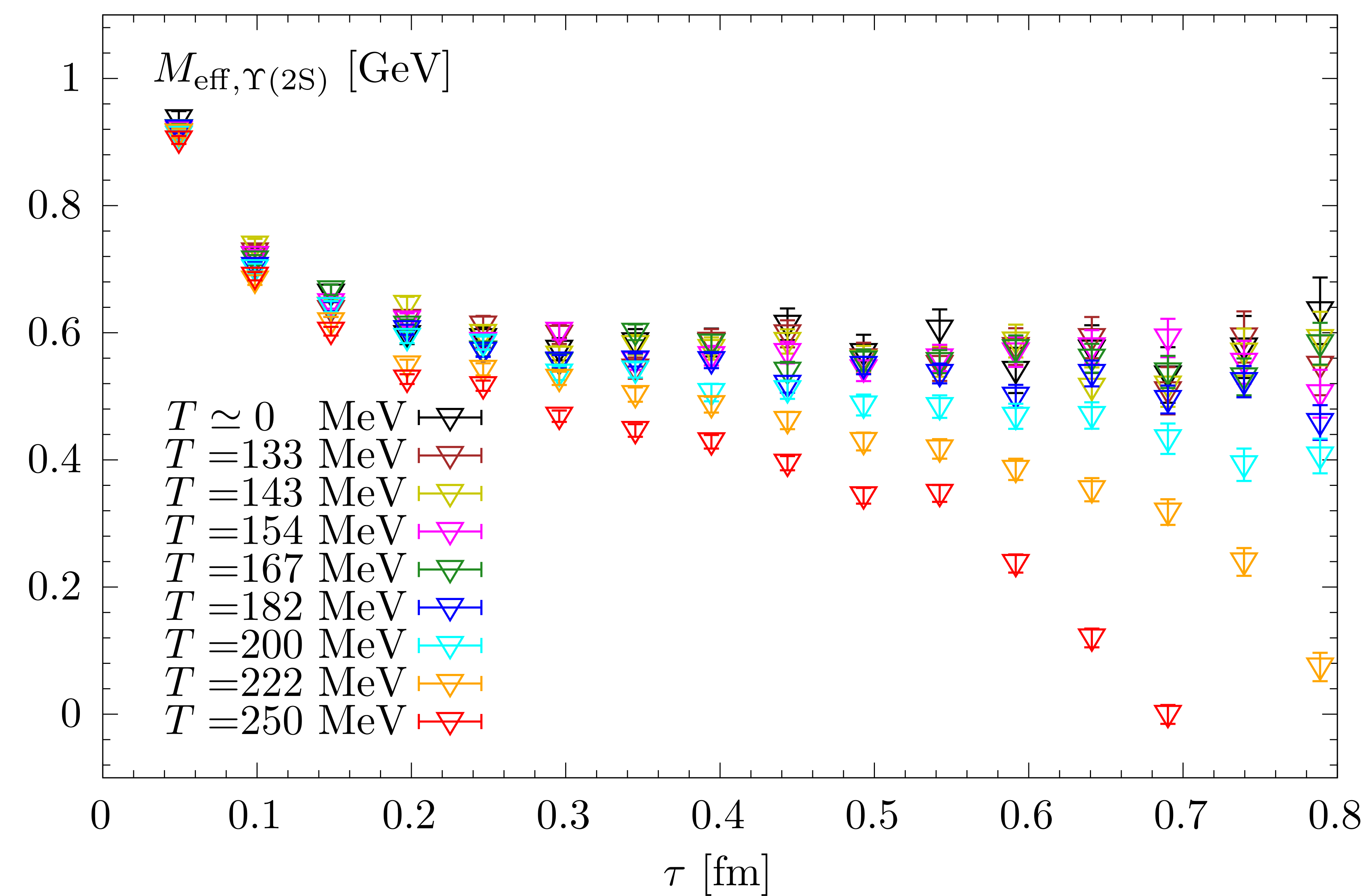
INTEGRATED OUT m_b **Hard scale** $am_b \geq 1$ → $m_Q v$ **Soft scale** $m_Q v^2$ **Ultrasoft scale**

Bodwin, Braaten, Lepage (1997)

Integrating out m_b removes the relativistic antiparticle sector, so heavy quarks propagate only forward in τ.

$$C(\tau, T) = \int d\omega\, \rho(\omega, T) e^{-\omega\tau}$$

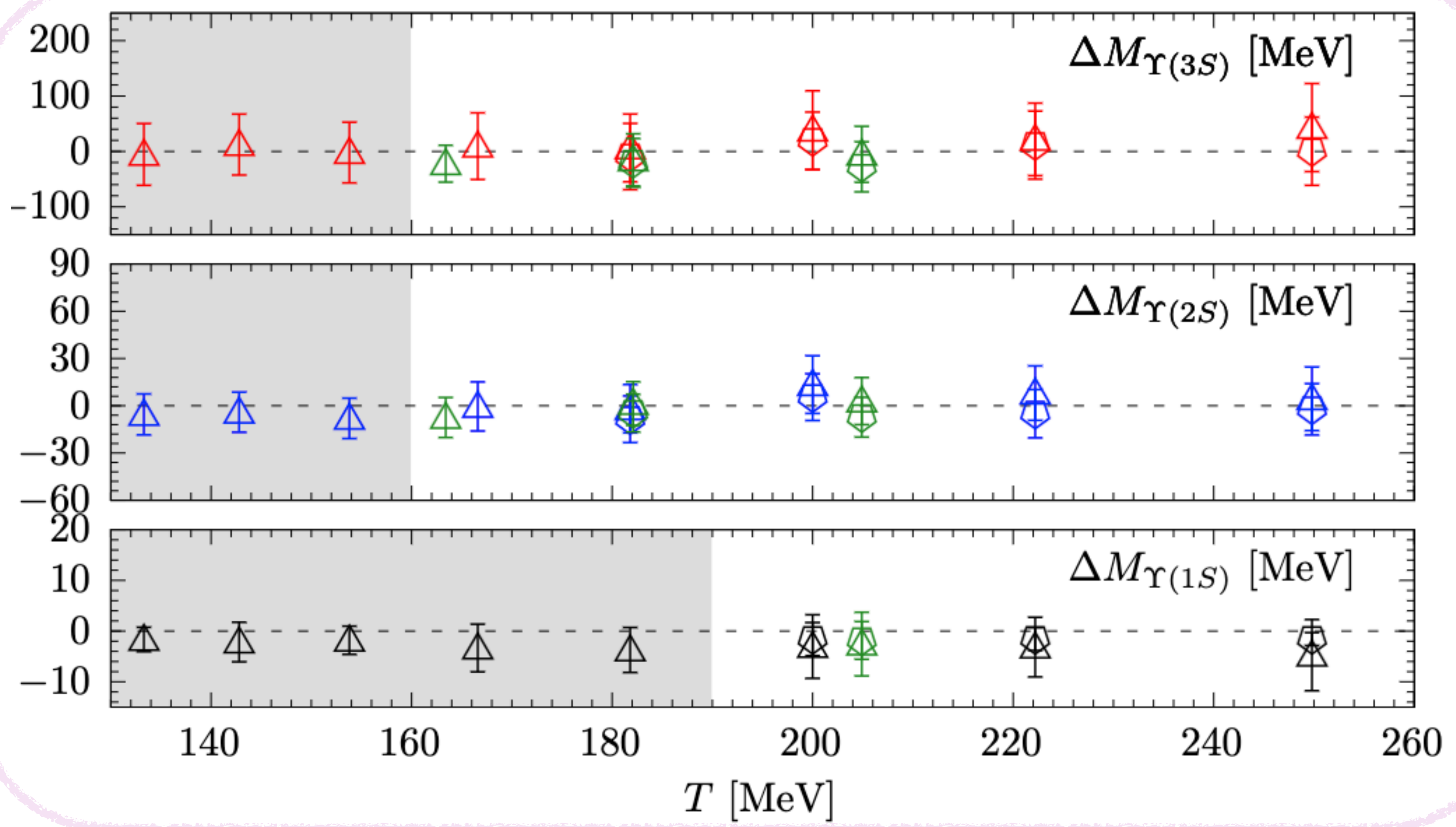


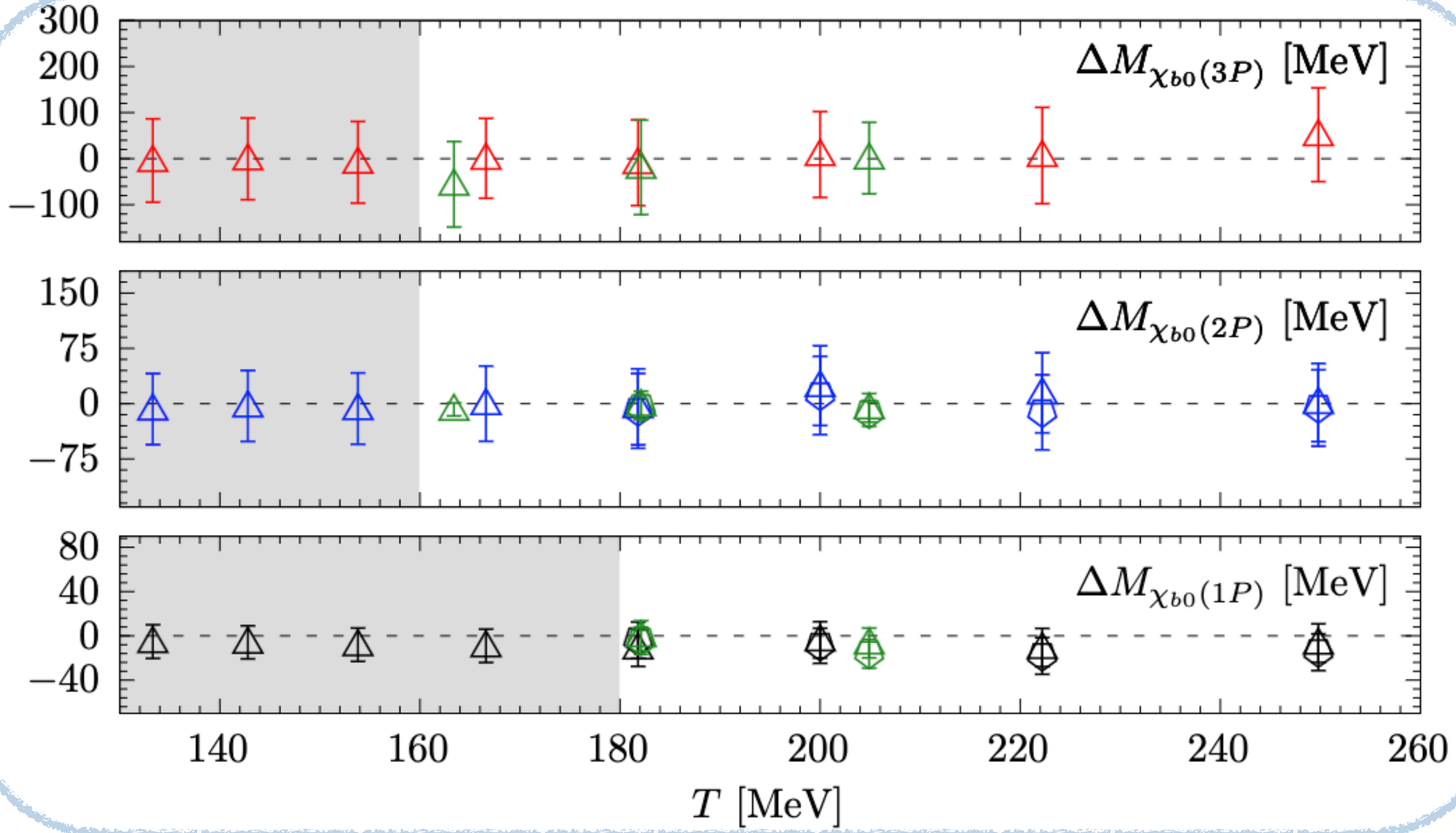


NRQCD RESULTS

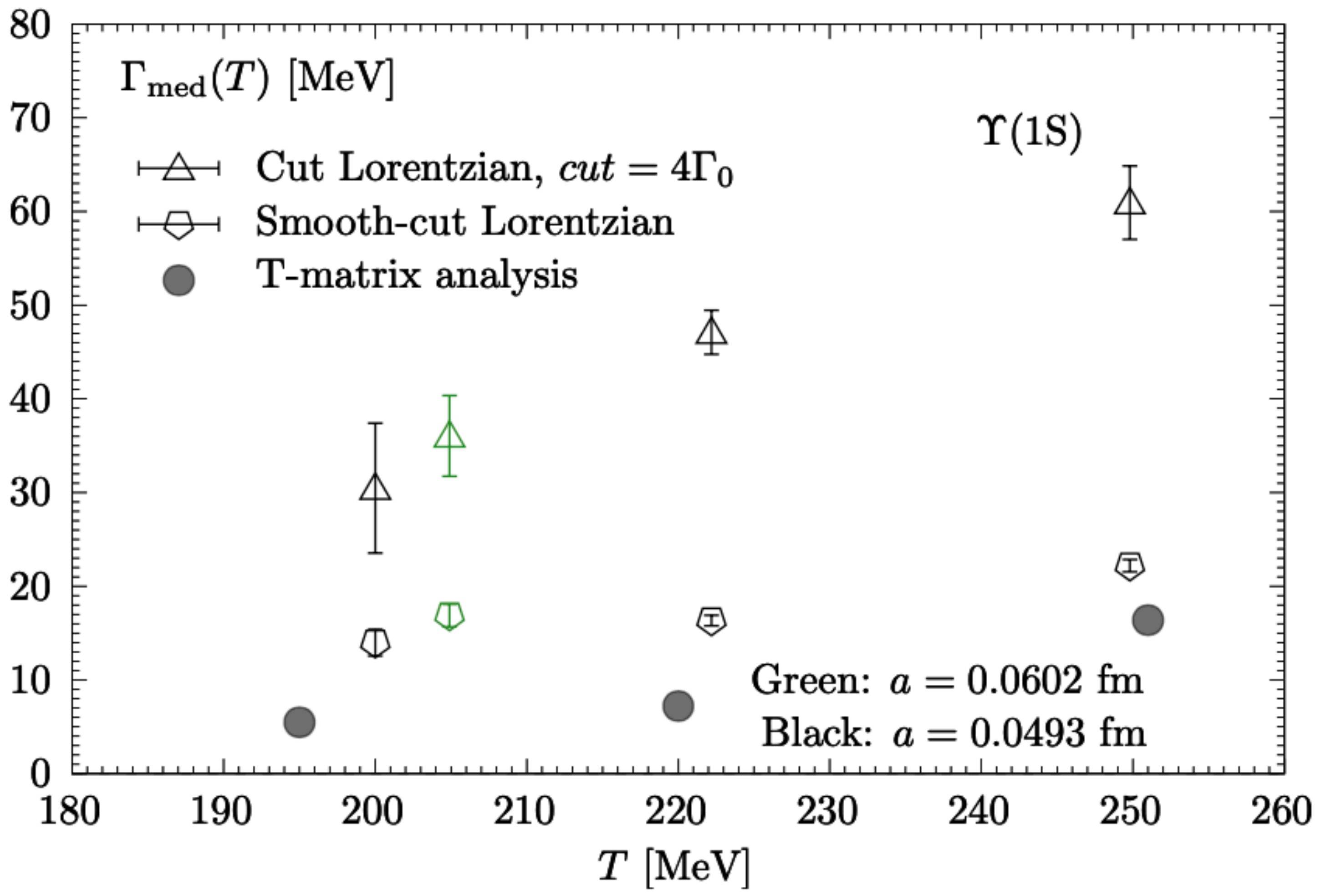
Ding, Huang, Petreczky, Larsen, Meinel, Mukherjee, Tang (2025)

