Precisely determining the ground state mass of Spin-3/2 Ω_{ccc} baryon from Lattice QCD

Lattice 2025 MUMBAI

03/11/25

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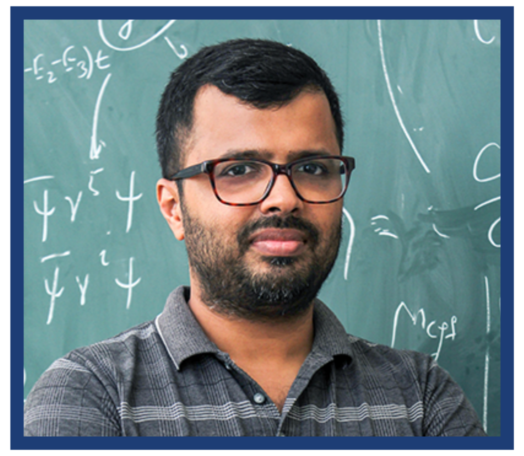
M Padmanath



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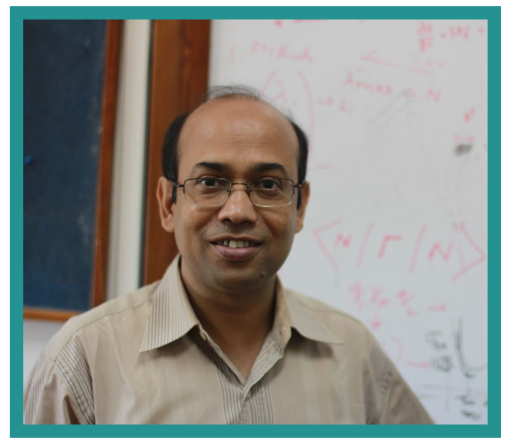


Nilmani Mathur

Computing Resources and Collaboration

EXPERIMENT

Observation of the doubly charmed baryon Ξ_{cc}^{++}

PRL **119** (2017) 11, 112001
LHCb Collaboration

Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$

PRL **118** (2017) 18, 182001
LHCb Collaboration

- **Conventional hadron spectroscopy still thrives:** besides exotics, many interesting states continue to be discovered.
- Discoveries of doubly charmed baryon Ξ_{cc}^+ (ccu) and excited Ω_c^0 resonances at the experimental facilities.
- Experiments aim for precise measurements of masses, widths, and lifetimes, motivating theoretical predictions for tests at LHCb and Belle.

Anticipating many more hadrons, including our target Ω_{ccc} expected to be discovered as experiments reach higher luminosities.

Motivation

IS THE CCC A NEW DEAL FOR BARYON SPECTROSCOPY?

J. D. Bjorken
Fermi National Accelerator Laboratory, Batavia, IL 60510

ABSTRACT

The possibility of experimental observation of the triply harmed ccc baryon Ω^{++}_{ccc} is explored. The conclusion is that it s very difficult, but not unthinkable.

AIP Conf.Proc. **132** (1985) 390-403
Bjorken

- Direct detection difficult, unless lighter hadrons are better understood.
- But

nature physics

Article https://doi.org/10.1038/s41567-022-01838-y

Observation of triple J/ψ meson production in proton-proton collisions

Nature Phys. ***19*** (2023) 3, 338-350
CMS Collaboration

THEORETICAL

- Single-flavored baryons (like Ω^-) were crucial in establishing color and the quark model, laying the foundation of QCD.
- Ω_{ccc} and Ω_{bbb} are the heavy-flavor analogues, predicted by QCD.
- Ω_{ccc} -> clean system to study quark-quark interactions and confinement, free from light-quark complications.

BUT

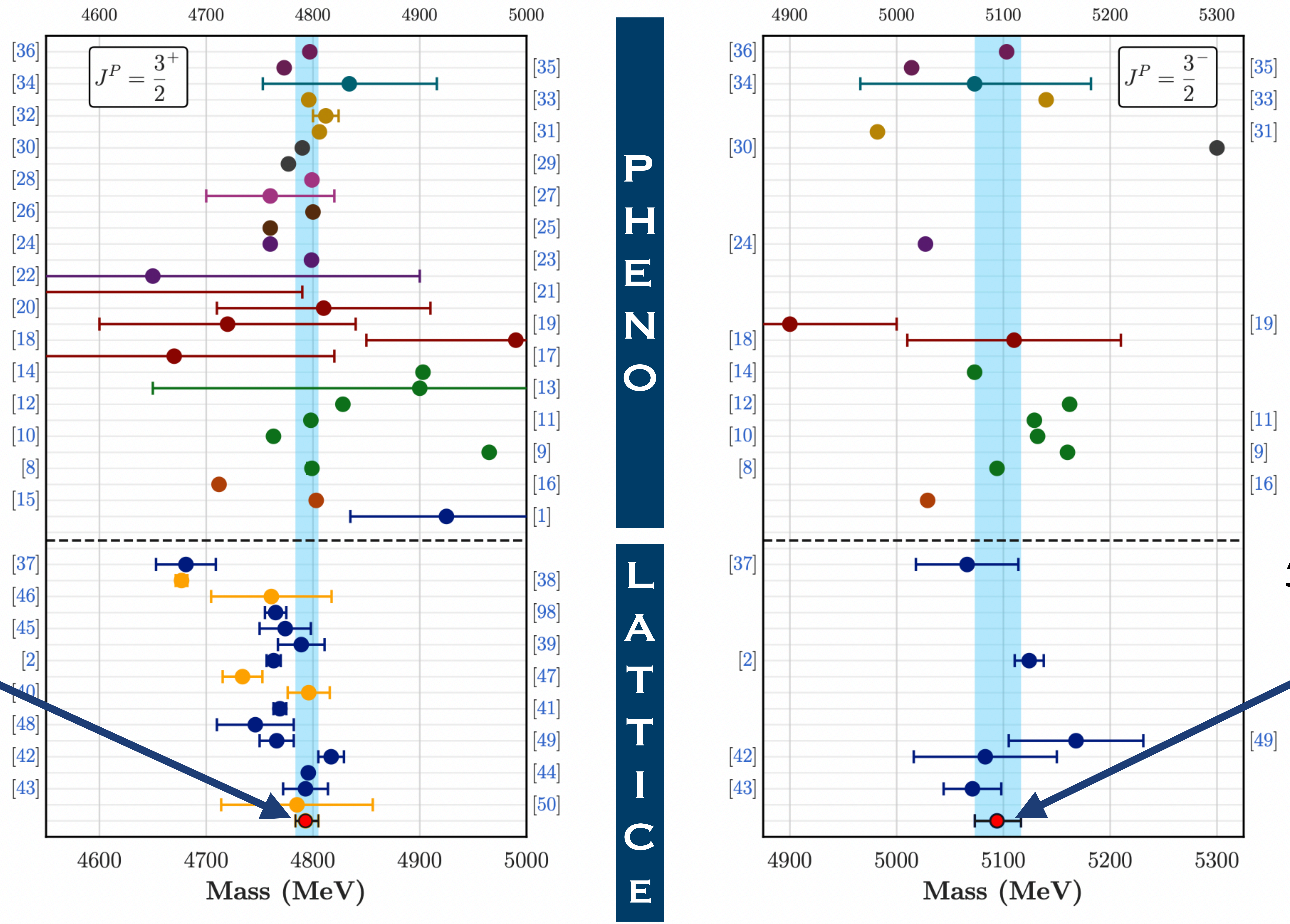
- Even with heavy quarks constituents phenomenological models predictions are spread over 400 MeV.
- Lattice predictions as well spread over 100 MeV for $\Omega_{ccc}(3/2^+)$.

