The fate of Hybrid Charmonium at finite temperature

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in collaboration with

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The 1^{-+} Charmonium

Interest in exotics

- ✓ Several states outside quark-constituent model.
- ✓ XYZ states await full theoretical understanding.
- ✓ $J^{PC} = 1^{-+}$ manifestly exotic.
- ✓ Temperature as a probe of structure?

Our goal: Systematic study at $T > 0$!
First application of :

- ✓ Distillation.
- ✓ Distillation profiles.
- ✓ HadSpec basis of operators.

J. A. Urrea-Niño *et al.*, LATTICE 2025, 2512.11638

On the lattice until now

- ✓ Systematic study of T_1^{-+} charmonium at $T = 0$ by HadSpec. L. Liu *et al.*, JHEP 2012, 126 (2012)
- ✓ Distillation + 18 derivative-based operators. J. J. Dudek *et al.*, Phys. Rev. D 77, 034501 (2008)

Obstacles to overcome
Correlations are affected by:

- × Periodic temporal BC effects.
- × Finite temperature effects.

Spectral analysis requires enough temperatures and temporal points.

Spectroscopy tools: how do they extend?

Zero temperature

At operator level:

- ✓ HadSpec $\bar{q}\Gamma q$ basis: subduction to remember continuum J. J. J. Dudek *et al.*, Phys. Rev. D 77, 034501 (2008)
- ✓ Distillation. M. Peardon *et al.*, Phys. Rev. D 80, 054506 (2009)
- ✓ Distillation profiles. J. A. Urrea-Niño *et al.*, Phys. Rev. D 106 (2022) 3, 034501

At correlation level:

- ✓ Spectral decomposition with known form.

→ Well-established methodology!

Non-zero temperature

At operator level:

- × $\{\Gamma, \gamma_0\} \neq 0$ introduces constant to correlator. Phys. Rev. D 75, 094502 (2007), Phys. Rev. D 84, 094504 (2011) , Phys. Rev. D 112, 014506 (2025)
- × Time-reversal symmetry of operators can lead to both cosh() and sinh() in correlation matrix. G. Bailas *et al.*, Eur. Phys. J. C 78 (2018) 12, 1018

At correlation level:

- × Spectral function no longer known.

→ Additional symmetries and unknowns to consider!

Our approach and setup

A good operator basis is fundamental! Reminder by J. R. Green, LATTICE 2025, arXiv:2602.23244

We preserve as much as we can:

1. Build all HadSpec operators for each irrep R^{PC}.
2. Separate by behaviour under $\{\Gamma, \gamma_0\}$ and time-reversal.

Advantages

- ✓ Additional constants are avoided.
- ✓ Correlation matrix has cosh() form.

Disadvantages

- × Reduced list of operators.
- × More constraints for operators.

The T_1^{-+} case: a dramatic cut

1. We start with 18 HadSpec operators.
2. Time-reversal leaves 2 sets of 9 operators.
3. Enforcing $\{\Gamma, \gamma_0\} = 0$ leaves only 1!

We will need to deal with this...

FASTSUM's Gen2 Ensemble: G. Aarts, *et al.*, JHEP 02 (2015) 186 arXiv:1412.6411.

- ✓ Gauge action: Anisotropic + Symanzik-improved + tree-level tadpole improvement.
- ✓ Fermion action: Anisotropic $N_f = 2 + 1$, Clover-improved & Stout smearing.

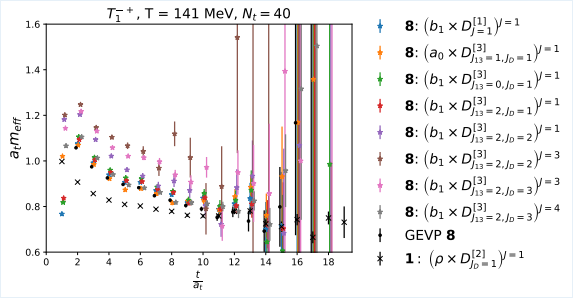
- $\xi = \frac{a_s}{a_t} \approx 3.5$, $a_s \approx 0.12$ fm, $a_t^{-1} \approx 5.7$ GeV.
- $m_\pi \approx 385$ MeV, lattice sizes $N_t \times 24^3$.
- $T = 0$ ($N_t = 128$) used by HadSpec for exotic charmonia. L. Liu *et al.*, JHEP 2012, 126 (2012)