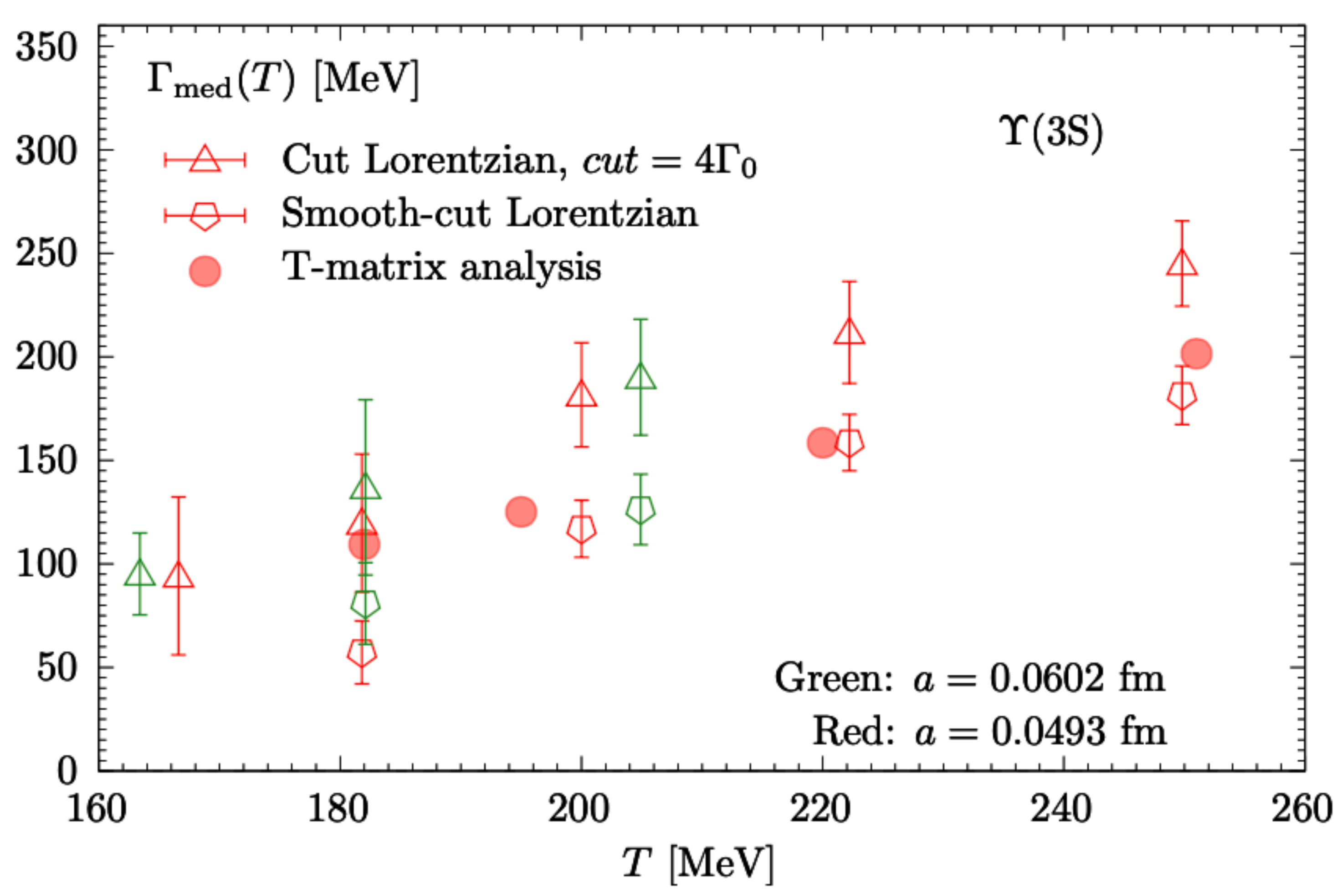
S STATES

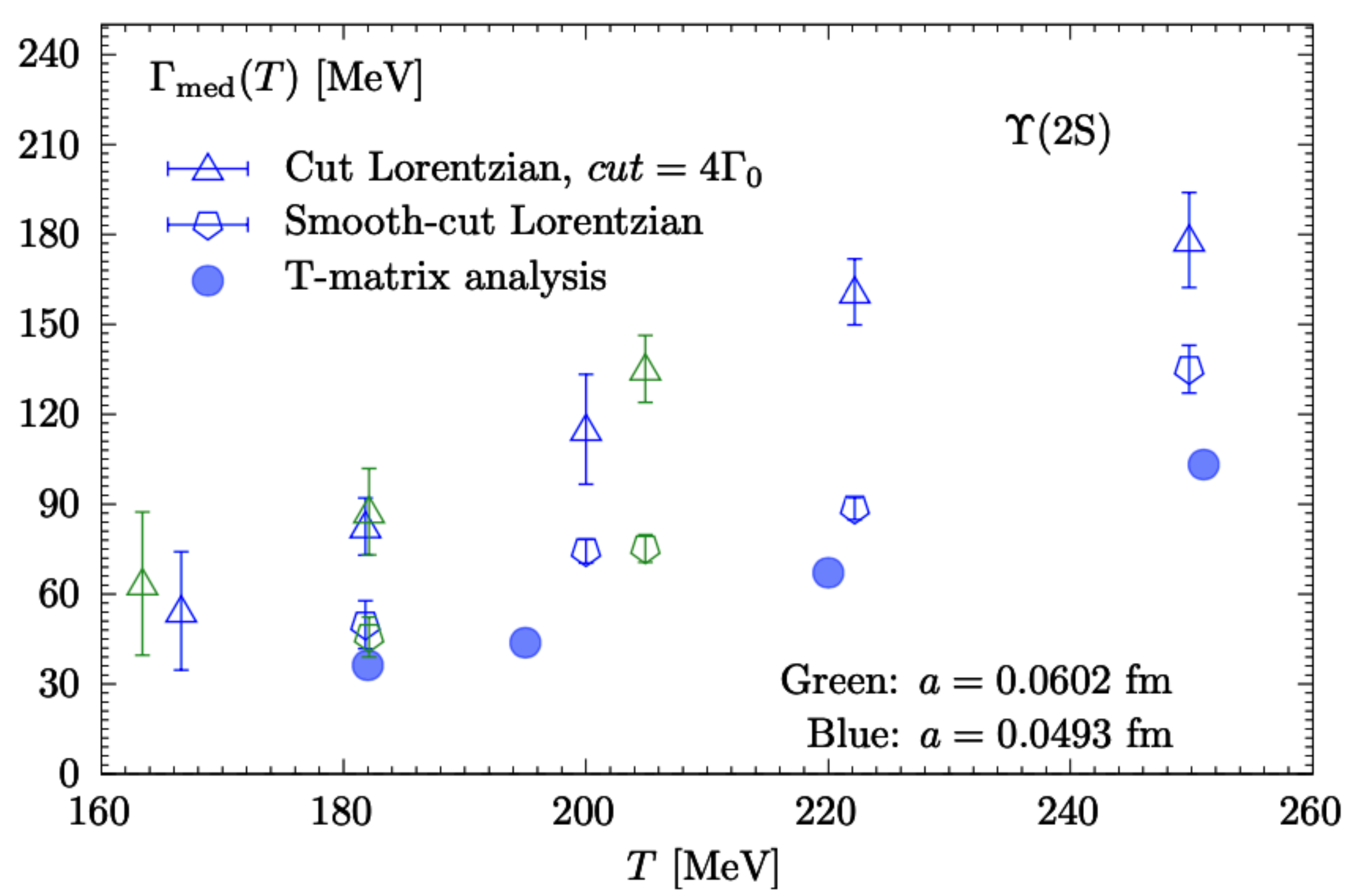




P STATES







NRQCD RESULTS

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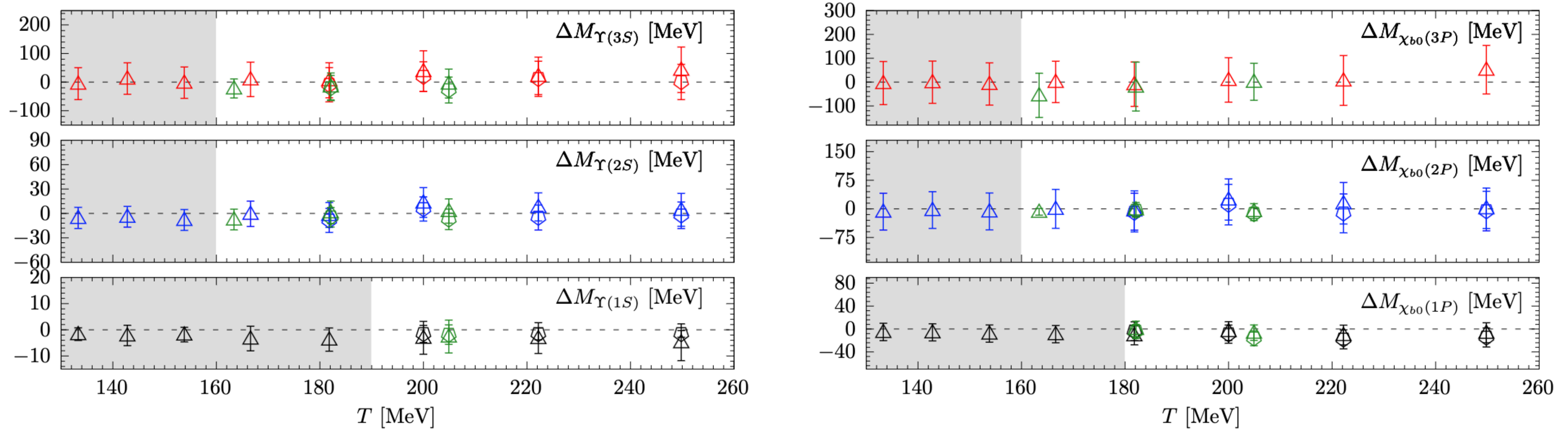
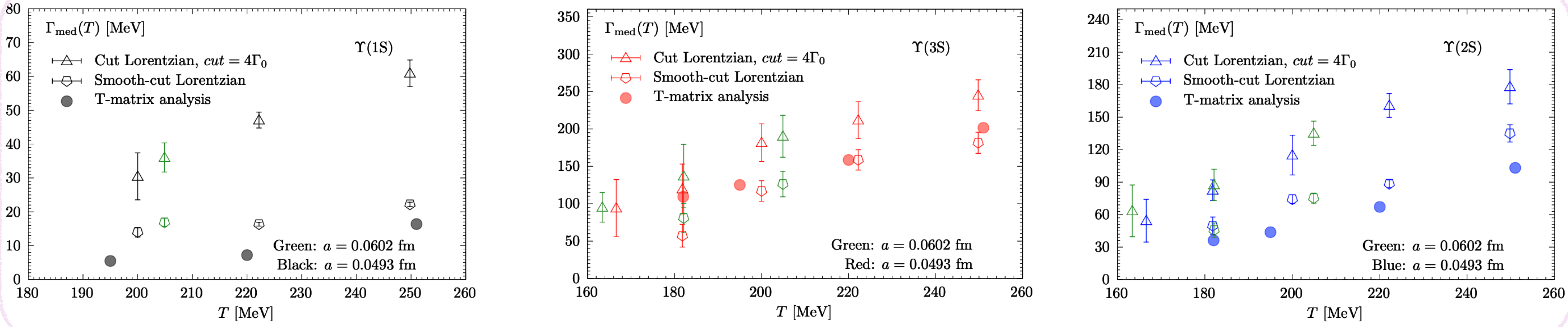


S STATES



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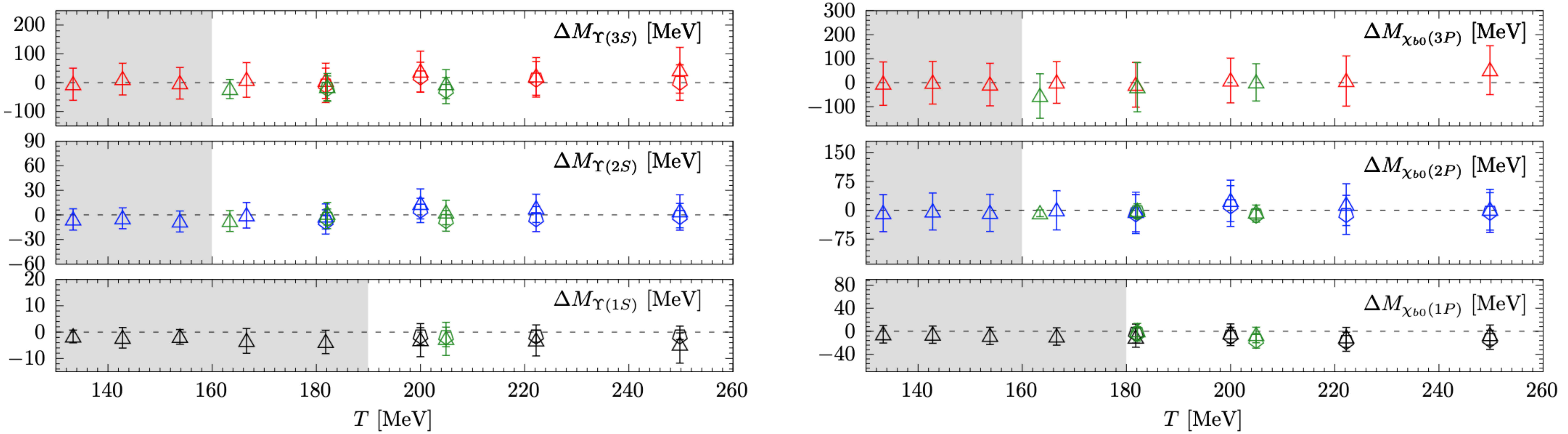
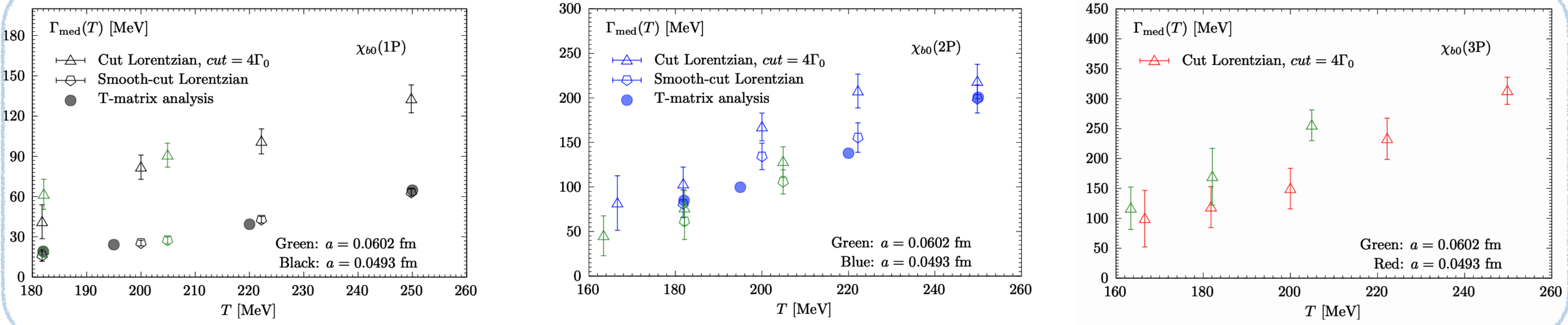
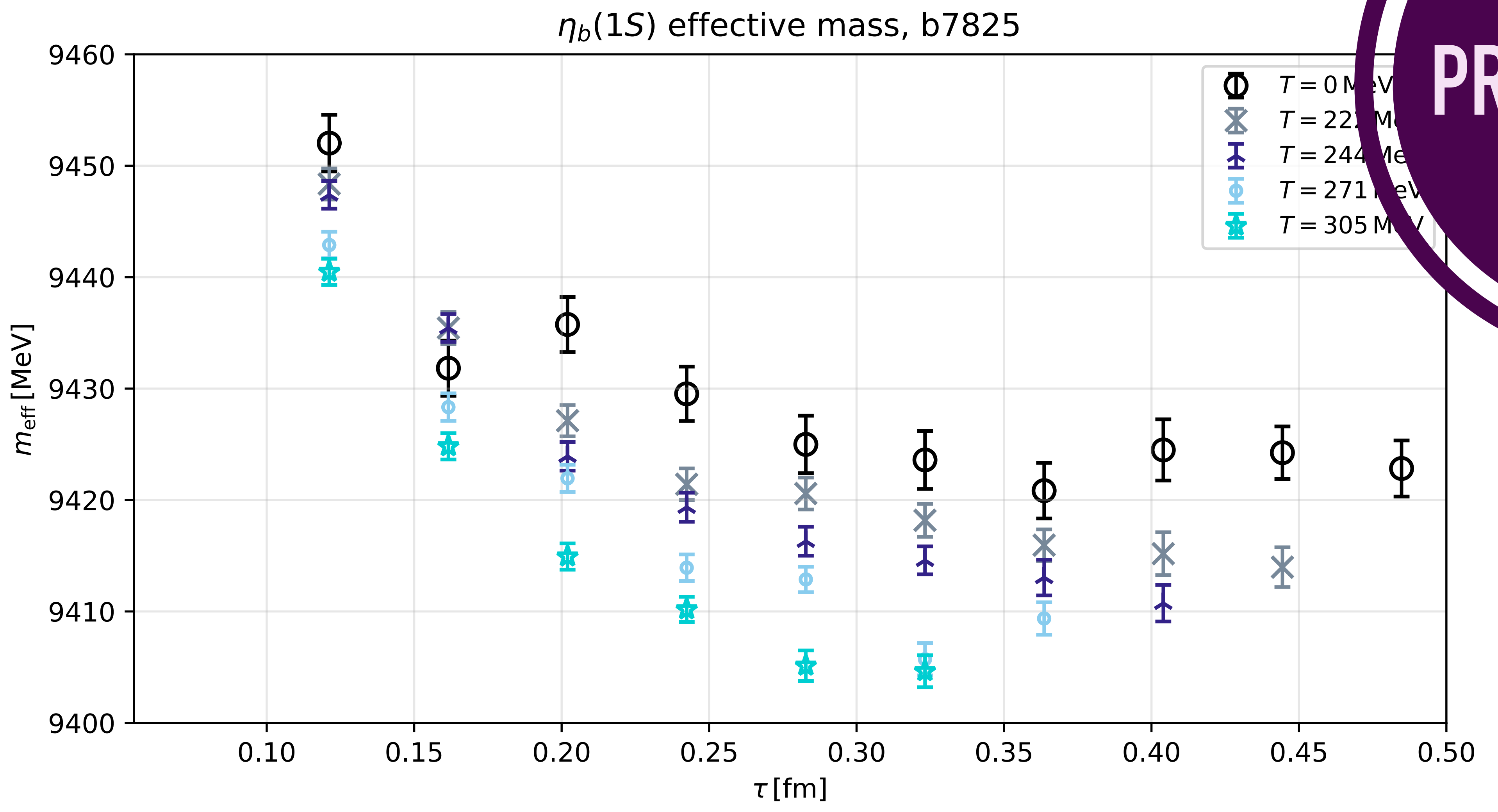