HENCE THIS PRECISE STUDY

PRECISE RESULT

arXiv:2411.12729[hep-lat] **NSD**, Chakraborty, Radhakrishnan, Mathur, Padmaanth

$4793(5)\left(^{+11}_{-8}\right)$ *MeV*



$5094(12)\left(^{+19}_{-17}\right)$ *MeV*

SETUP

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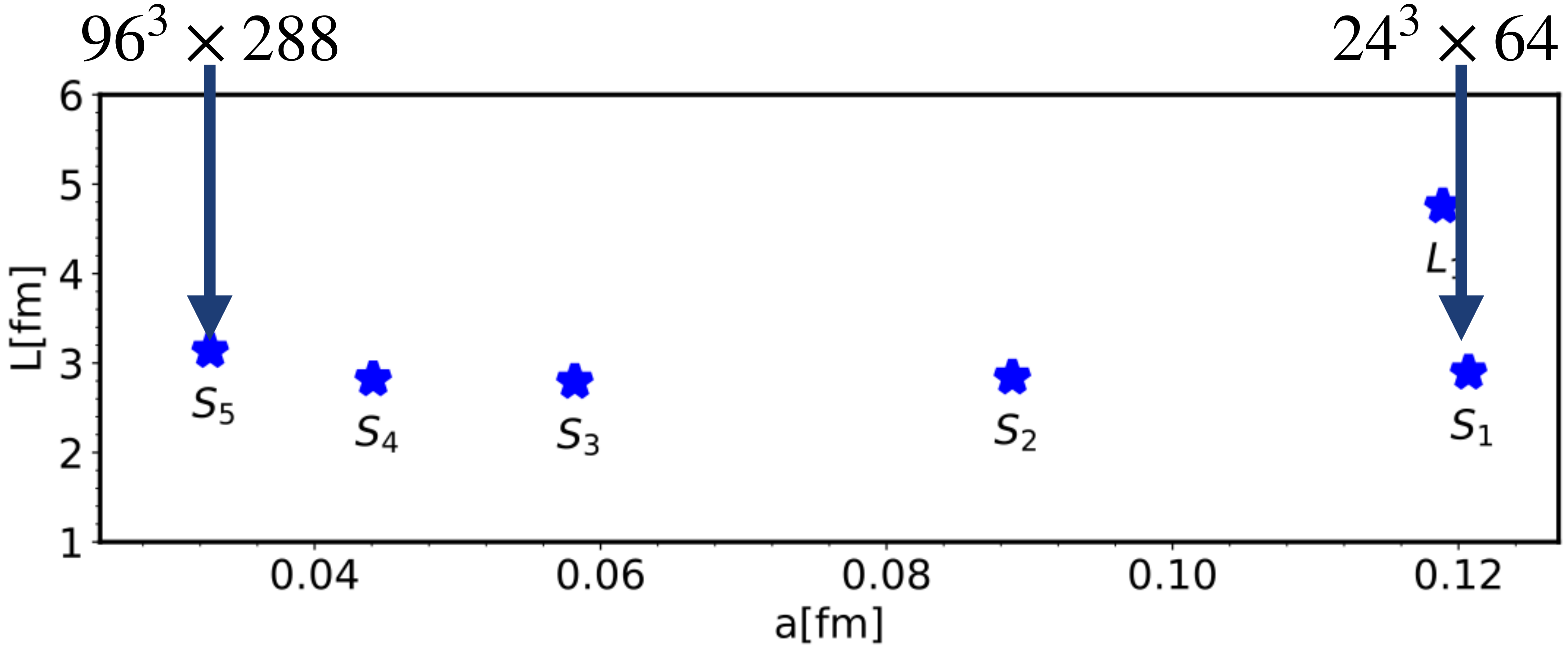
- Six $N_f = 2+1+1$ HISQ lattice ensembles generated by MILC collaboration.
- Two actions for valence quarks, HISQ and Overlap.
- Wall source to point sink setup for contractions.



- Correlation matrices are analyzed variationally using the Generalized Eigenvalue Problem (GEVP) to extract energy levels.

- Free from $\mathcal{O}(a)$ discretization errors, enabling cleaner continuum extrapolations.
- Good control over operator mixing.
- Suitable for heavy quark systems.

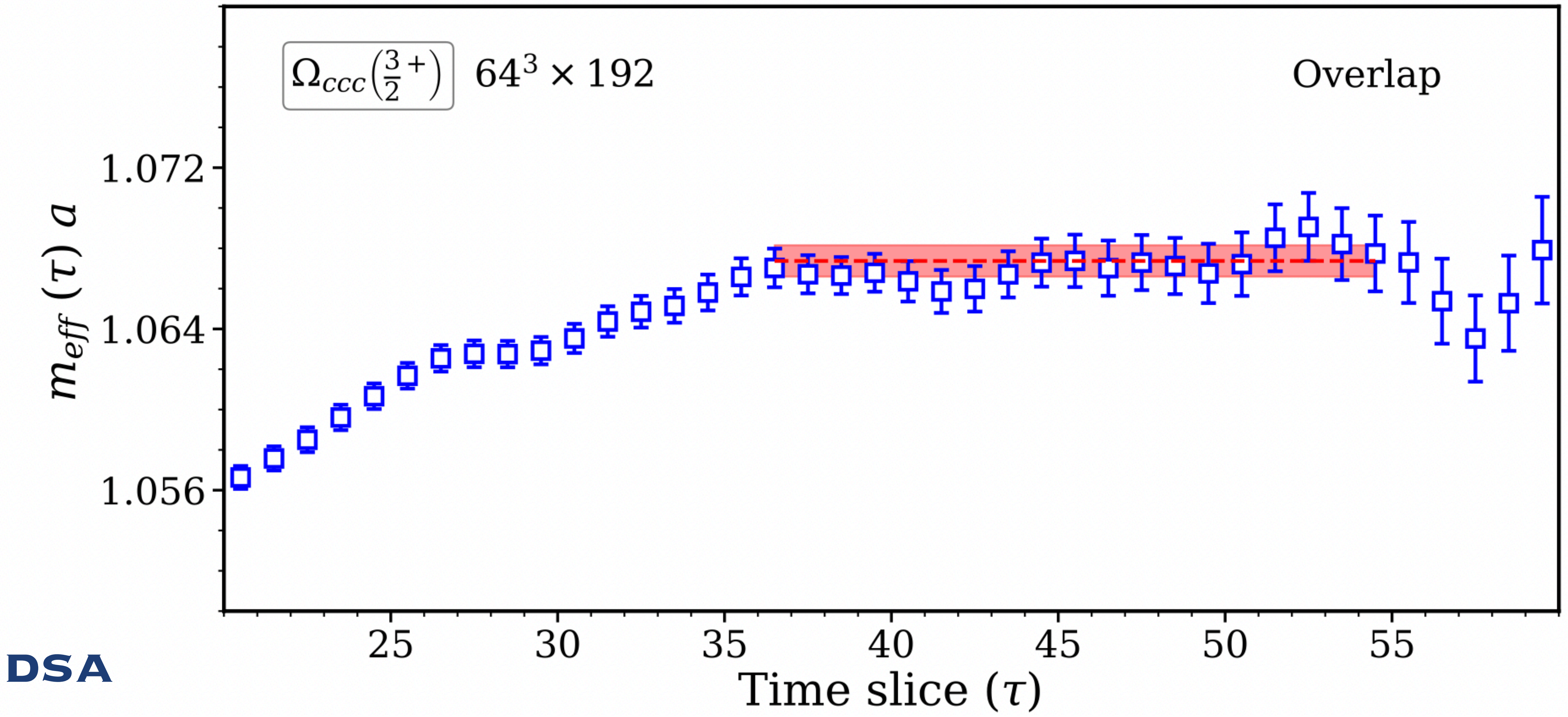
Color-Anti, Flavor-Symm-> Spin-Symm->3/2-> H^+ irrep