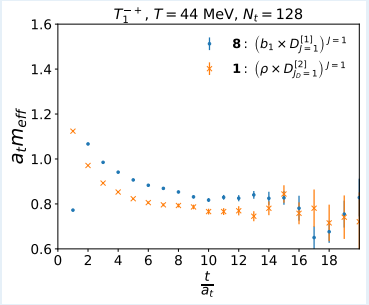
- ✓ Temperatures above and below T_c!

N_t	T (MeV)	T/T_c	N_{cfgs}
128	44	0.243	**305**
40	141	0.777	498
36	156	0.864	496
32	176	0.972	987
28	201	1.11	966
24	235	1.30	991
20	281	1.56	975
16	352	1.94	983

The T_1^{-+} operator problem

We have **8** T-even "bad" operators and **1** "good" one. Additional constant contribution.





! Large excited-state contamination in all **8**. Even after GEVP!

✓ **1** Hybrid operator outperforms all **8**!

✓ We have one very good operator...

× ... but how to increase the basis size?

We have few operators $\bar{q}\Gamma q$ after additional constraints, e.g. 2 for A_1^{-+}, **1** for T_1^{-+}.

× Small GEVPs are not optimal for mapping spectrum.

How to get more operators?

× Larger number of derivatives (≥ 4) a la HadSpec is noisier and complicated.

Distillation profiles Urrea-Niño *et al.*, PRD 106 (2022) 3, 034501, PRD 112 (2025) 7, 074502, PRD 114 (2026) 1, 014509

- ✓ Extends on existing "good" operators.
- ✓ Negligible additional cost.
- ✓ Can increase basis size $\approx 5 \rightarrow \approx 20$.
- ✓ Shown to work well for $T = 0$ spectroscopy.

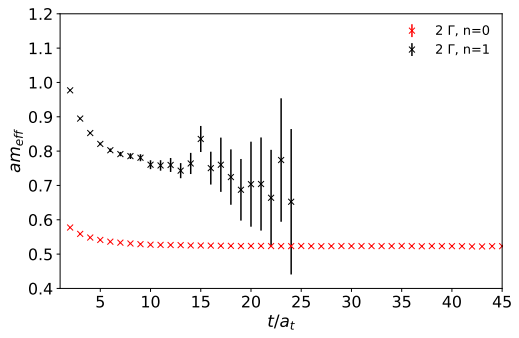
For each Γ operator we introduce 7 different Gaussian profiles.

- ✓ Keep physical information from the Γ, allow better resolution of states with profiles.

Test case: the A_1^{-+} spectrum

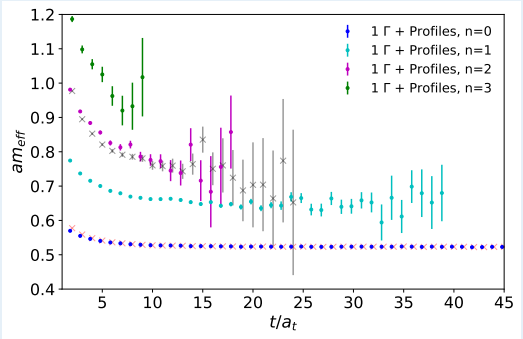
Here we have **2** representative "good" Γ operators: $\gamma_4\gamma_5$ and $\gamma_i\mathbb{B}_i$. $\mathbb{B}_i = \epsilon_{ijk}\nabla_j\nabla_k$ is a hybrid operator.

We check how the resolved spectrum changes as we increase the operator basis at $T = 0$.