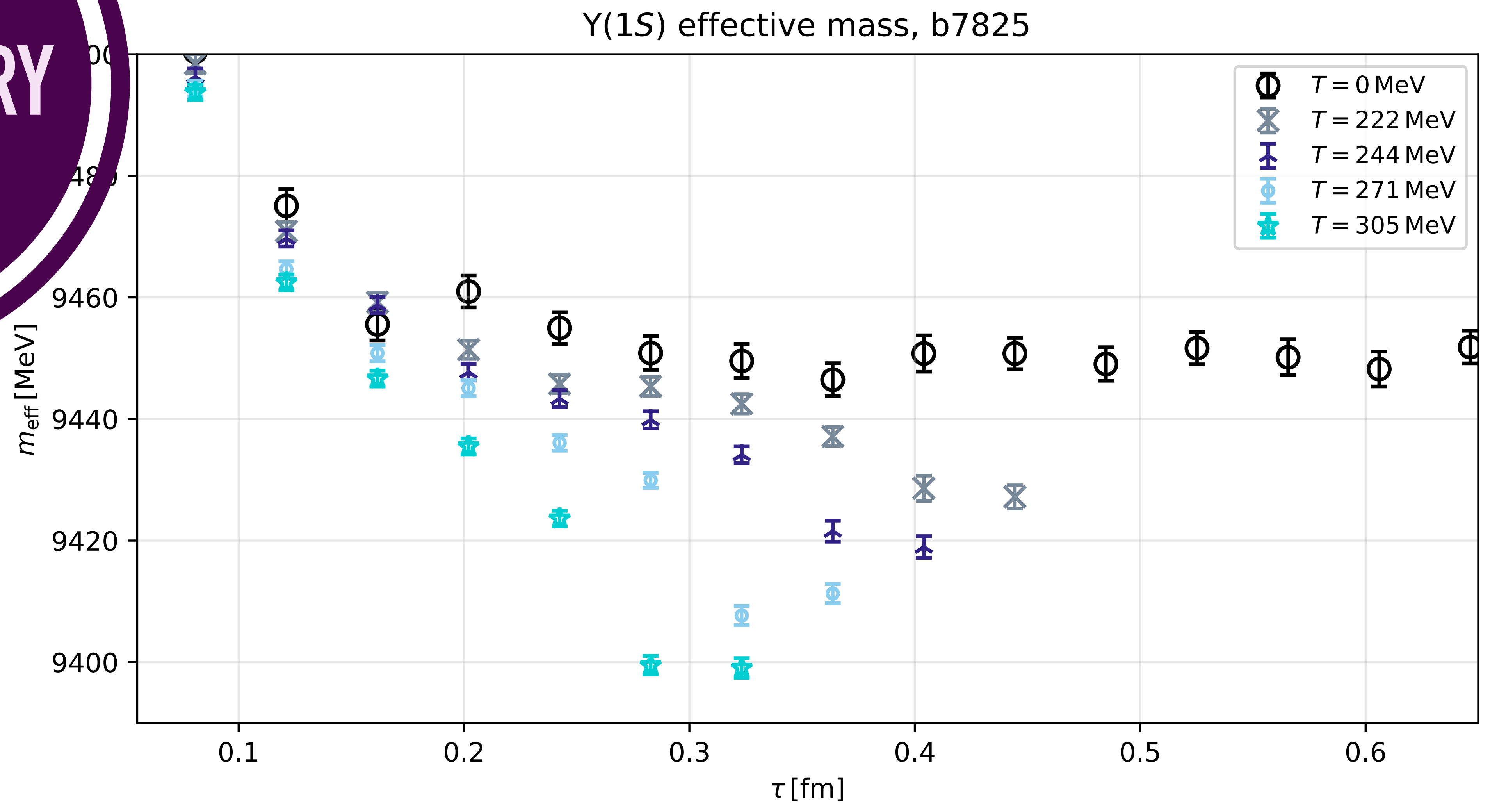
P STATES



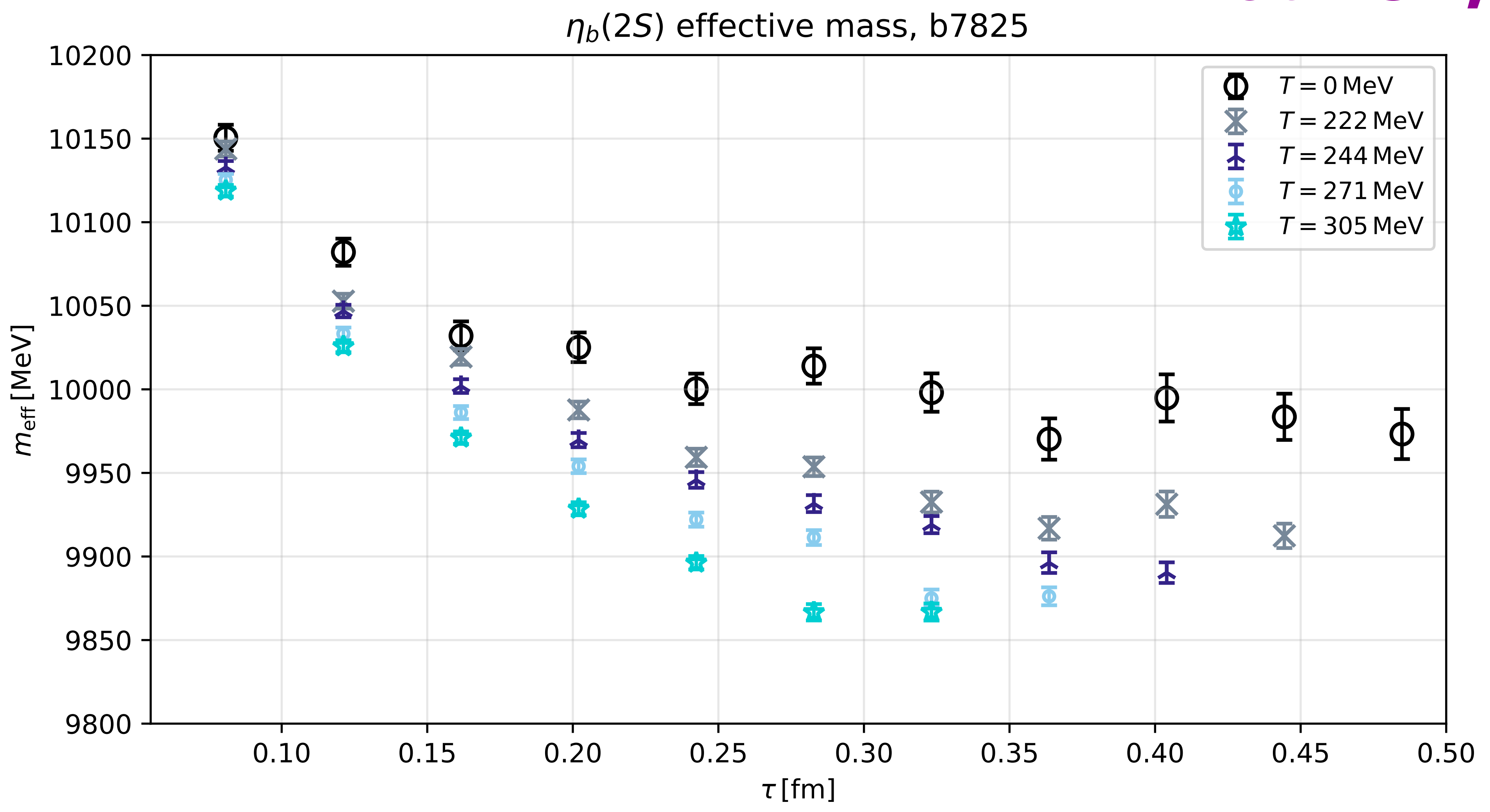
RELATIVISTIC BOTTOMONIUM

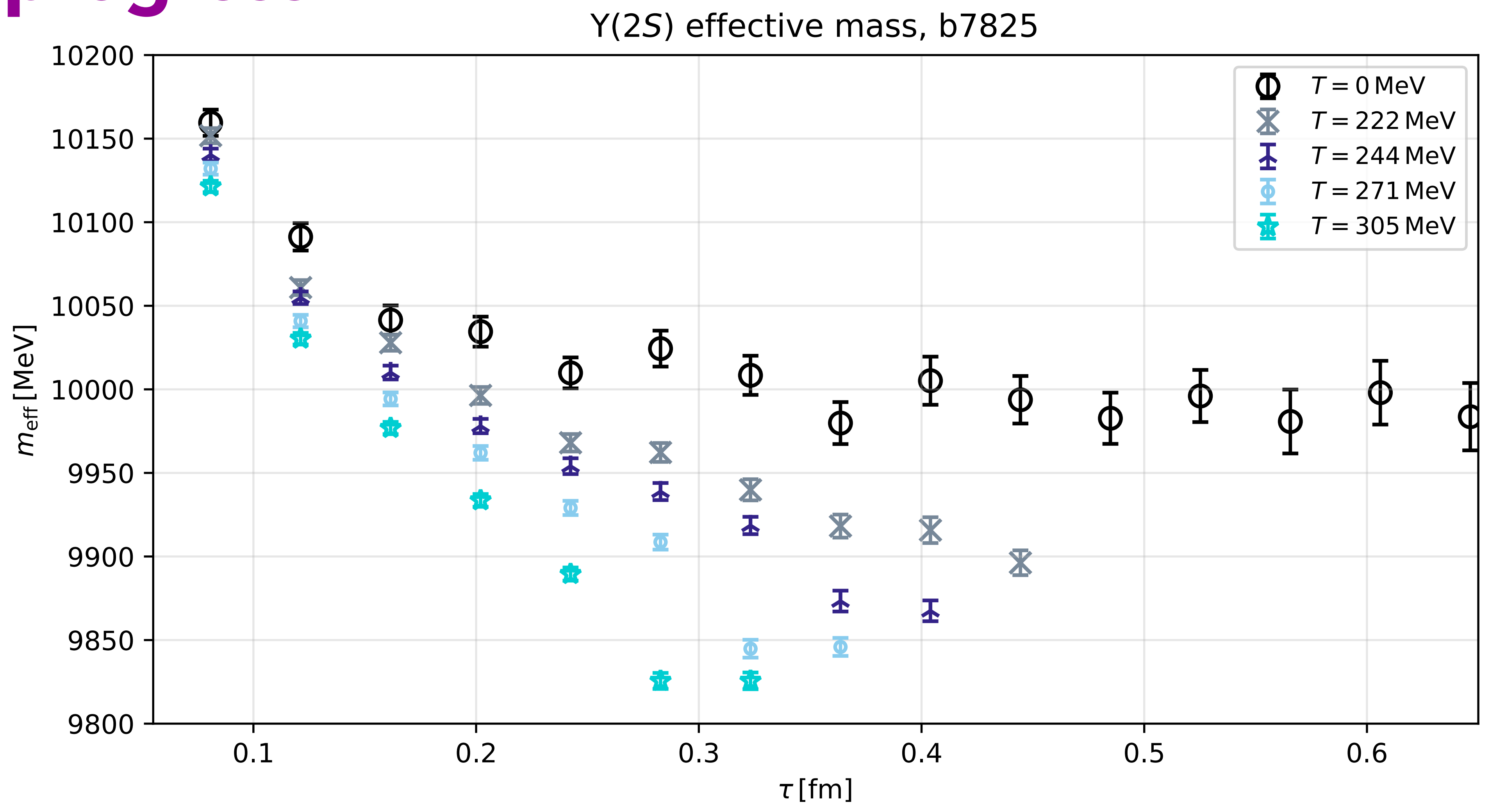
PRELIMINARY



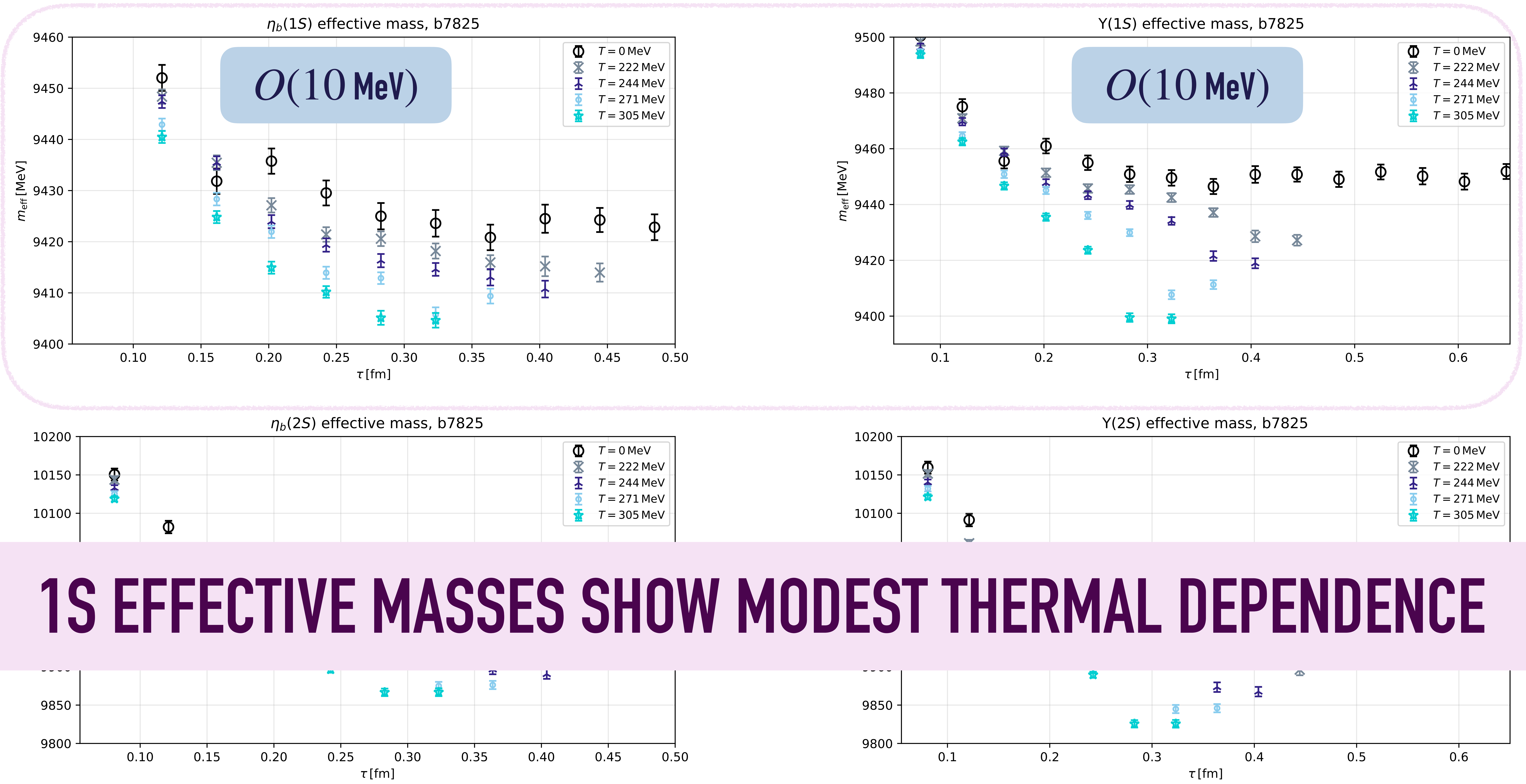


HotQCD, work in progress



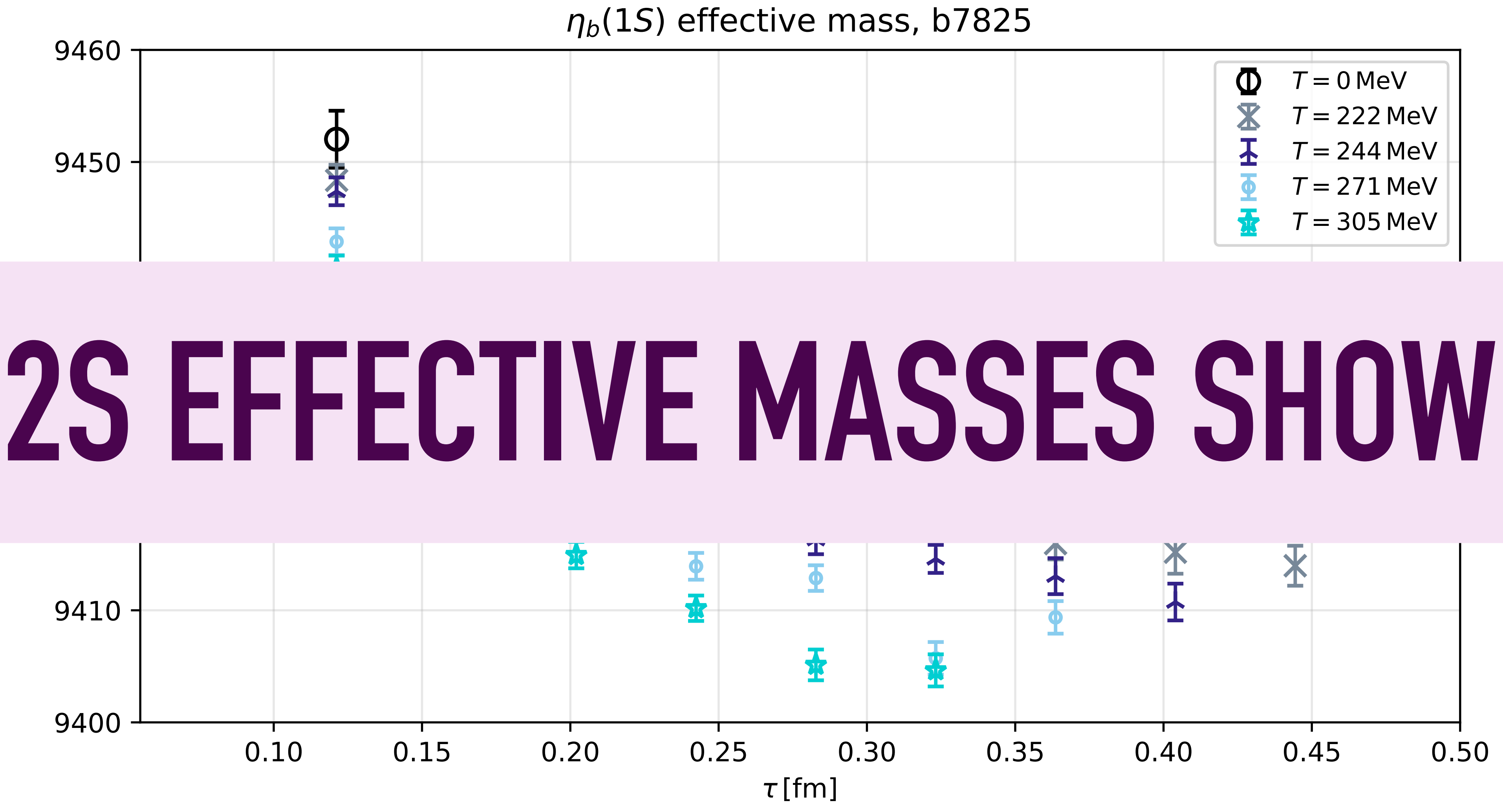


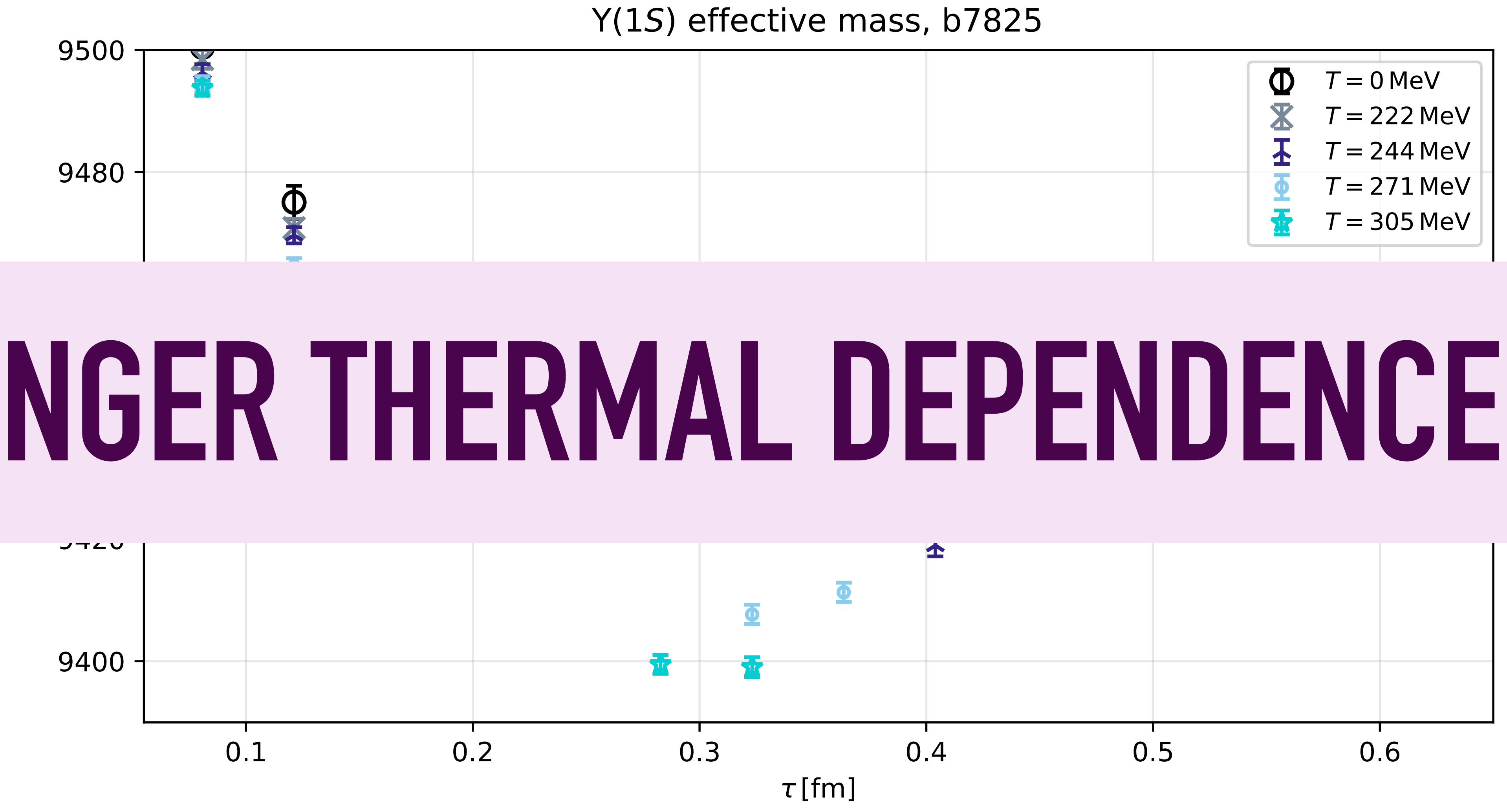
RELATIVISTIC BOTTOMONIUM



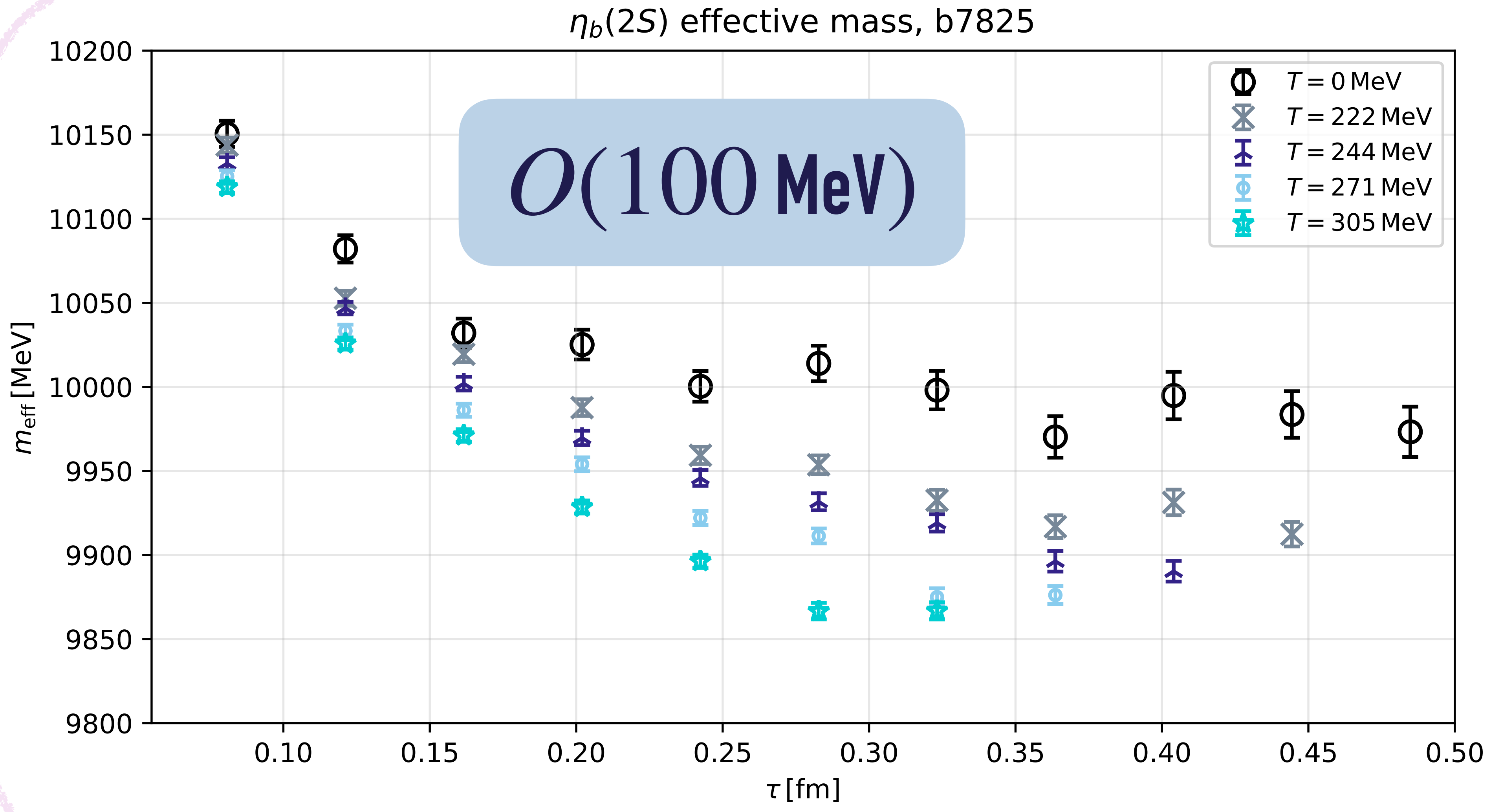
1S EFFECTIVE MASSES SHOW MODEST THERMAL DEPENDENCE

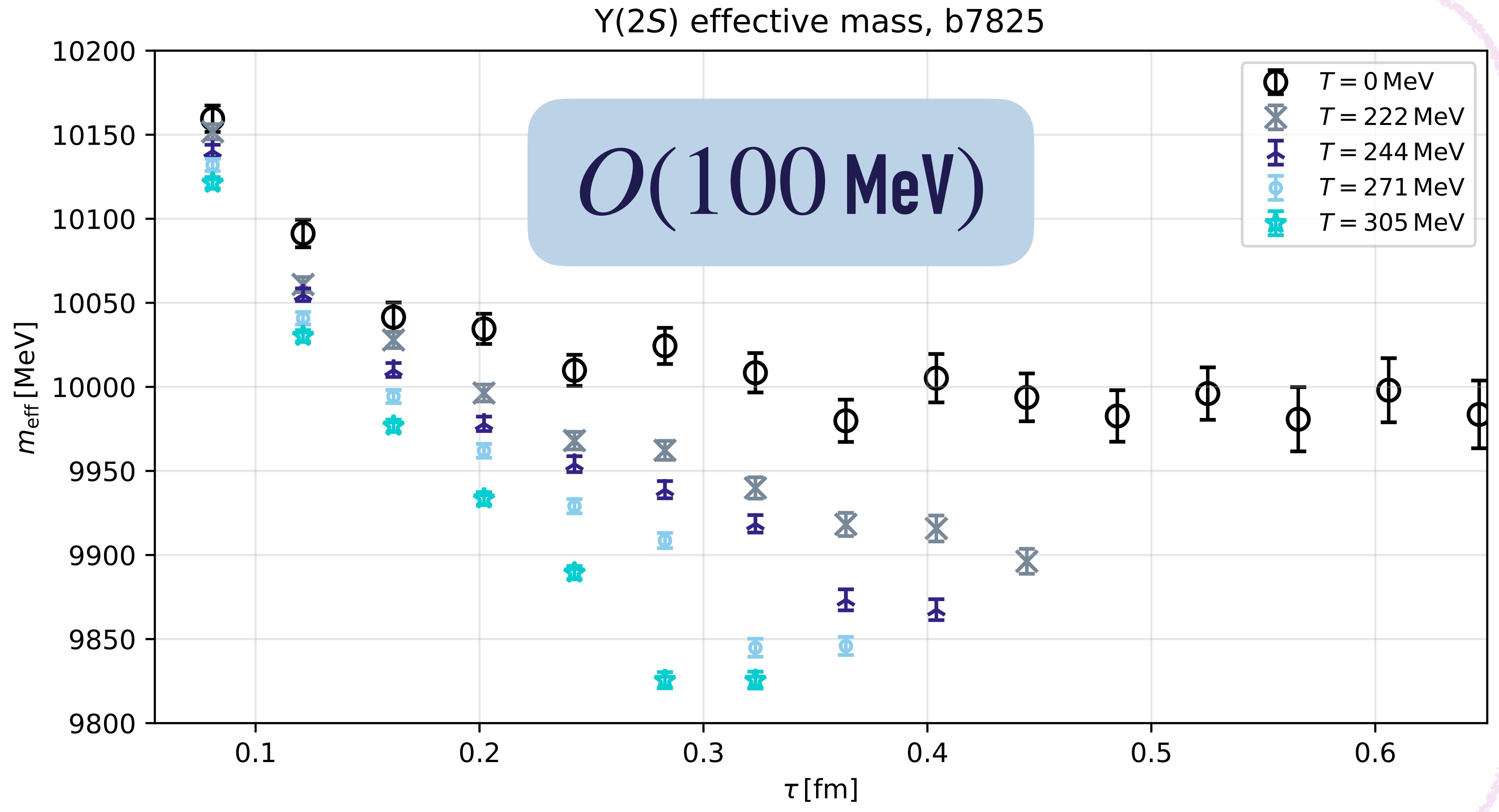
RELATIVISTIC BOTTOMONIUM





2S EFFECTIVE MASSES SHOW STRONGER THERMAL DEPENDENCE





CONCLUSIONS

CONCLUSIONS

Heavy quarks provide great probes of the quark-gluon plasmas: **quarkonium correlators** probe in-medium binding and broadening.

We isolate the 1S, 2S, and 1P charmonium contributions and constrain their in-medium peaks.

Extended operators provide clear sensitivity to individual charmonium states.

Mass shifts are small, particularly below $T \simeq 200$ MeV.

NRQCD provides a good description of non-relativistic bottomonia and we are working on relativistic results.

Thermal broadening is the dominant modification, and the thermal widths increase strongly with temperature.