S_z	Operator [N]	Spin	Operator [R]	Spin
+3/2	${}^1H_{3/2}$	$\{111\}_S$	${}^2H_{3/2}$	$\{133\}_S$
+1/2	${}^1H_{1/2}$	$\{112\}_S$	${}^2H_{1/2}$	$\{233\}_S+\{134\}_S+\{143\}_S$
-1/2	${}^1H_{-1/2}$	$\{122\}_S$	${}^2H_{-1/2}$	$\{144\}_S+\{234\}_S+\{243\}_S$
-3/2	${}^1H_{-3/2}$	$\{222\}_S$	${}^2H_{-3/2}$	$\{244\}_S$

$$xyz_S = xyz + yzx + zxy$$

$$C_b(t) = \begin{bmatrix} \mathcal{O}^N_{b,H}\mathcal{O}^N_{b,H} & \mathcal{O}^N_{b,H}\mathcal{O}^R_{b,H} \\ \mathcal{O}^R_{b,H}\mathcal{O}^N_{b,H} & \mathcal{O}^R_{b,H}\mathcal{O}^R_{b,H} \end{bmatrix}$$

- Using GEVP.



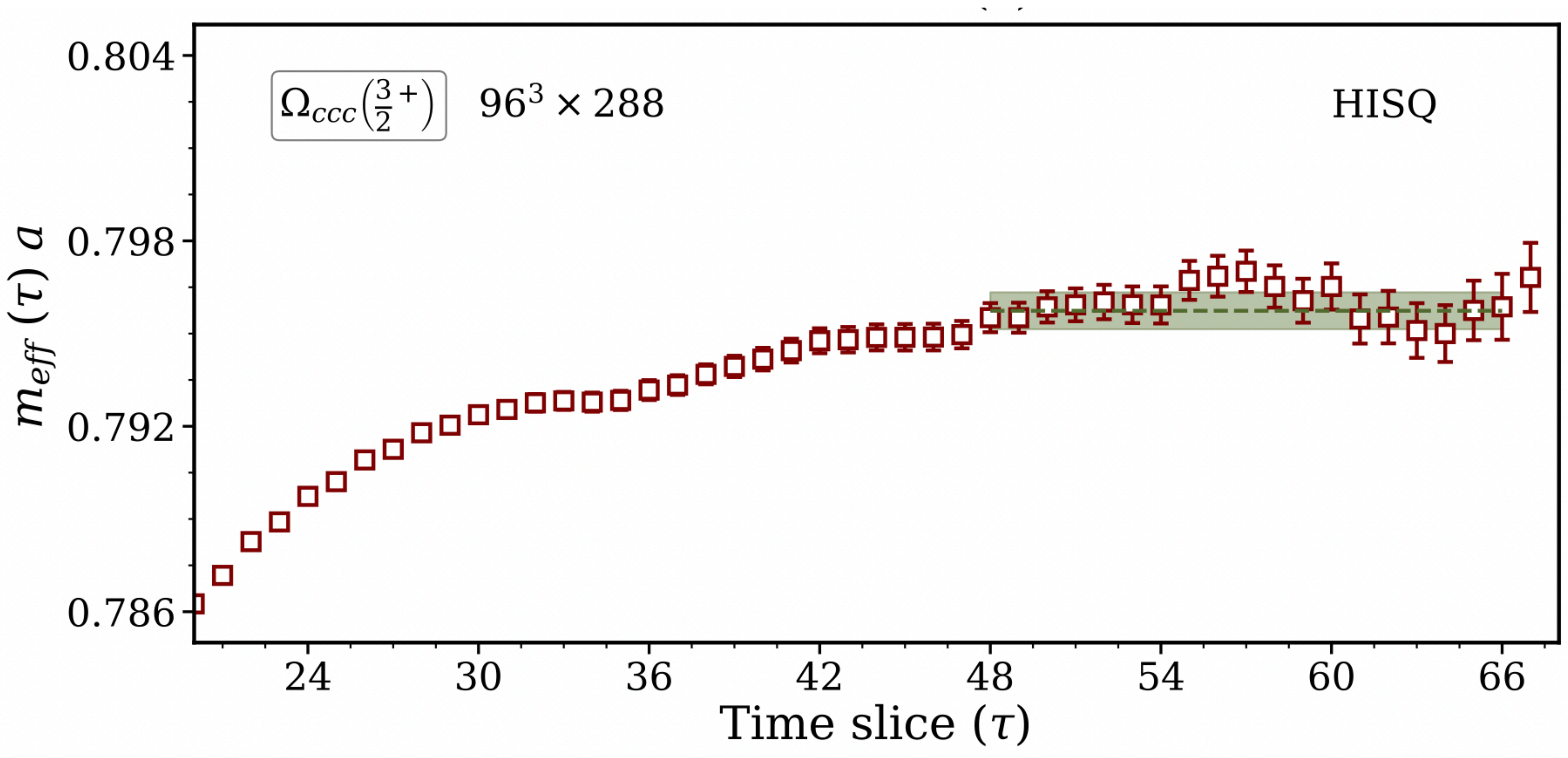
HISQ VALENCE

- ✦ HISQ action in both sea and valence improves consistency and eliminates mixed-action effects.
- ✦ Operator mixing can be nontrivial, but for single-flavor systems this issue is minimal.

$$\mathcal{O}_{\Omega_{ccc}}(t) = \epsilon_{abc} D_1 c^a(\mathbf{x}, t) D_2 c^b(\mathbf{x}, t) D_3 c^c(\mathbf{x}, t)$$

- ✦ HISQ operators respect approximate taste symmetry in addition to lattice rotational symmetry.
- ✦ This operator transforms in the 8′ irreps of geometric time slice (GTS) group -> A_2^-.