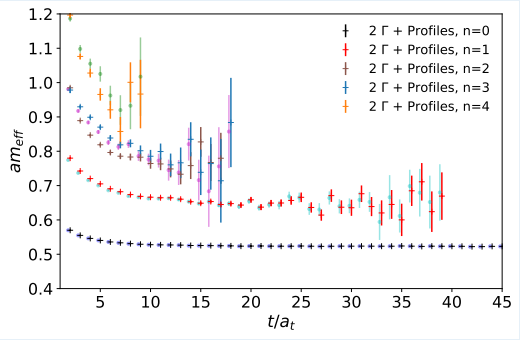
- 2 operators $\rightarrow$ 2 states.
- Clean ground state and signal for one excitation.
- $\times$ No higher levels accessible!
- $\times$ Are we missing intermediate states?

Let's add profiles to just $\Gamma = \gamma_4\gamma_5$ and see what happens...



- 7 operators $\rightarrow$ 7 states.
- ✓ Consistent ground state, signal for higher excitations.
- ✓ Intermediate state appears!
- ✓ $\gamma_i \mathbb{B}_i$ could not probe low states alone, profiles in $\gamma_4\gamma_5$ make up for this.
- × Are we missing other intermediate states?

Reminder: No additional perambulators or elementals need to be measured, simply introduce profiles at correlation level.



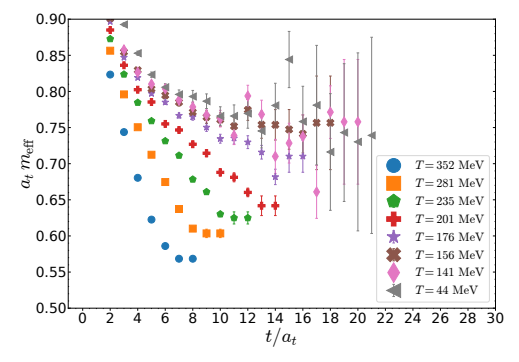
- 14 operators → Pruned down to 7 states.
- ✓ Consistent ground state, signal for higher excitations.
- ✓ Another intermediate state appears!
- ✓ $\gamma_4\gamma_5$ with profiles could not probe higher excitations, $\gamma_i\mathbb{B}_i$ with profiles helps with this.

Using profiles significantly helps resolve the spectrum compared to standard distillation but it does not replace having a sufficient bases of Γ operators. See also J. A. Urrea-Niño Monday @ 2 PM.

Combining different Γ with profiles provides the most complete approach. J. A. Urrea-Niño *et al.*, Phys. Rev. D 114 (2026) 1, 014509

We will do this for the T_1^{-+} once we have larger statistics.

T_1^{-+} across temperatures



Signal quality:

- ✓ Present at all temperatures.
- × Need additional statistics (configs, sources).

Mass extraction:

- ✓ Zero-temperature matches HadSpec results.
- ! Change in spectral function "breaks" the effective mass extraction.

A change of framework

Zero-temperature results come from a different codebase.

- ✓ Greater flexibility in distillation, e.g. profiles.
- × Difference in smearing of spatial links.

Reconstructed Correlators

Express correlator as: Phys. Rev. D **69**, 094507 (2004), JHEP **04** (2010), 099, Phys. Rev. D **86** (2012), 014509, arXiv:2209.14681

$$G(t) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} K_B(t, \omega; T)\, \rho(\omega) \quad \text{with} \quad K_B(t, \omega; T) = \frac{e^{-\omega t}}{1 - e^{-\omega/T}}$$

The (bosonic) kernel may be re-written (integer m)

$$K_B(t, \omega; 1/N_t) = \sum_{n=0}^{m-1} K_B\left(t + n\,N_t, \omega; \frac{1}{mN_t}\right)$$

and hence reconstructed correlator is given by

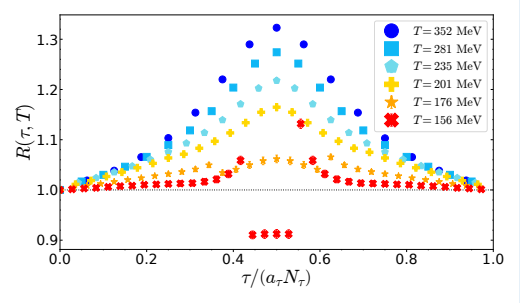
$$G_{rec}(t, T; T_0) = \sum_{n=0}^{m-1} G(t + n/T; T_0)$$