MODEST MASS SHIFTS → STRONG THERMAL BROADENING → STATE-SIZE HIERARCHY

THERMAL BROADENING DOMINATES OVER LARGE MASS MODIFICATIONS

THANKS FOR YOUR ATTENTION

BACKUP

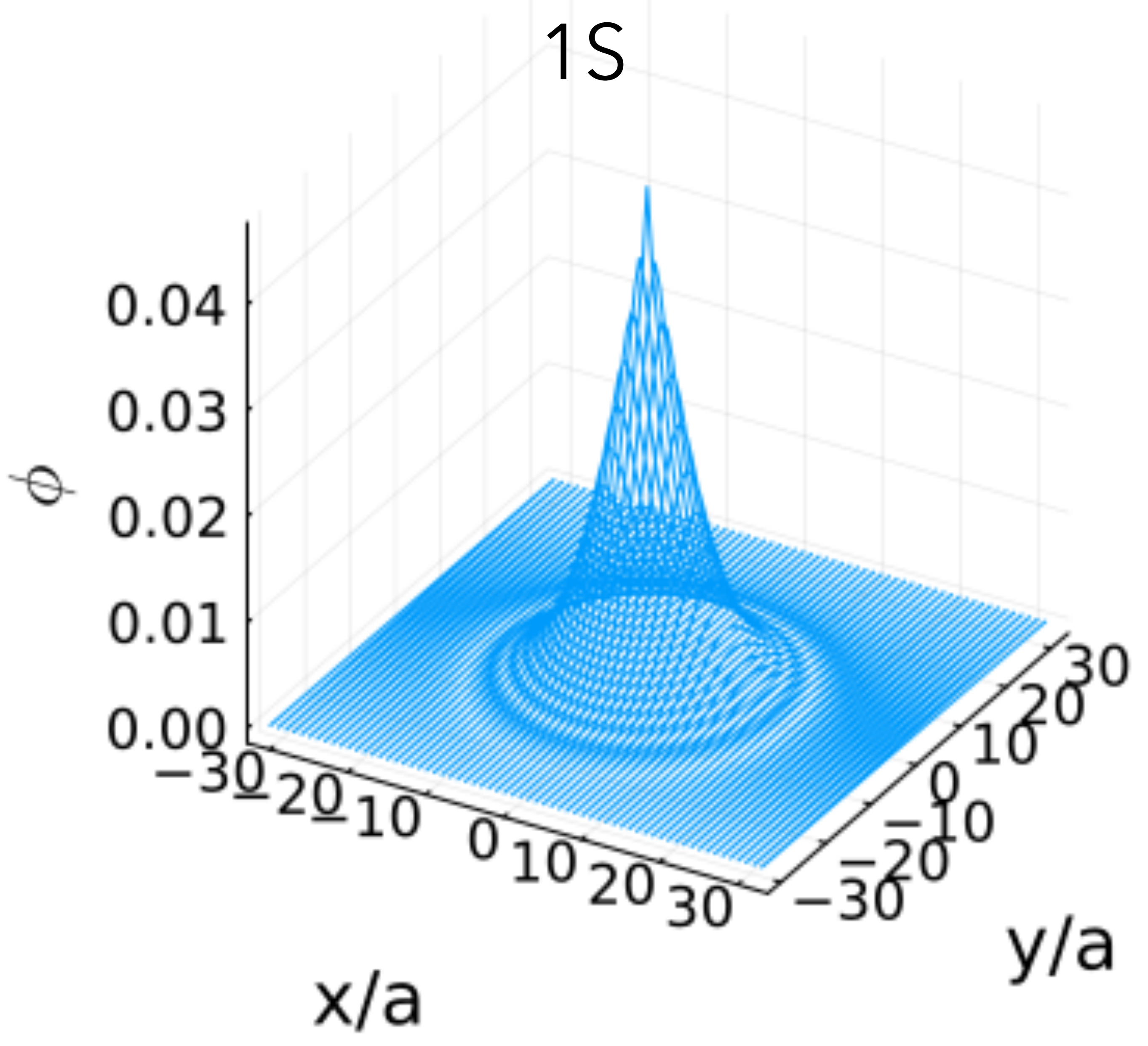
PHYSICAL STATES

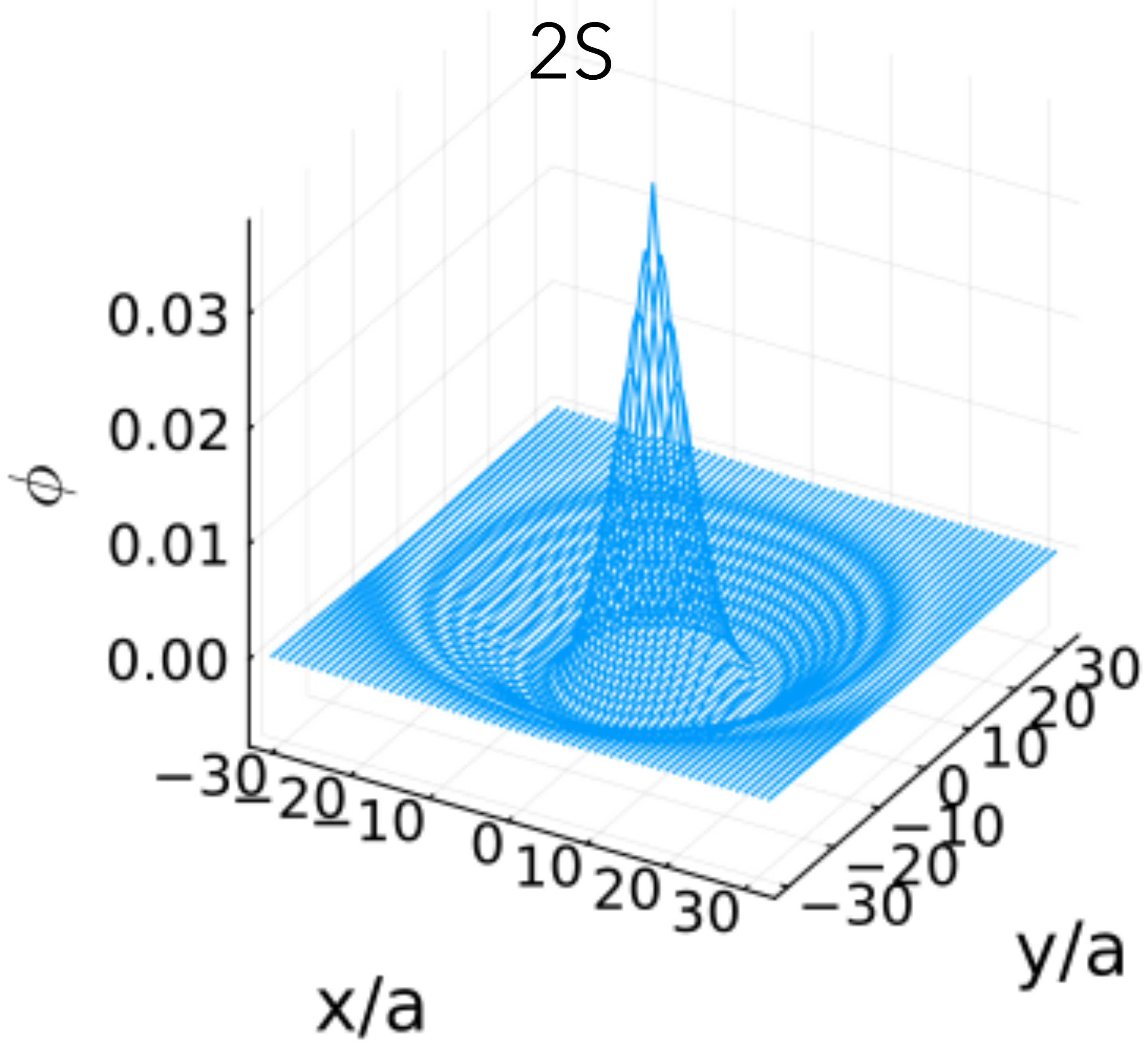
We construct these optimized operators by building trial wavefunctions from a potential model.

Solve a Schrödinger equation using: $V(r) = -\frac{0.166522}{r} + 0.1166289\,\mathrm{GeV}^2\, r + 0.382423\log(r\,\mathrm{GeV})\,\mathrm{GeV}$

DELTA DISTRIBUTION | 1S DISTRIBUTION | 2S DISTRIBUTION | 3S DISTRIBUTION

These sources approximate the shape of the state, improve signal, and give less overlap with higher states.





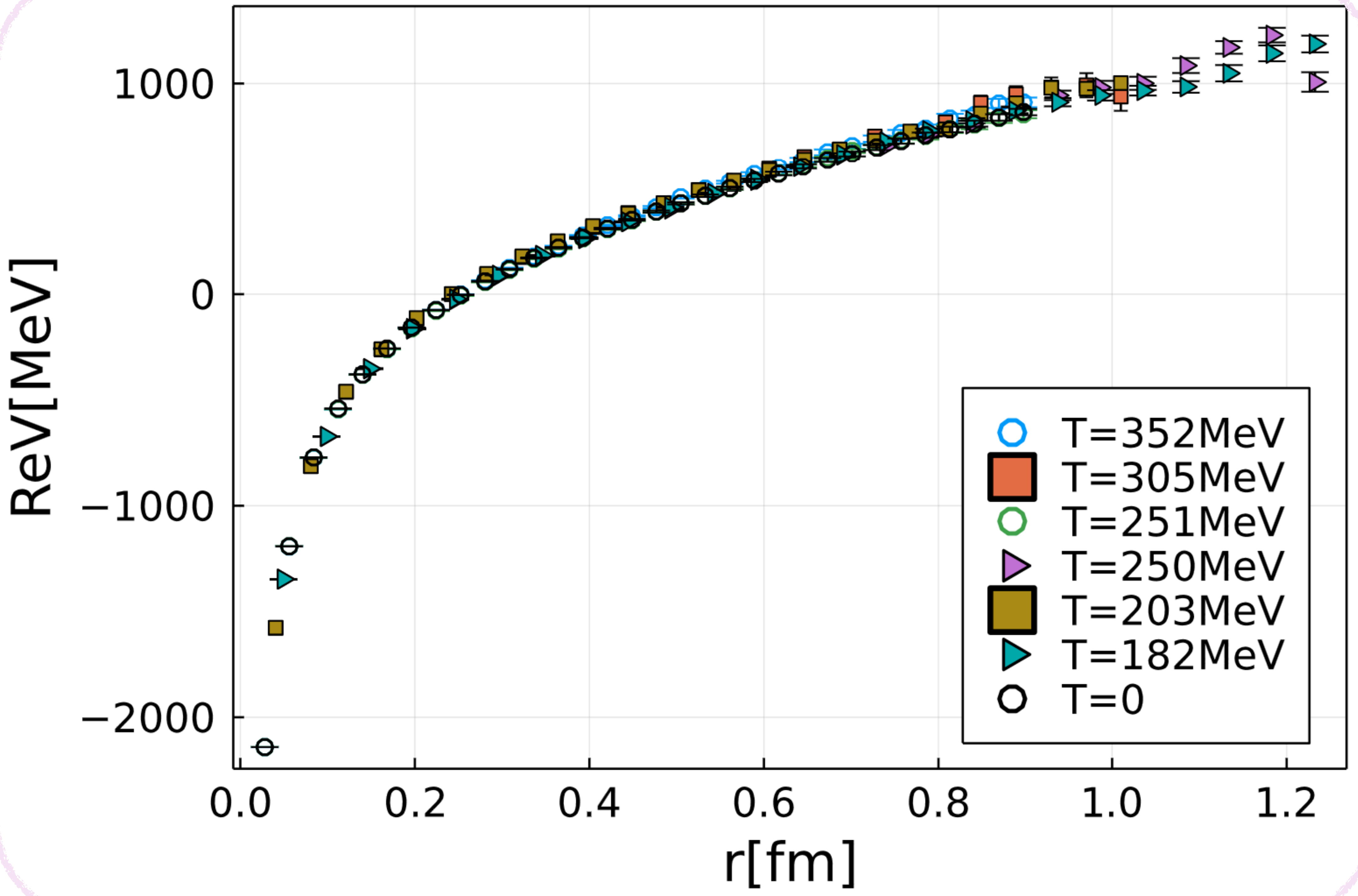
WILSON LINE CORRELATORS

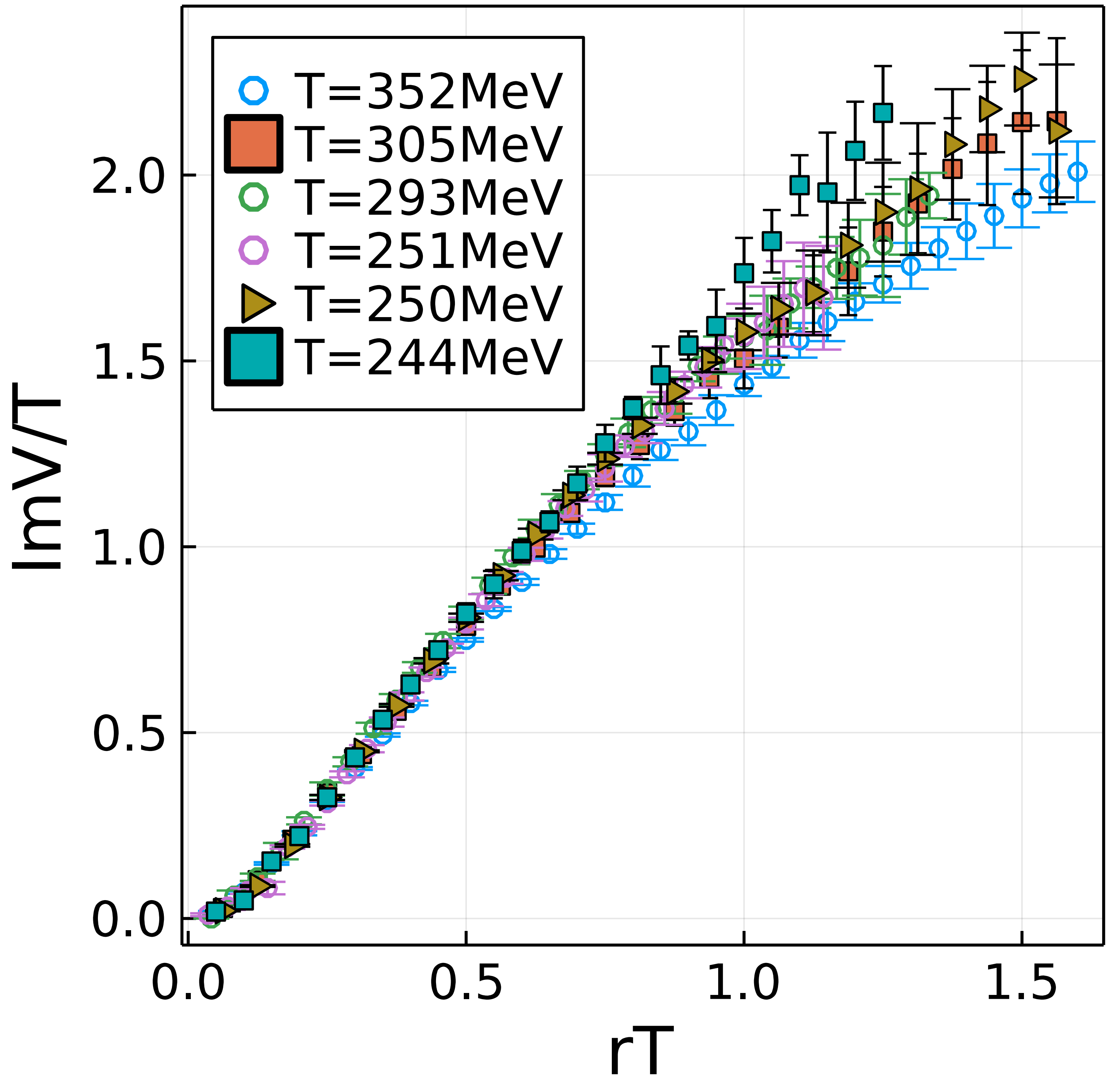
HotQCD (2024)

Similar thermal modifications are observed with previous Wilson Line correlators studies.

$$W(\tau, r, T) = \int_{-\infty}^{\infty} d\omega \, e^{-\omega\tau} \rho_r(\omega, T)$$

Two infinitely heavy quarks separated by a distance r





NO SIGNAL OF SCREENING

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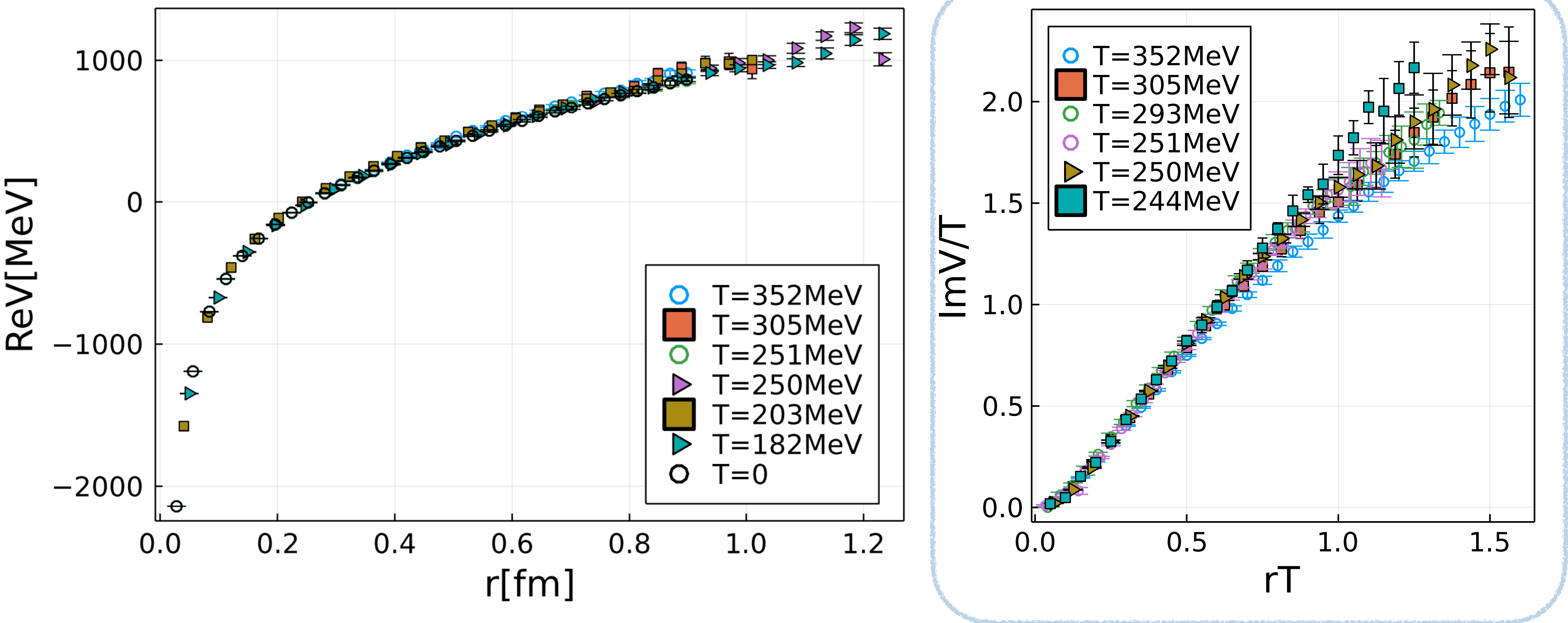