- ✦ Single and two exponential fit forms used



SIGNAL

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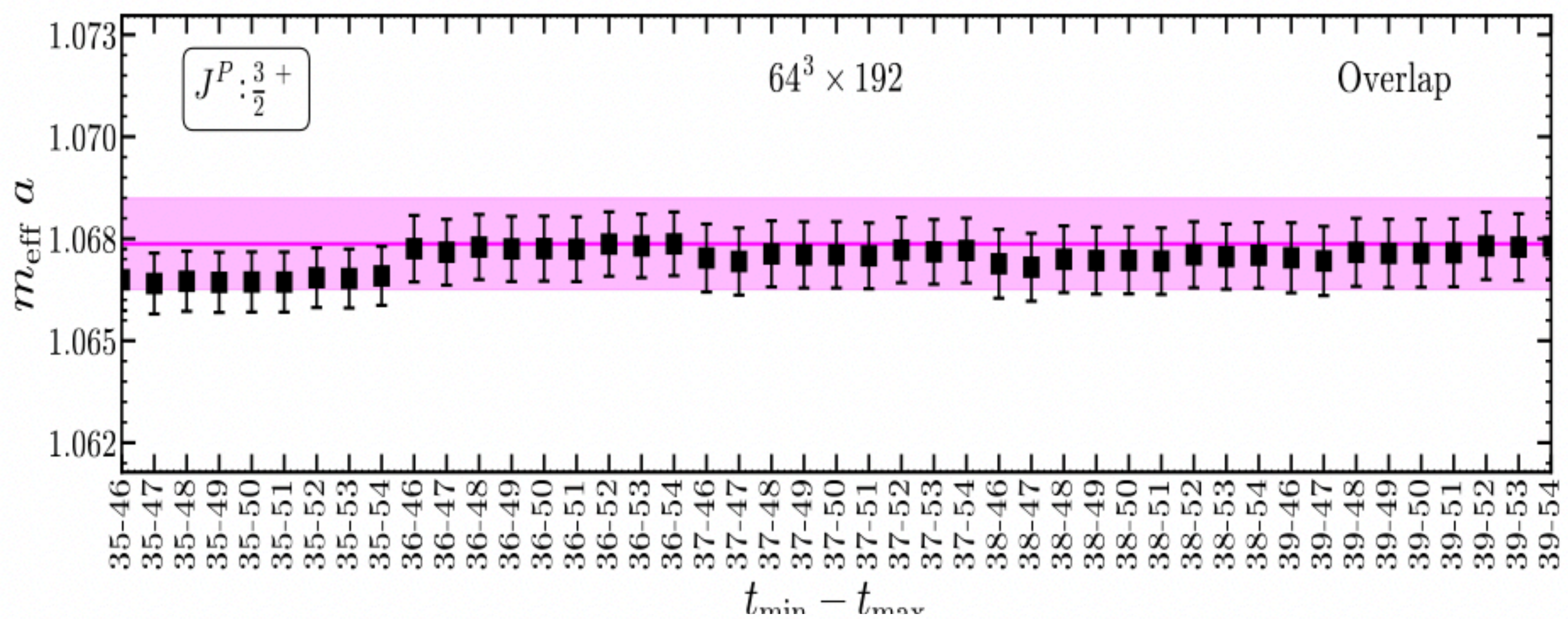