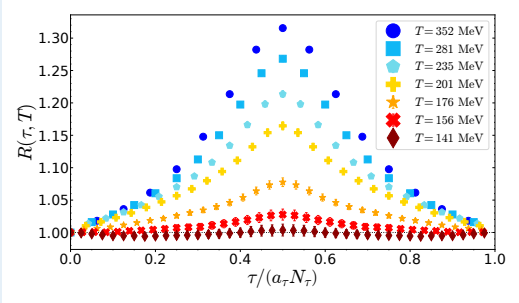
- Remove trivial temperature dependence of Kernel $K_B(t, \omega; T)$
- Allow robust investigation of **change** to spectral function $\rho(\omega)$. Not its form.

Consider ratios

$$R(t, T) = G(t, T)/G_{\text{rec}}(t, T; T_0)$$

A_1^{-+} reconstructed Ratio: "Zero" temperature choice





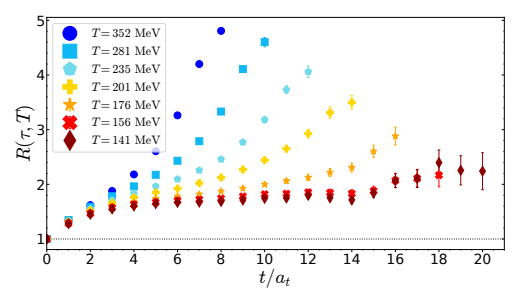
At LATTICE25: J. A. Urrea-Niño *et al.*, LATTICE 2025, 2512.11638

- ! Reconstructed correlator ratio using $N_t = 40$, $T \sim 141$ MeV as zero temperature.
- × Odd mid-behaviour below T_c.

Now:

- ✓ Using $N_t = 128$, $T \sim 44$ MeV resolves this!
- ✓ Systematics are fixed.
- ✓ Removed unwanted finite-T effects.

T_1^{-+} reconstructed ratio



× Ratio not close to 1.

✓ Still coincides at low temperatures.

→ T_1^{-+} is more sensitive to framework change.

! "Different" distillation vectors influence T_1^{-+} operator.

✓ Little difference before $T = 176$ MeV ($T \sim T_c$)

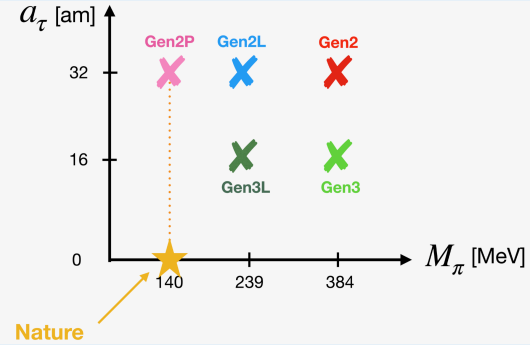
✓ Difference from 1 emerging at $T = 176$ MeV ($T \sim T_c$)

✓ Increasingly large difference $T \geq 201$ MeV

! Much more significant difference than A_1^{-+}.

The future

FASTSUM has other ensembles[2]



Gen3 configurations:

- ✓ similar characteristics as Gen2...
- ✓ ... but **twice** as many temporal points at each temperature.
- ✓ Significant improvement in MEM systematics.
- × Charm and bottom masses tuned.
- ✓ Will be analyzed with the new framework: more operators!

[2] Gen2P & Gen3L in preparation

Conclusions and Outlook

From LATTICE2025:

- ✓ Distillation extends well to finite temperature.
- × Operator choice is more constrained than in zero temperature.
- × Zero-temperature data was missing.

Now:

- ✓ New code framework combines distillation profiles with "good" HadSpec operators.
- ✓ Zero-temperature data available for proof-of-principle reconstructed correlators.

What comes next?

- ✓ Increase statistics for zero temperature.
- ✓ Move to Gen3: more temperatures, more data points, unified framework.
- ? Look at B-mesons, D-mesons and bottomonium.
- ? Different volumes for scattering at finite temperature → Read J. Hoffmann *et al.*, arXiv:2607.22346.

A_1^{-+} across temperatures