THERMAL MODIFICATIONS

$$\Gamma_{\text{static}}(r, T) \simeq c\, rT^2$$

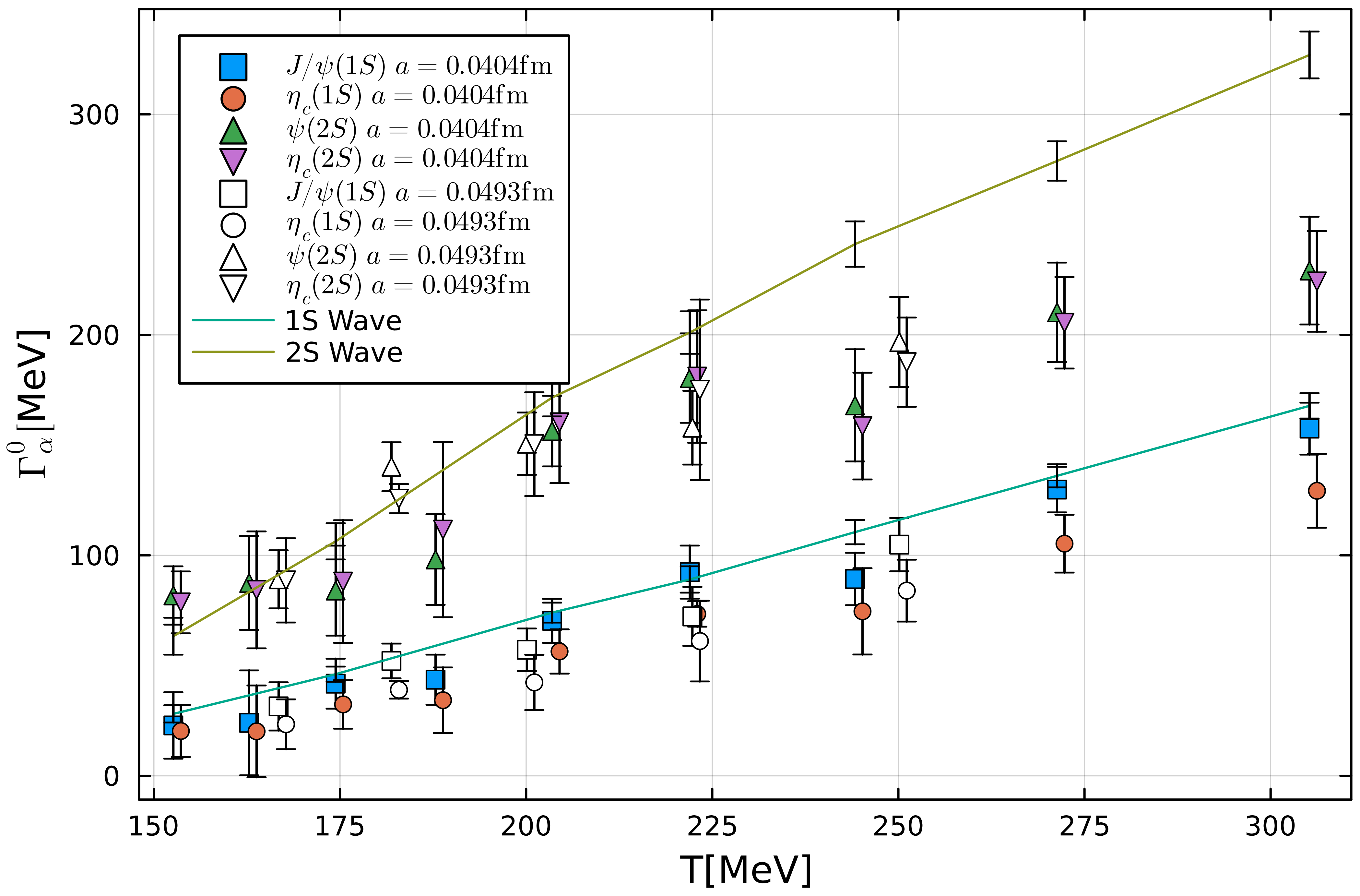
BACKUP

STATIC-POTENTIAL + QUARKONIUM WIDTHS

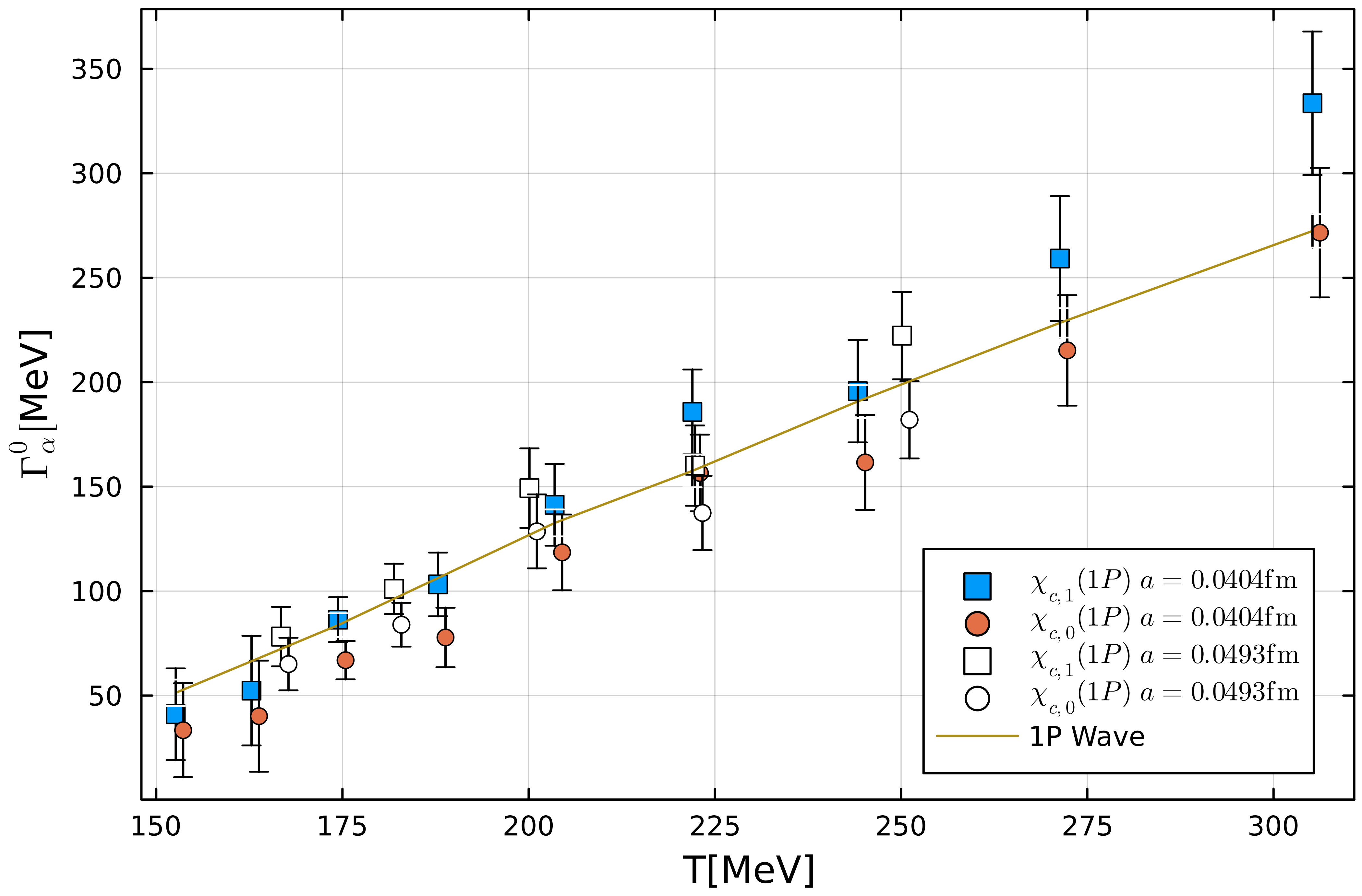
WLC gives the width at fixed r, and the quarkonium wavefunction how to sample the r dependence.

$$\Gamma_n(T) \simeq cT^2 \int d^3r\, r\, \left|\phi_n(\mathbf{r})\right|^2 = cT^2 \langle r \rangle_n$$

LINES: WLC AVERAGE



RELATIVISTIC CHARMONIUM



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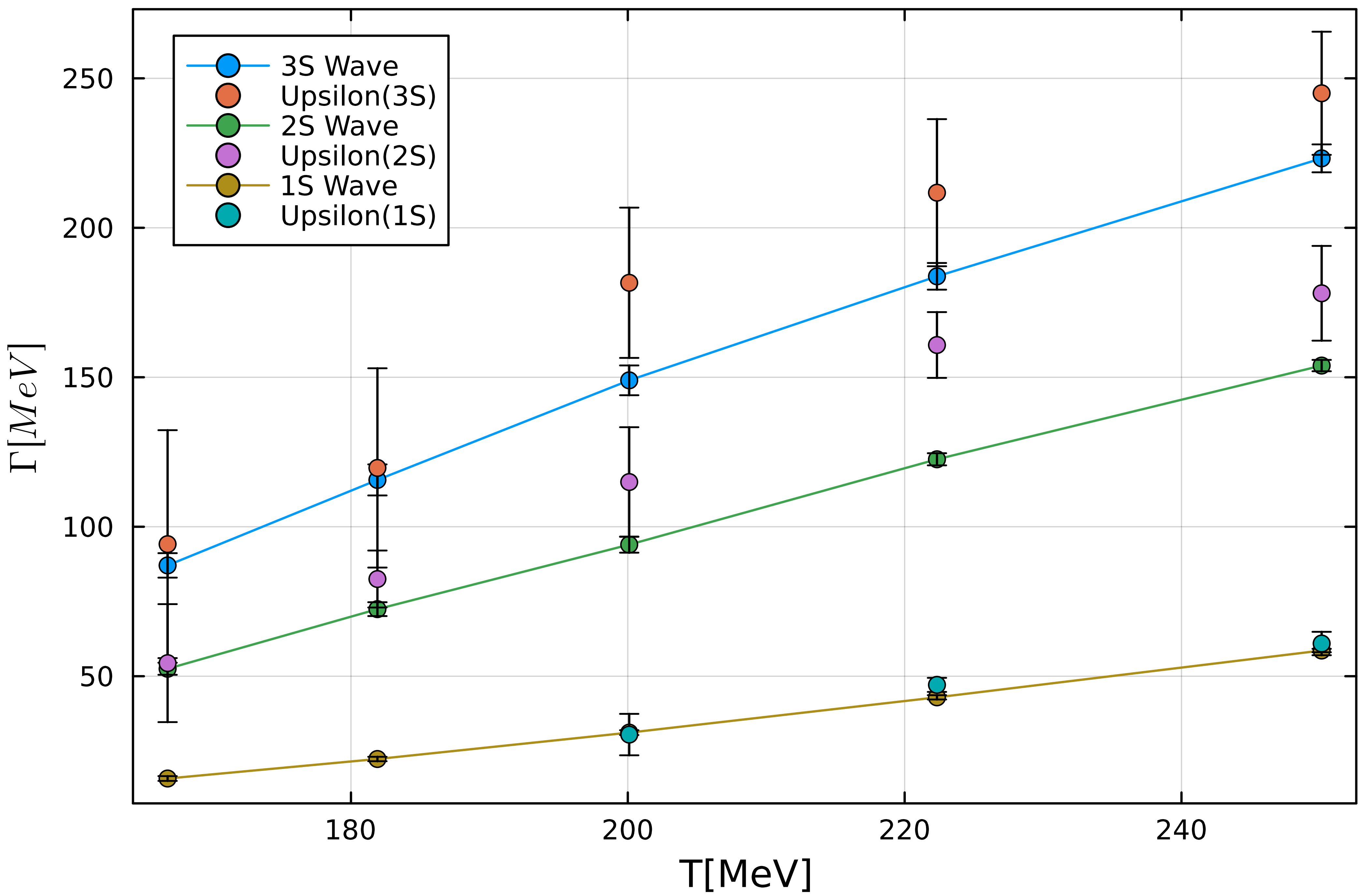
LINES: WLC AVERAGE

RELATIVISTIC BOTTOMONIUM



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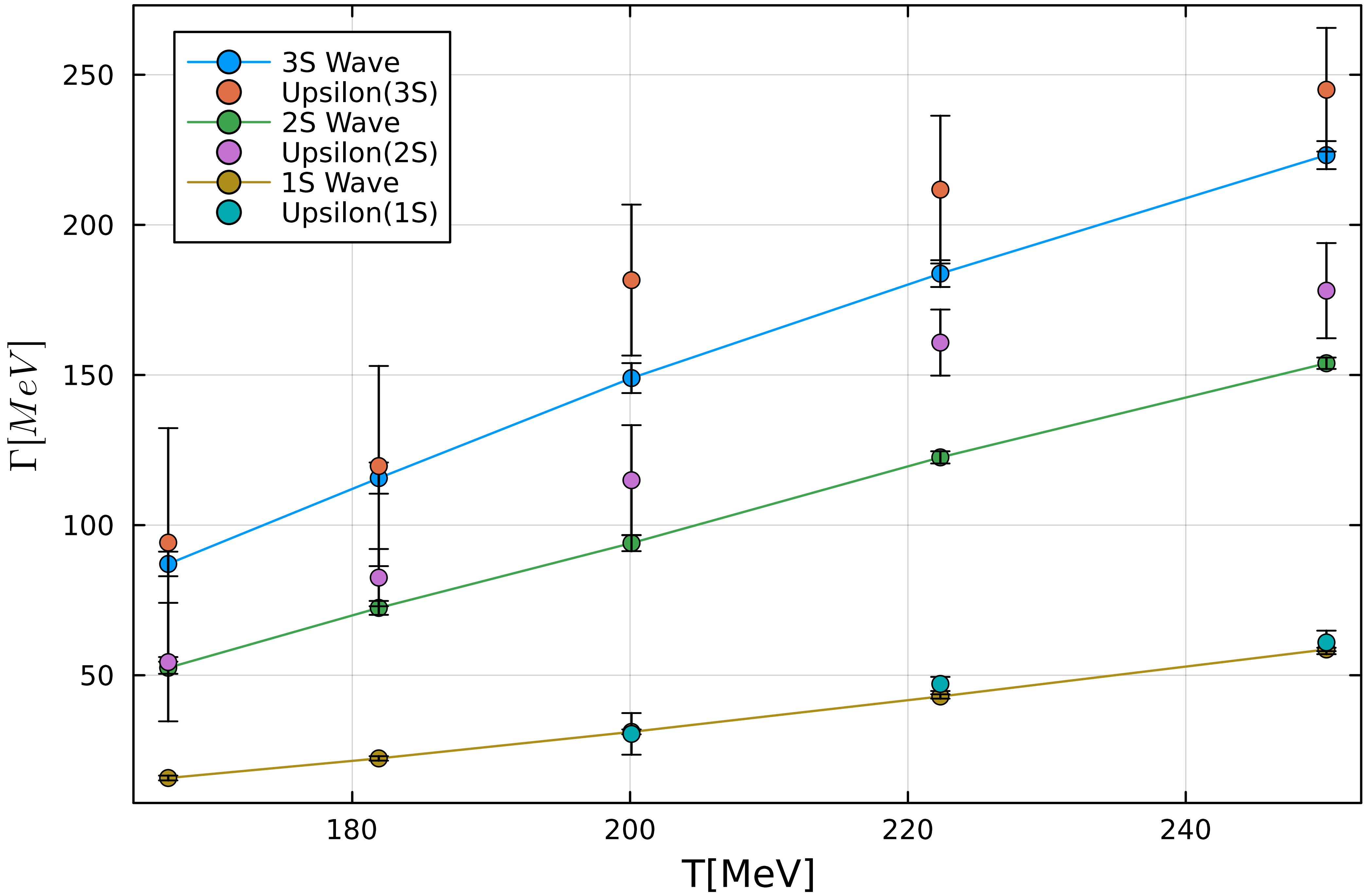
LARGER STATES SAMPLE LARGER $r \longrightarrow$ LARGER THERMAL WIDTHS



MOTIVATION

Why are point-like operators tricky.

Point-like correlators are dominated by short-distance/continuum physics.

Large changes in the spectral function may produce very small changes in the correlation function.

THE INVERSE PROBLEM IS ILL-POSED

BROADENING MAY HAVE LITTLE IMPACT

On the lattice, we extract the correlation function $G(\tau, T)$.

Lattice correlation

$$G^i(\tau, T) = \int_0^\infty d\omega\, \sigma^i(\omega, T) K(\omega, \tau, T)$$

$$G^i_{\rm rec}(\tau, T) = \int_0^\infty d\omega\, \sigma^i(\omega, 0) K(\omega, \tau, T)$$

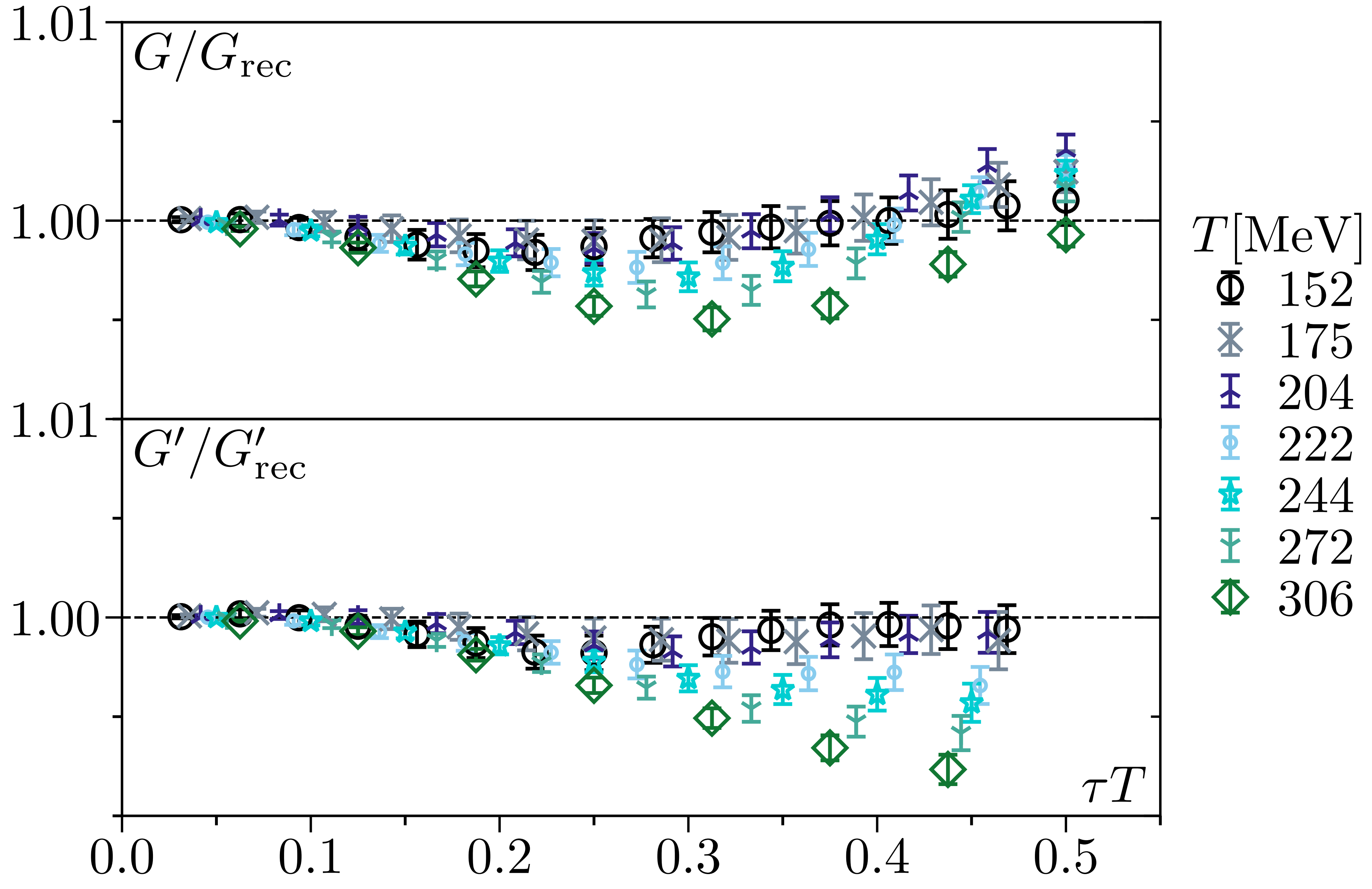
Reconstructed correlation

The kernel smooths spectral details, so deviations of $G^i(\tau, T)/G^i_{\rm rec}(\tau, T)$ from unity can be very small.