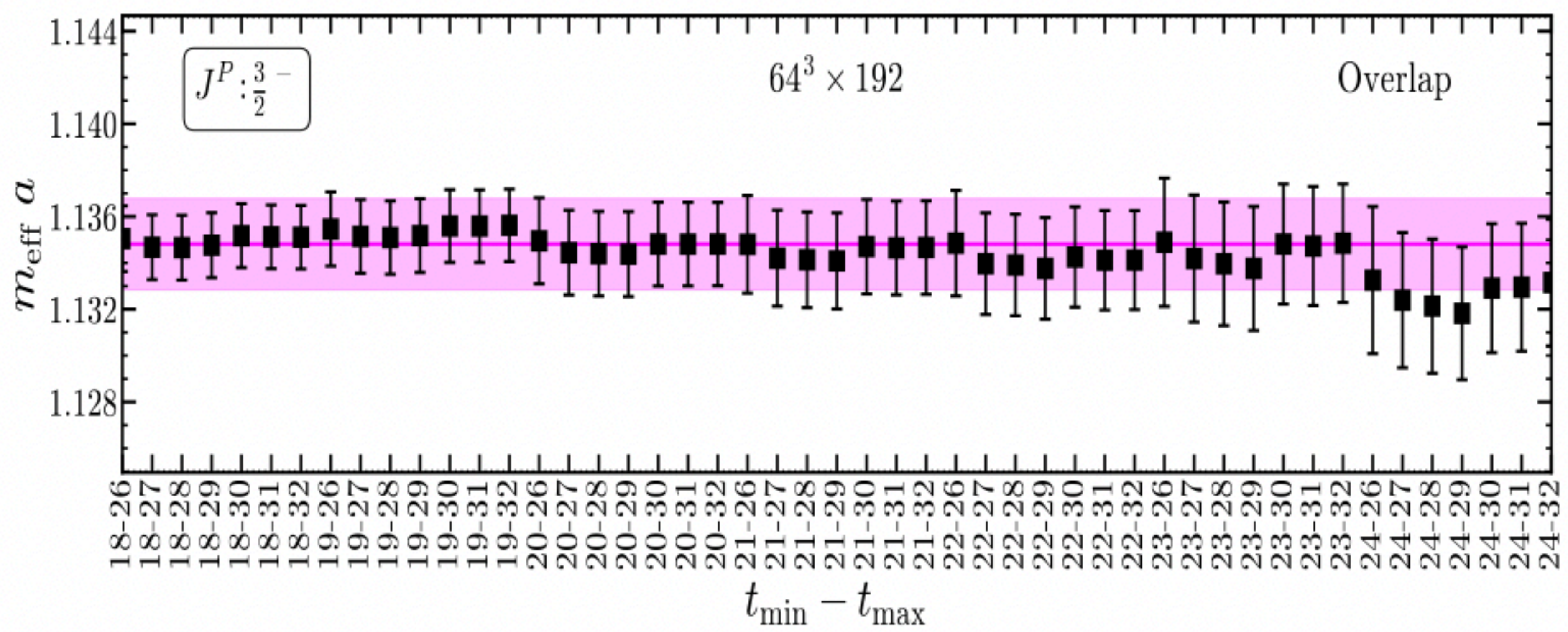
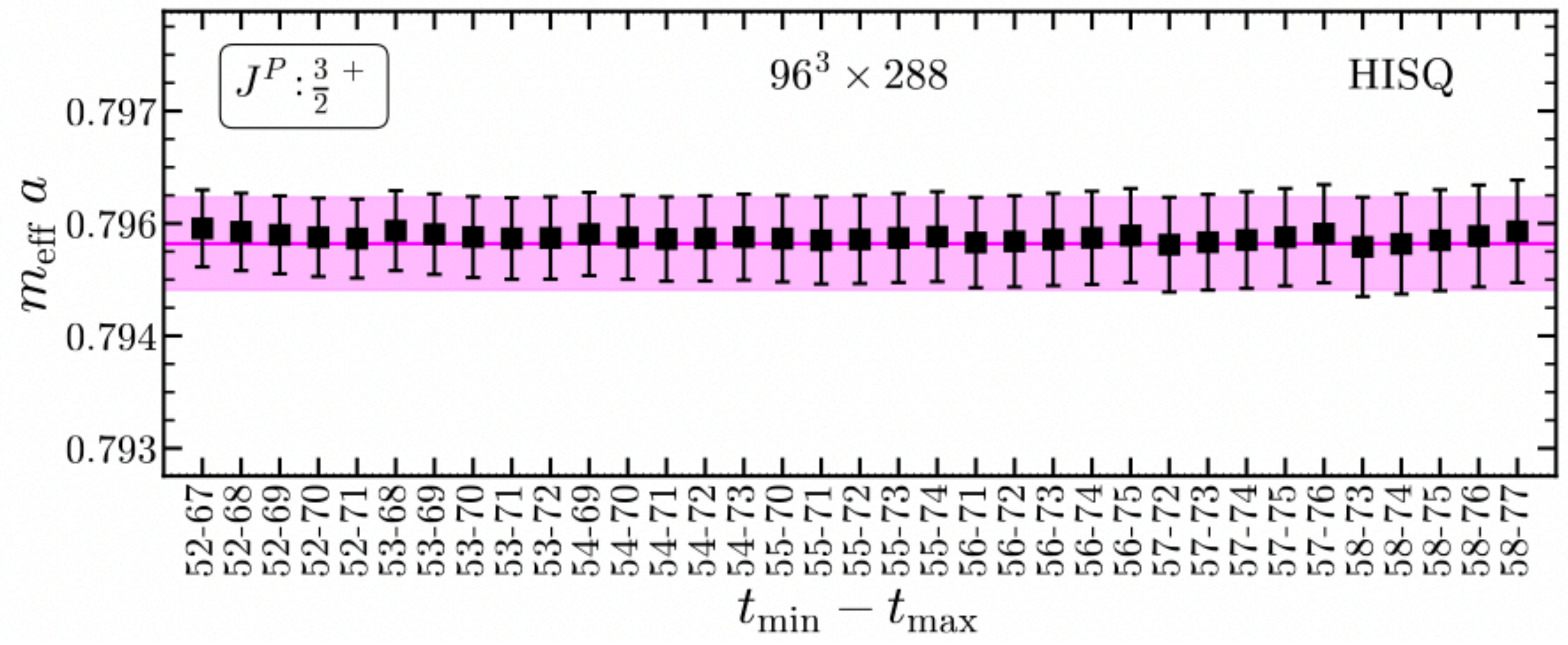
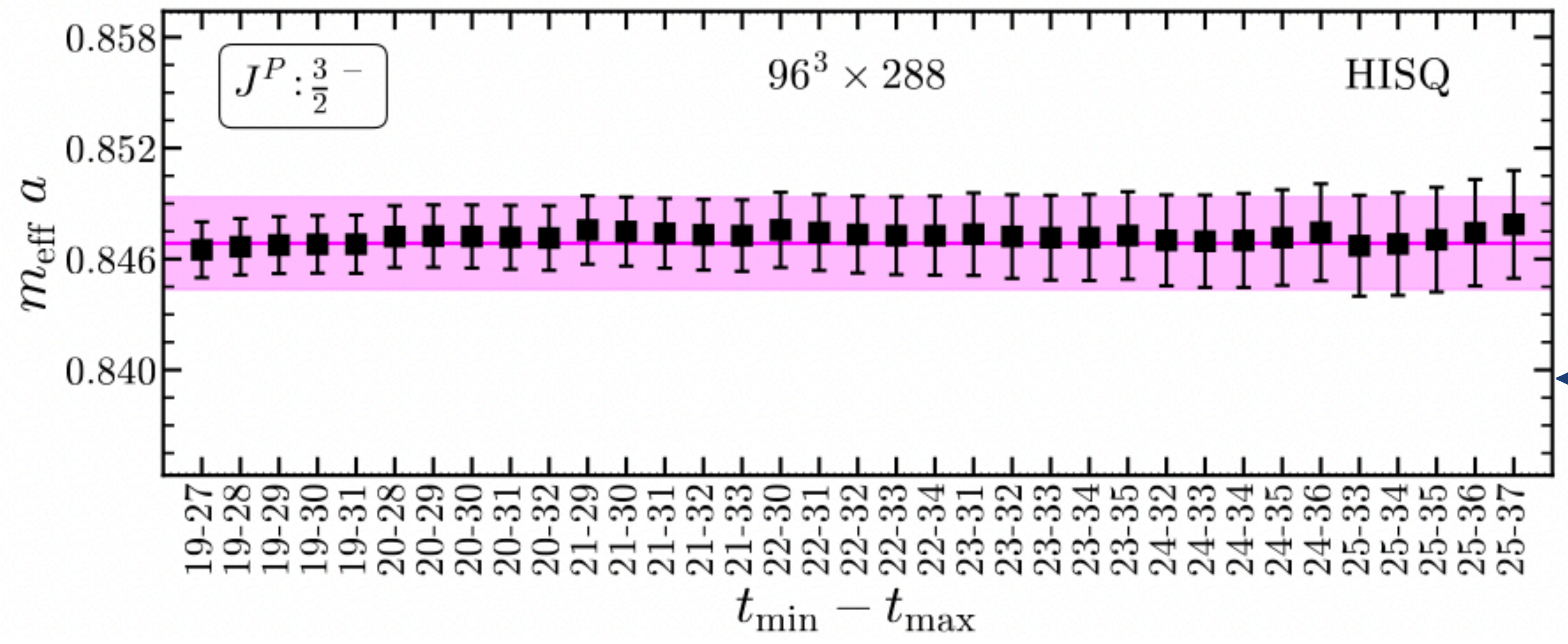


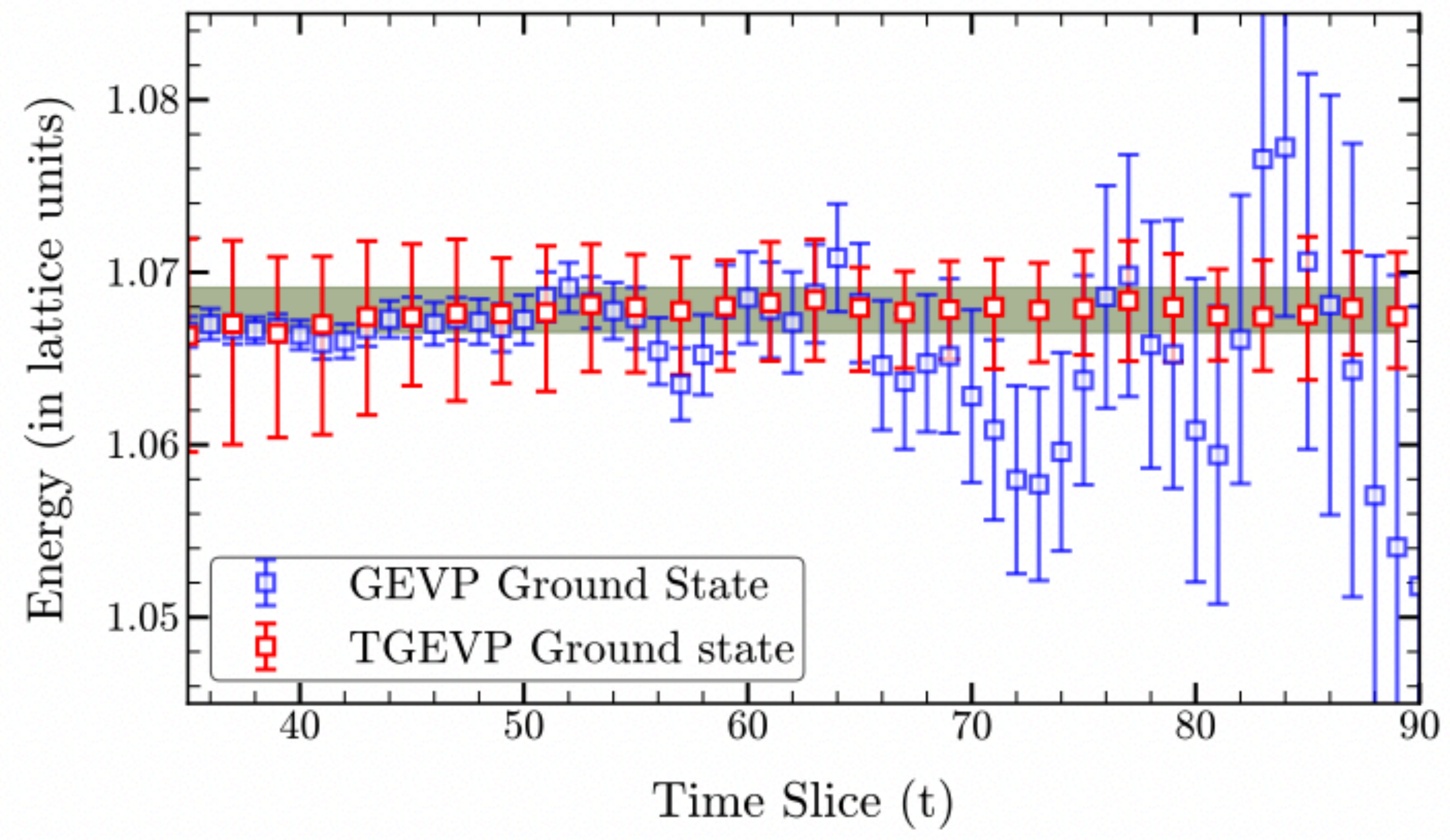


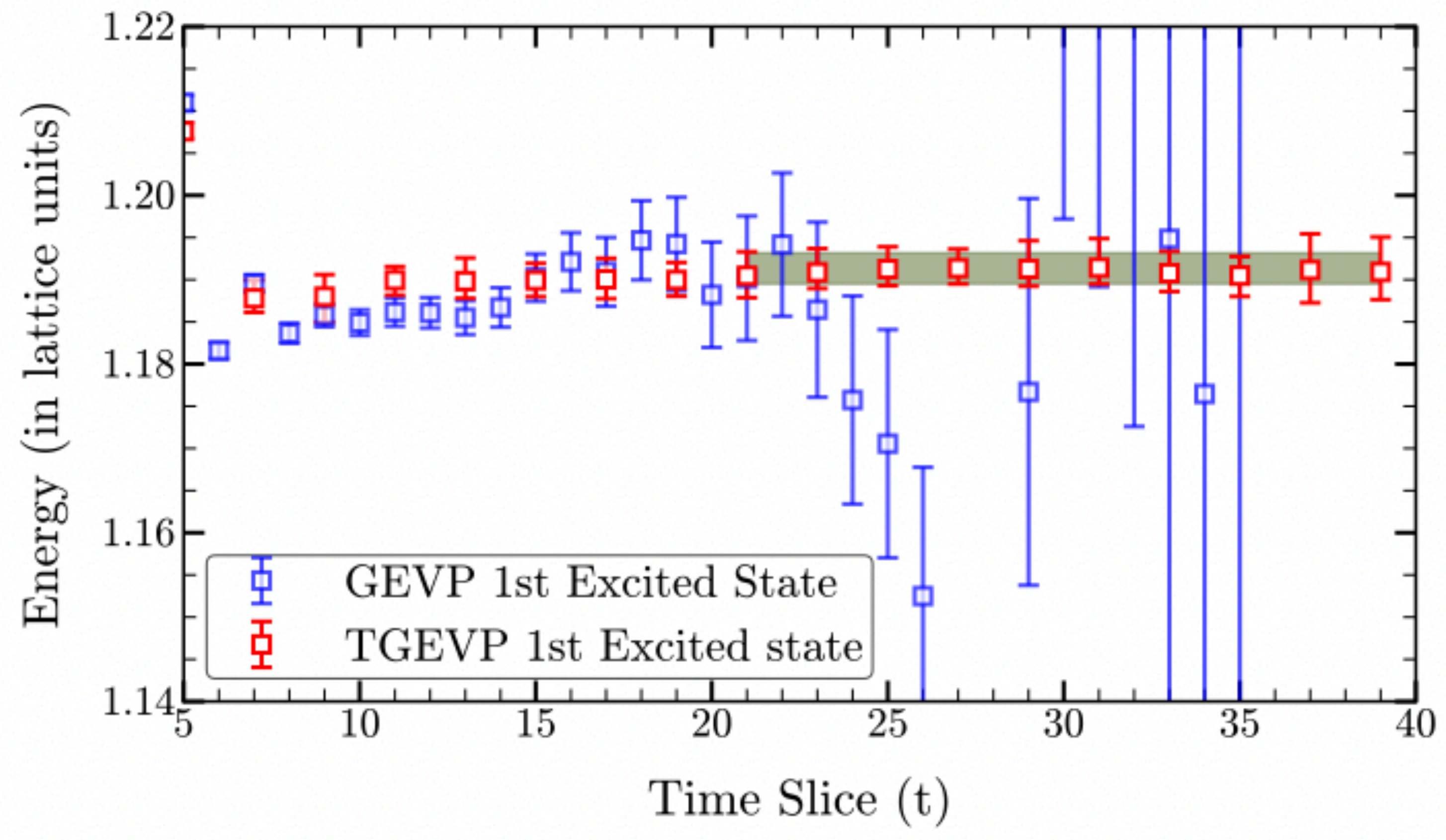




- ✦ Correlator smoothing in HISQ.