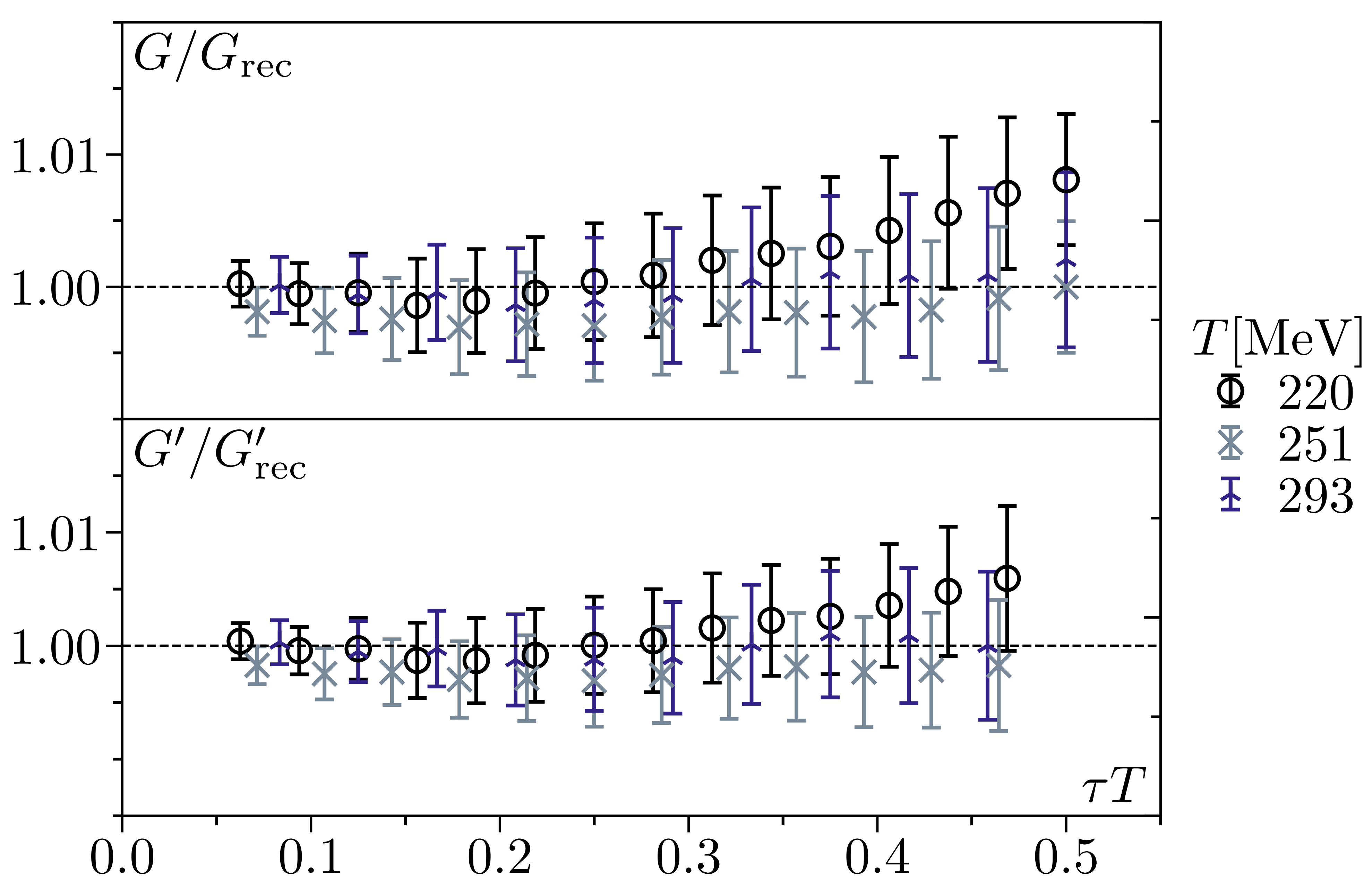
Moreover, similar ratios do not imply similar spectral functions.

CORRELATION FUNCTION RESULTS

The kernel smooths spectral details, so the ratio $G^i(\tau,T)/G^i_{\mathrm{rec}}(\tau,T)$ can be very small



Charmonium

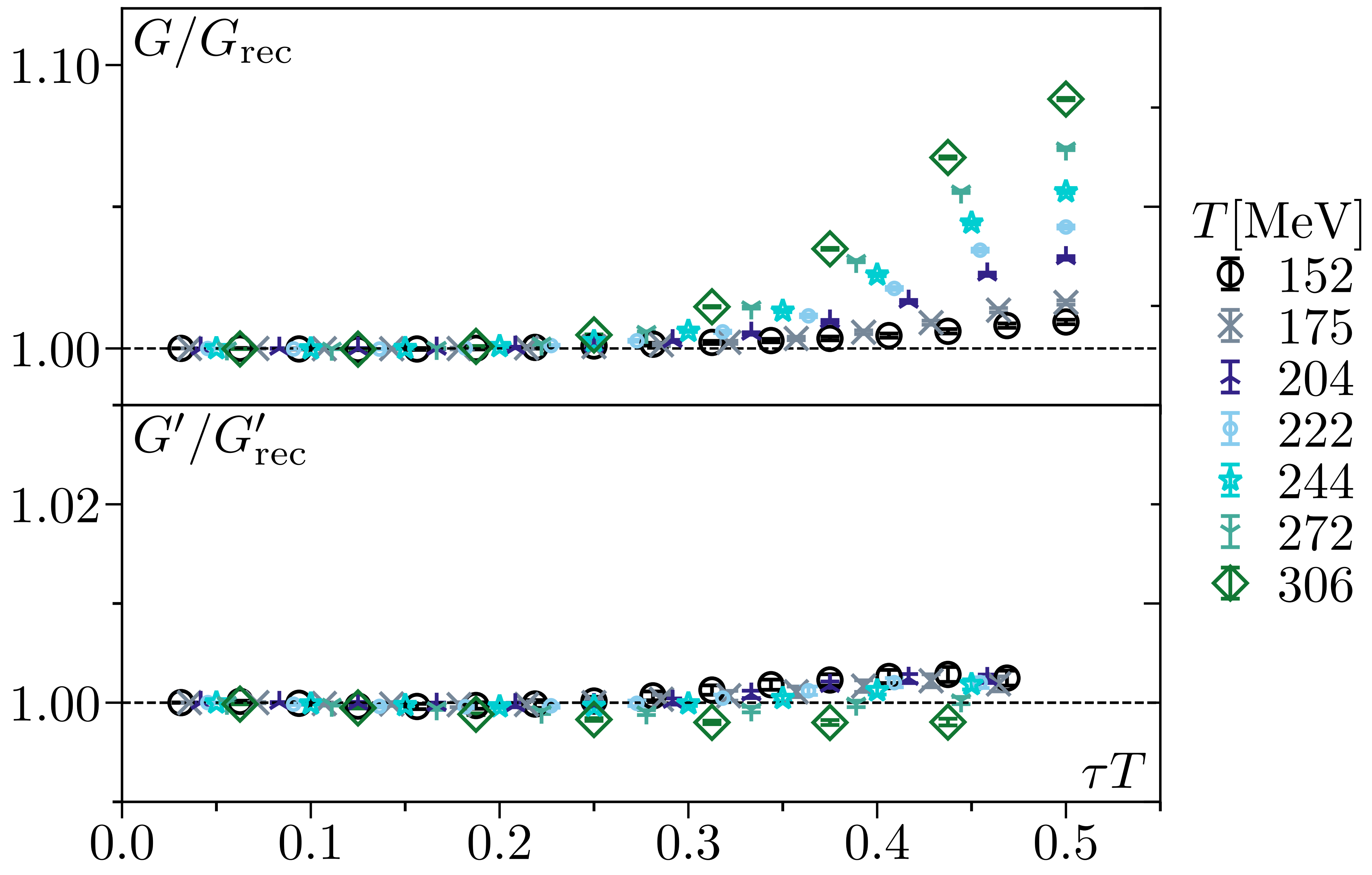


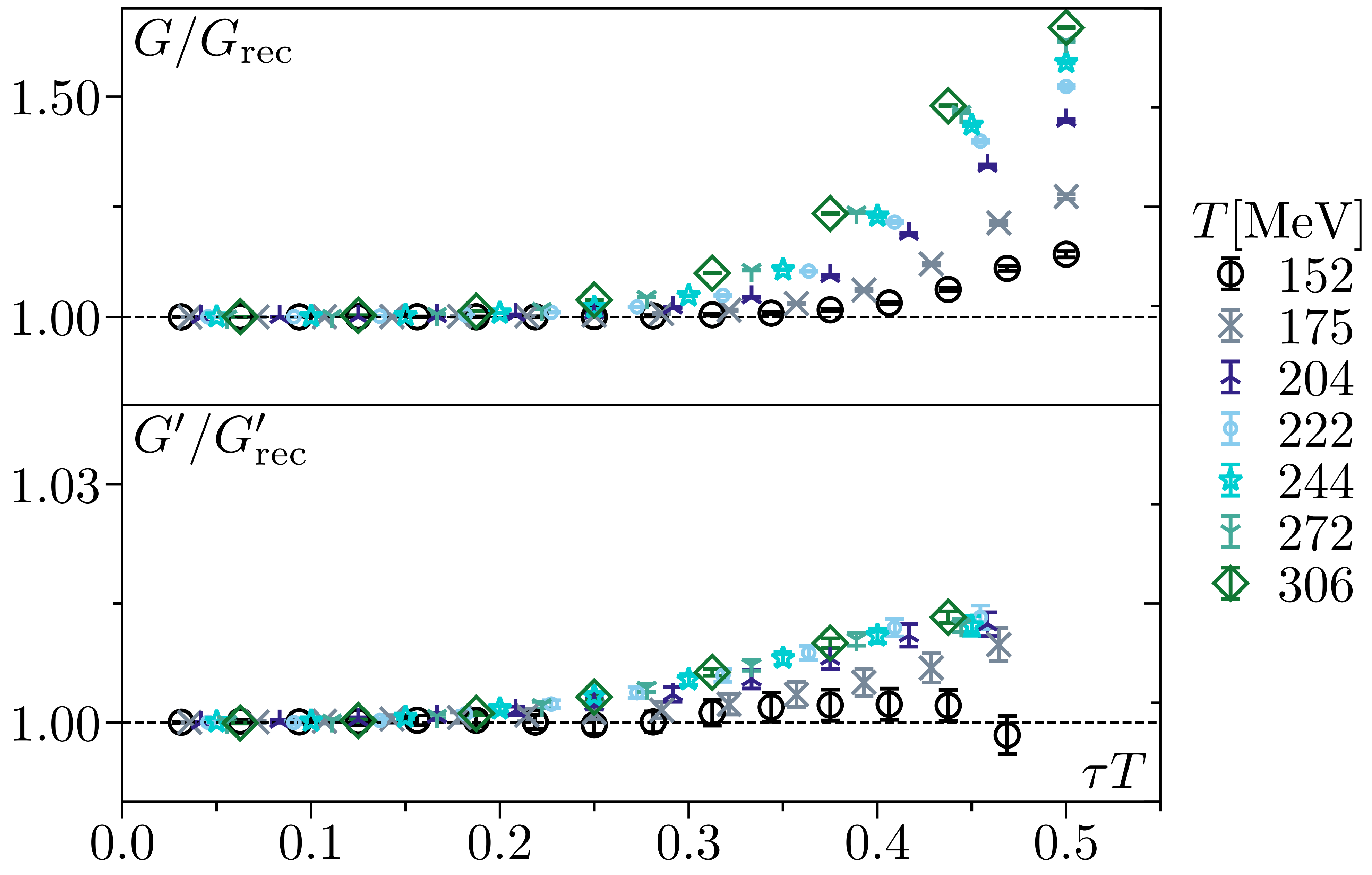
Bottomonium

PSEUDO-SCALAR CHANNEL

CORRELATION FUNCTION RESULTS

The kernel smooths spectral details, so the ratio $G^i(\tau,T)/G^i_{\rm rec}(\tau,T)$ can be very small





VECTOR CHANNEL

SCALAR CHANNEL

This larger effect is mainly due to a zero mode, not necessarily to spectral broadening

A DELIBERATELY SIMPLE SPECTRAL MODEL

We can prepare a very simple and naive model for the spectral function.

SOME PEAKS ✔ + SOME WIDTHS ✔ + SOME BROAD DISTRIBUTIONS

$$\delta(\omega - M_i) \longrightarrow \frac{1}{\mathcal{N}_i} \frac{\Gamma_i(\omega)}{(\omega - M_i)^2 + \Gamma_i^2(\omega)}$$

$$\Gamma_i(\omega) = \Gamma_i^0\, \Theta\left(4\Gamma_i^0 - \left|\omega - M_i\right|\right)$$

Γ_i^0: lattice width around the peak

$$\sigma(\omega, T=0) = \sum_i F_i^2\, \delta(\omega - M_i) + \sigma^{\mathrm{cont}}(\omega)\, \Theta(\omega - s_0)$$

M_i: the vacuum masses

F_i: decay constants

$\sigma^{\mathrm{cont}}(\omega)$: high-energy continuum

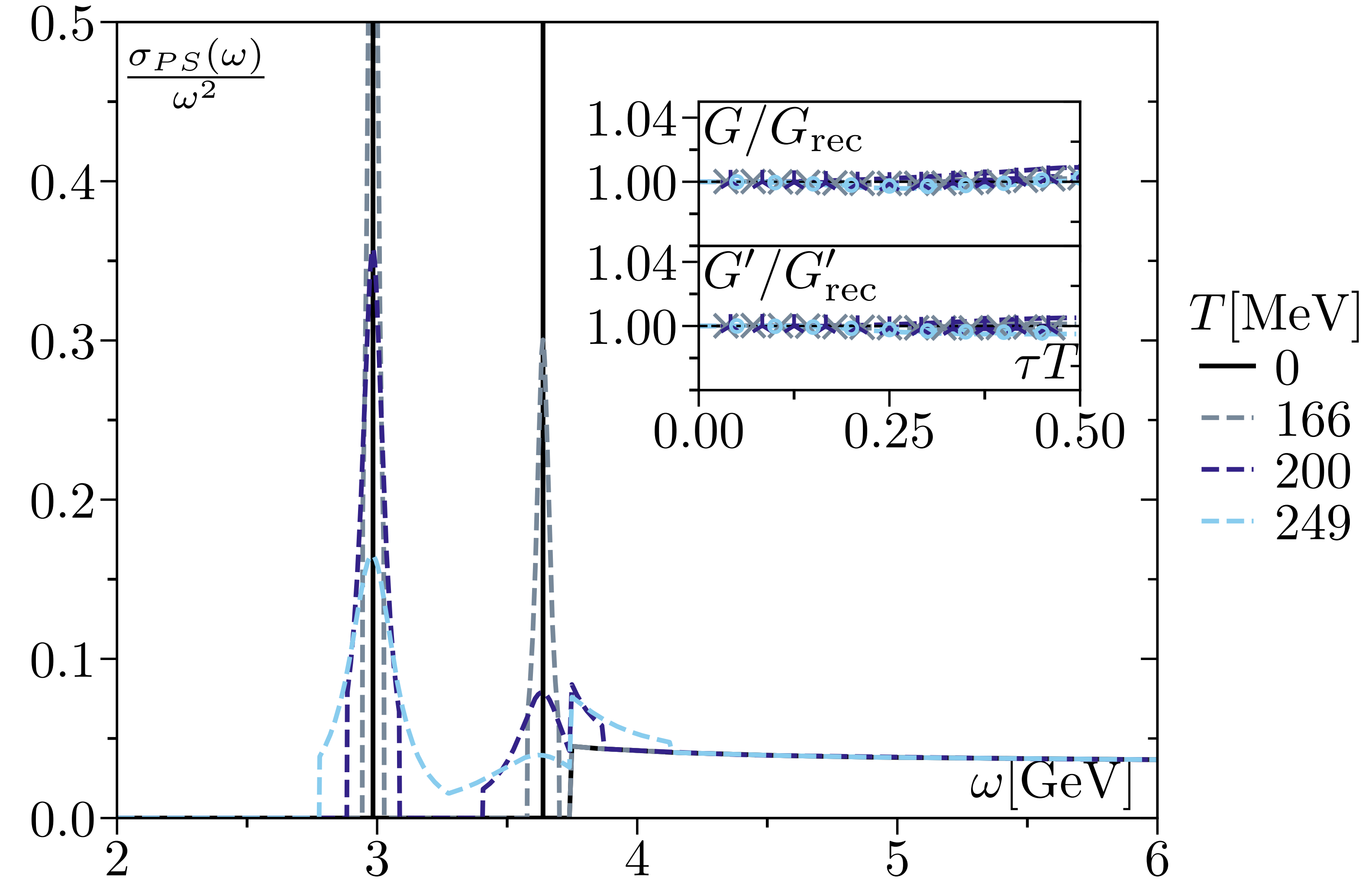
s_0: open-heavy threshold

We cannot infer the spectral function uniquely from the small point-like ratio. **...BUT...**