Next talk by Archana





Using TGEVP

- ✦ Used symmetry properties of baryon correlators to increase signal quality in Overlap.
- ✦ Bigger operator basis in Overlap to confirm no excited state contamination.

PRD **112** (2025) 7, 074506
Chakraborty, Sood, Radhakrishnan, Mathur

STRATEGIES

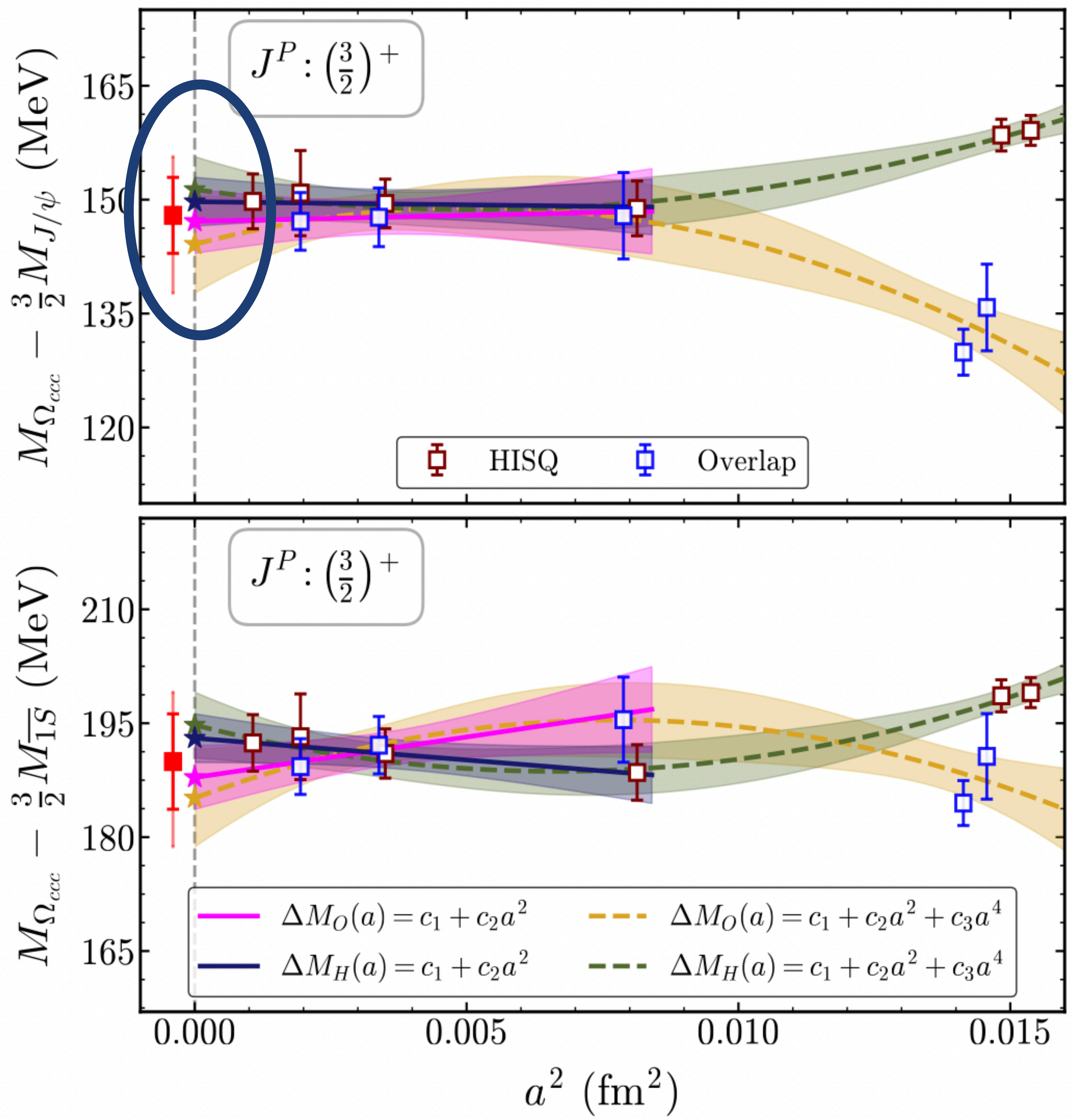
Countering Discretization

- Large bare quark mass -> discretisation effects, heavy hadrons -> In our case $\mathcal{O}(ma^2)$.
- To counter this we study mass splittings instead of making conclusions from effective masses directly.

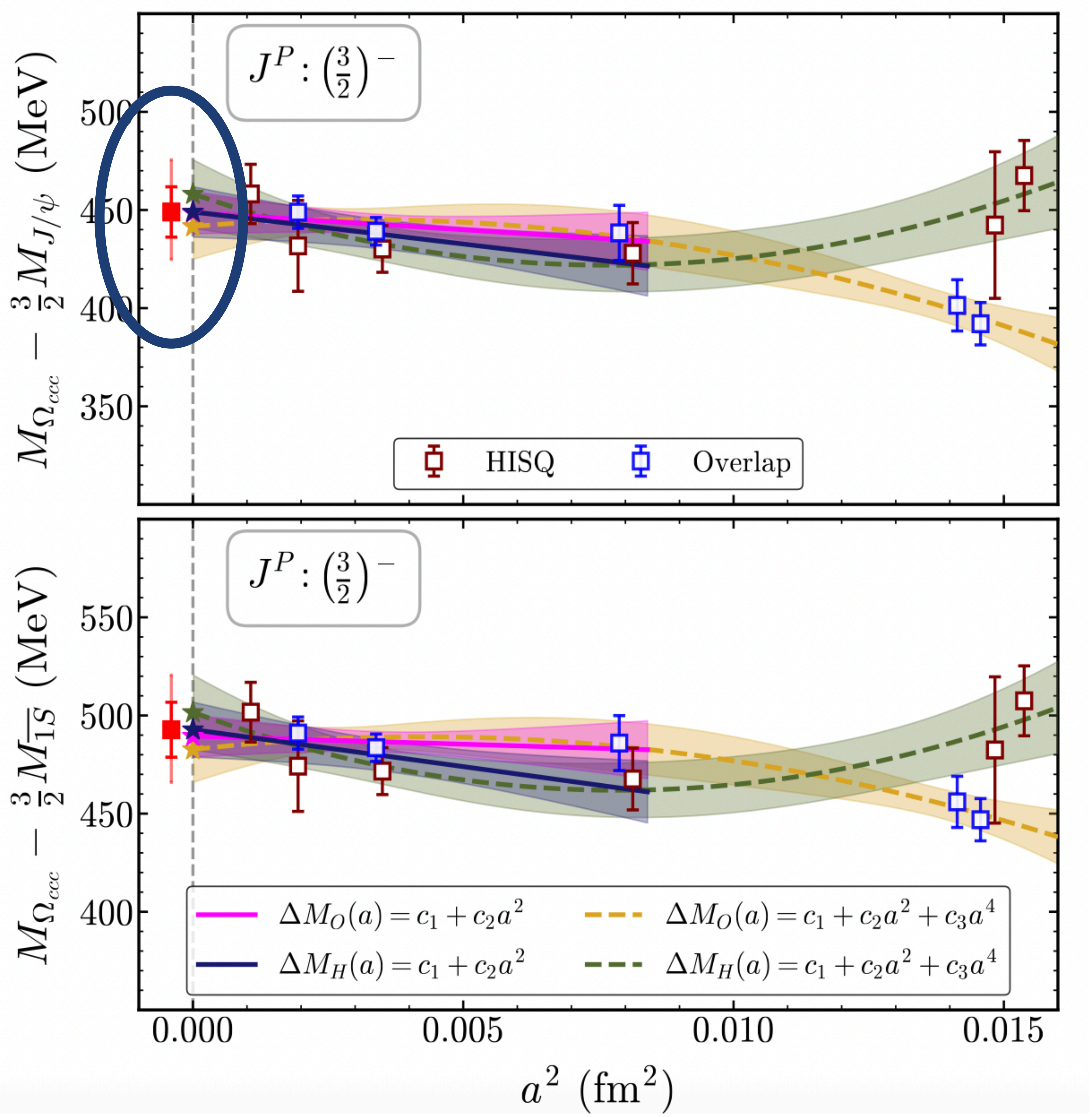
$$a\Delta M_{\Omega_{ccc}} = [aM^L_{\Omega_{ccc}} - \frac{3}{2}aM^L_{c\bar{c}}]$$