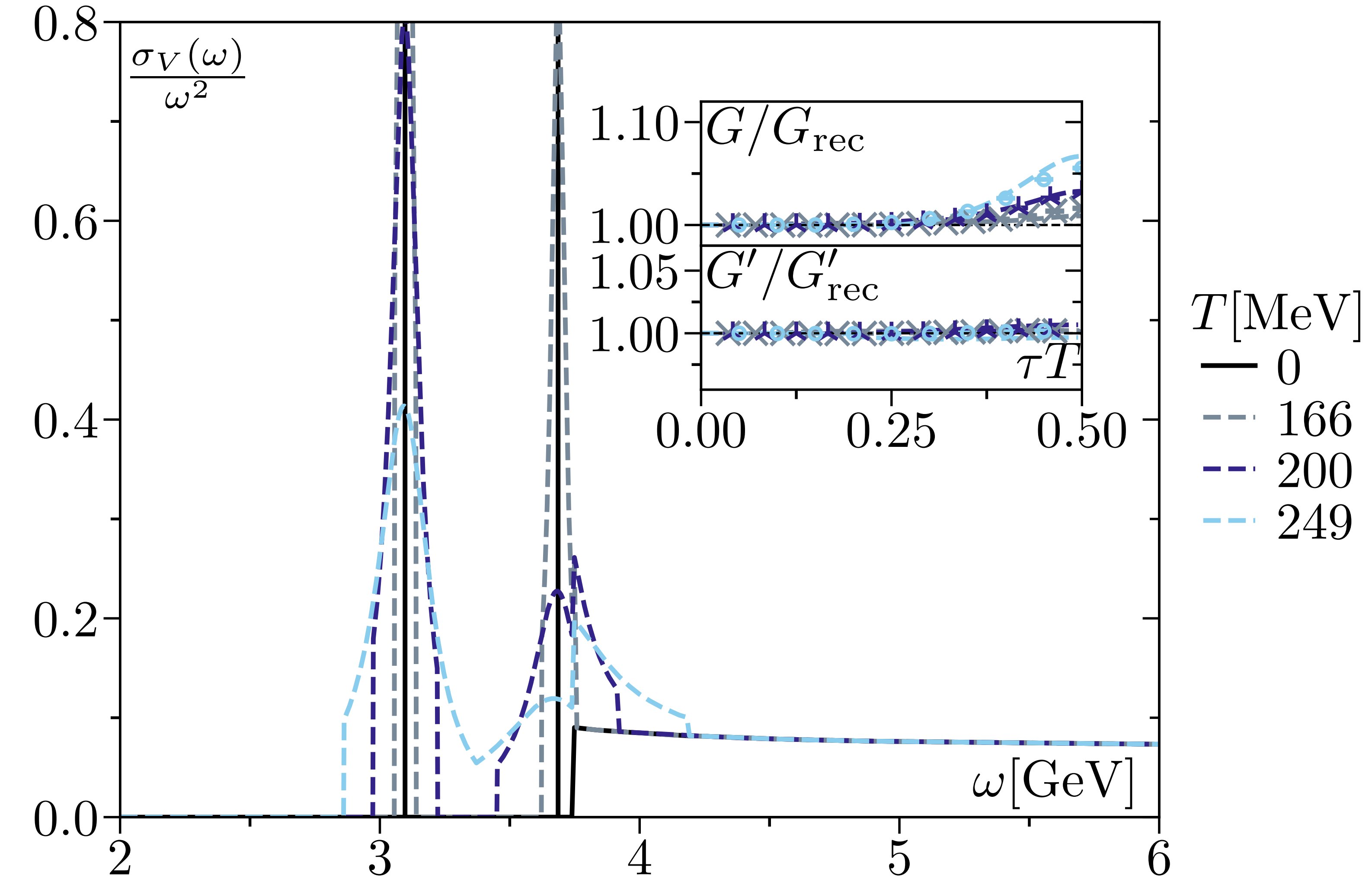
Once we have independent information from extended operators, we can ask whether a simple spectral model using those widths is at least compatible with those ratios.

A DELIBERATELY SIMPLE SPECTRAL MODEL

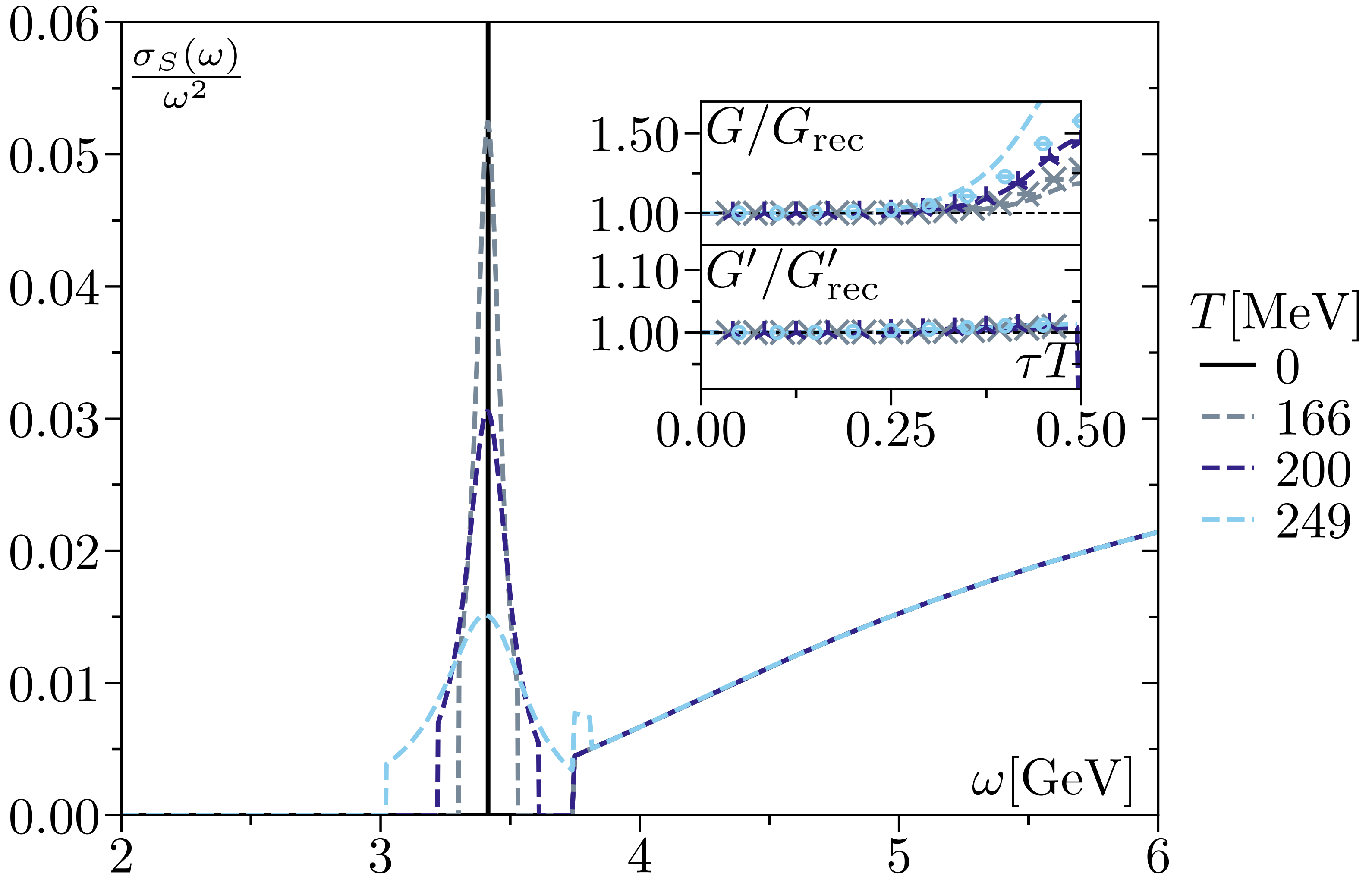
NO ZERO-MODE



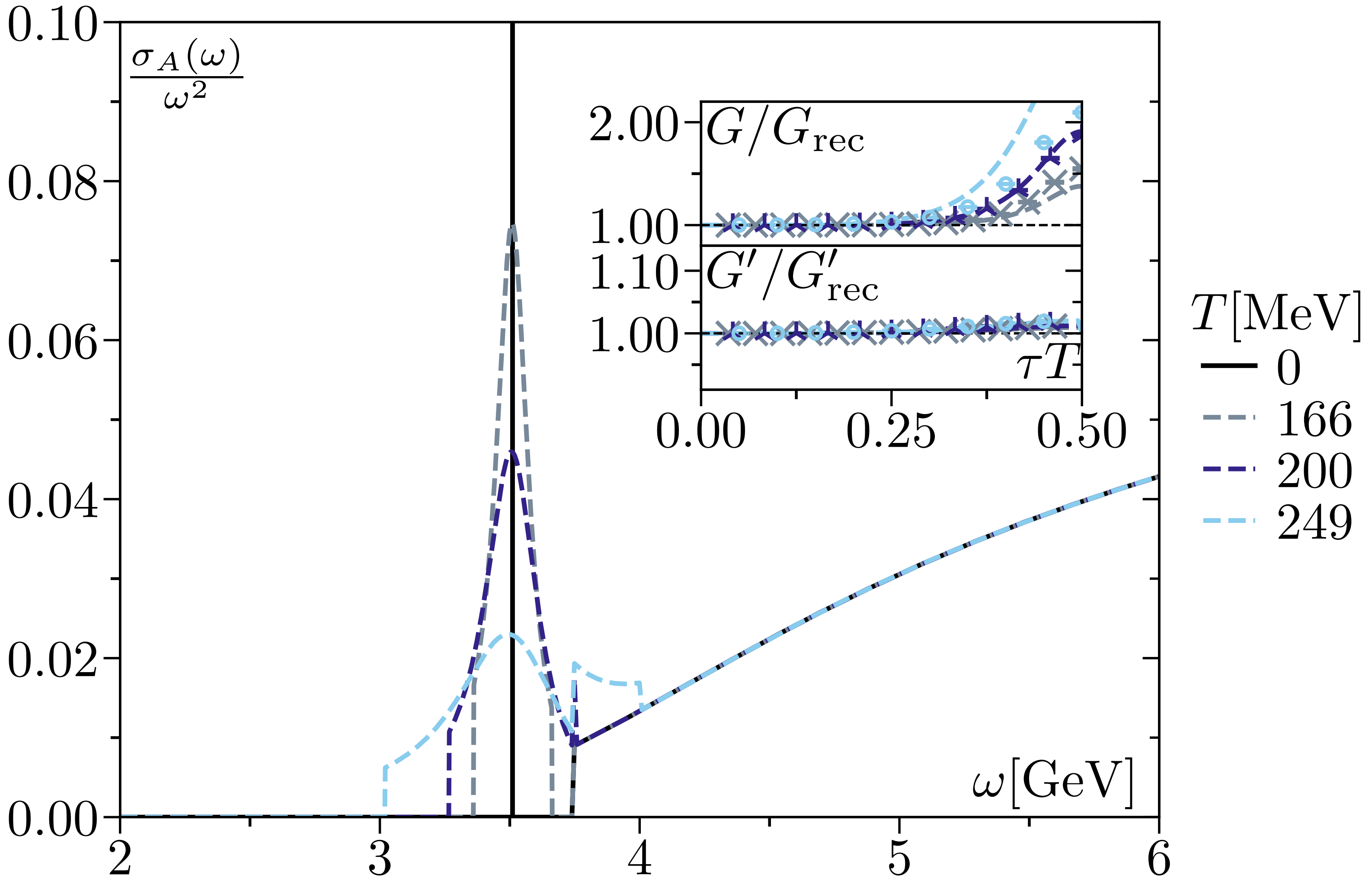
ZERO-MODE



ZERO-MODE



ZERO-MODE

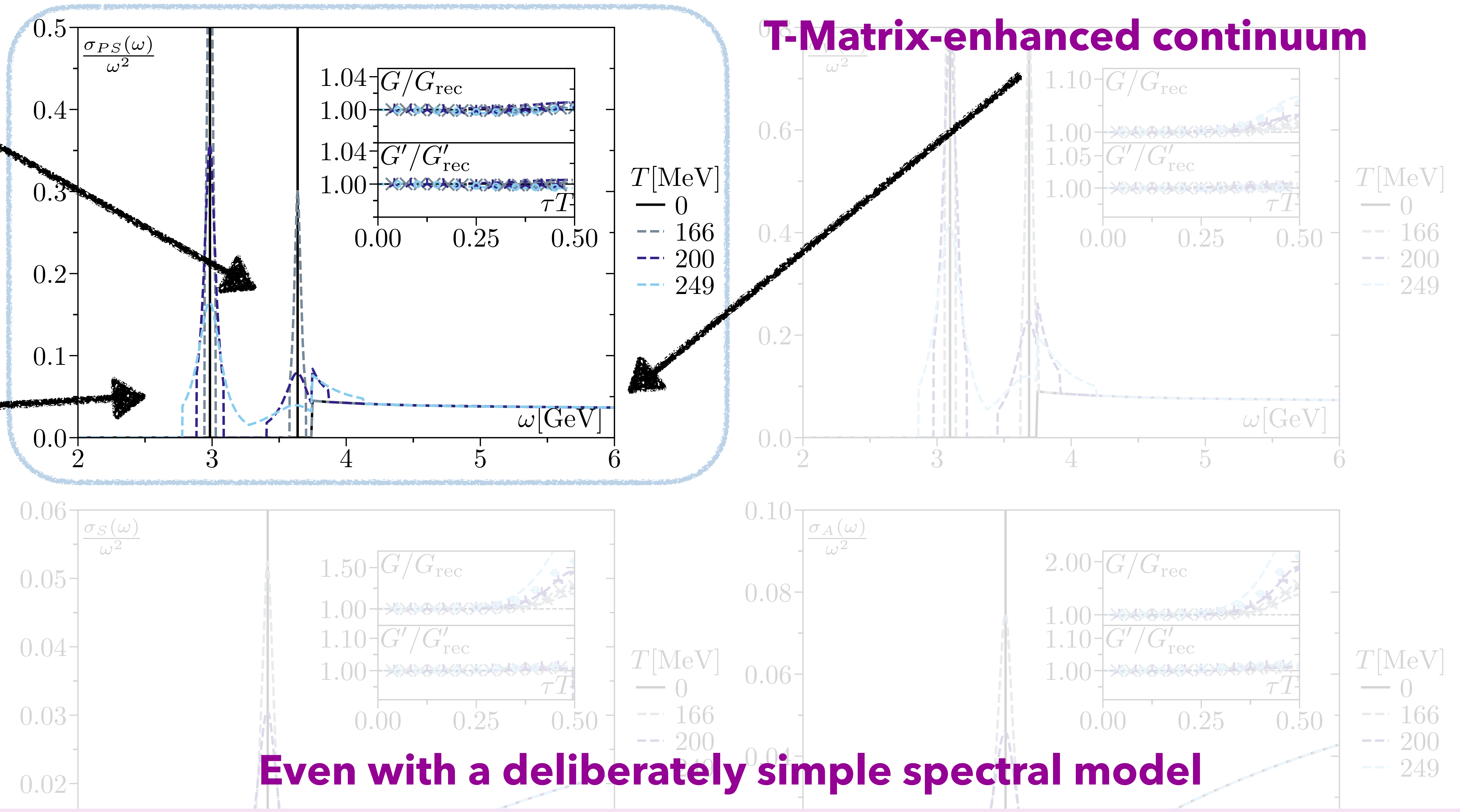


A DELIBERATELY SIMPLE SPECTRAL MODEL

Mild overlap

T-Matrix-enhanced continuum

Broad peaks



Even with a deliberately simple spectral model

THE RECONSTRUCTED POINT-LIKE RATIOS REMAIN CLOSE TO 1