- Two choices- J/ψ and spin-averaged $\overline{1S}$.
- J/ψ masses on lattice closer to continuum value on each lattice.
- Spin-averaged $\overline{1S}$ - Charm quark mass tuned using this.

$4793(5)\binom{+11}{-8}\ MeV$



$5094(12)\binom{+19}{-17}\ MeV$

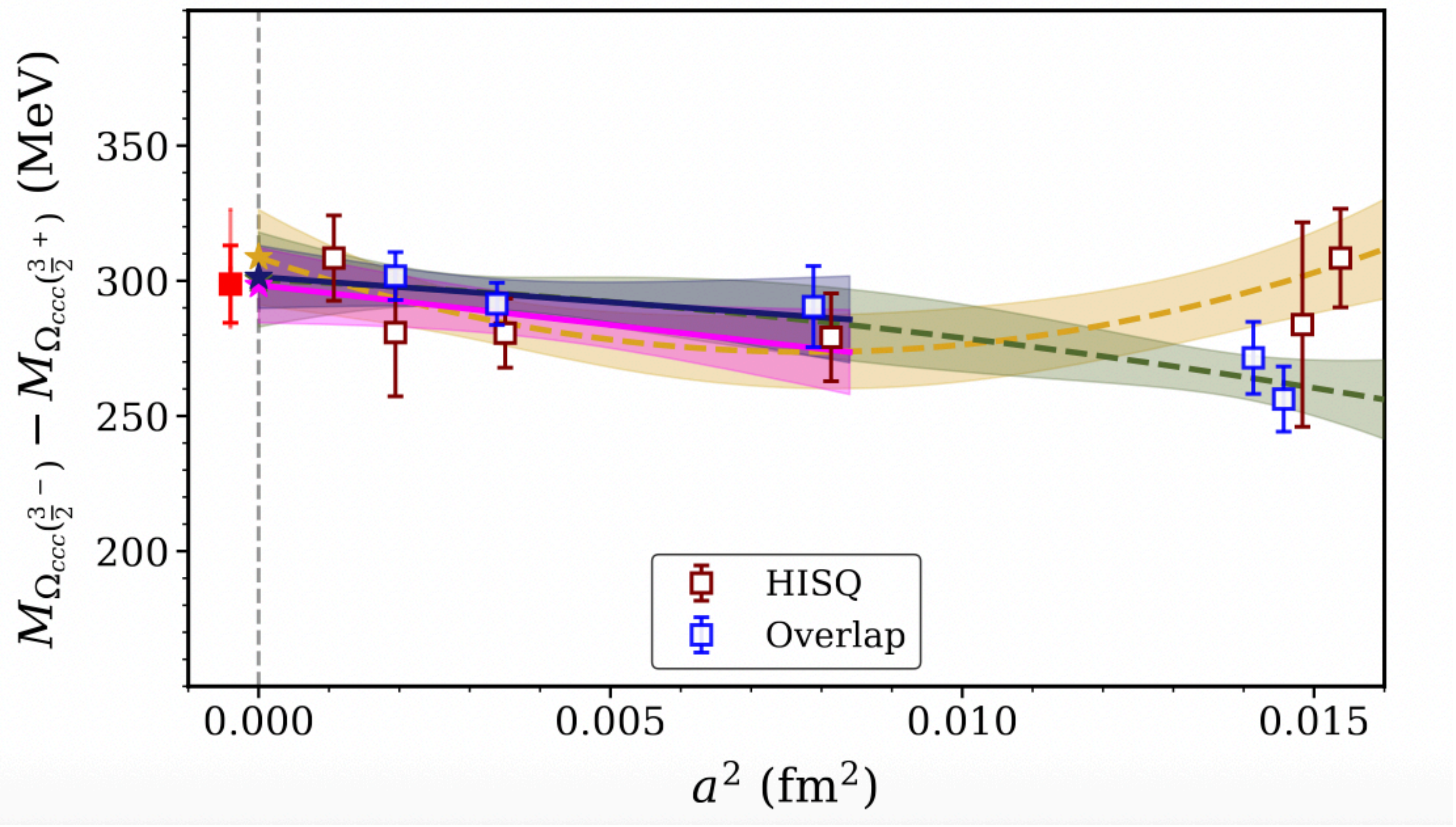


✦ Hyperfine Splitting number matches with experimental in the continuum.

✦ For HISQ data, tried other fitting forms which also gives consistent results.

$$f_3(a) = c_1 + c_2 a^2 + c_5 \alpha_s(1/a)(m_c a)^2$$

$$f_4(a) = c_1 + c_4 a^4 + c_5 \alpha_s(1/a)(m_c a)^2$$



✦ $\left(\frac{3}{2}\right)^-$ and $\left(\frac{3}{2}\right)^+$ splitting

ERROR BUDGET

$\left(\frac{3}{2}\right)^{+}$

- Statistical (bootstrap, fit windows) ≈ 5 MeV
- Discretization (different fit forms, different actions) ≈ 4 MeV
- Scale setting ≈ 3 MeV
- Charm quark mass tuning ≈ 2 MeV
- Unphysical sea quark mass (chiral extrapolation) ≈ 5 MeV
- Taste splitting (two tastes for Ω_{ccc}) ≈ 2 MeV
- Mixed action (Overlap) ≈ 2 MeV
- Finite size ≈ 1 MeV
- Electromagnetic correction (estimated perturbatively for both Ω_{ccc} and J/ψ) $\approx \binom{+7.8}{+0.0}$

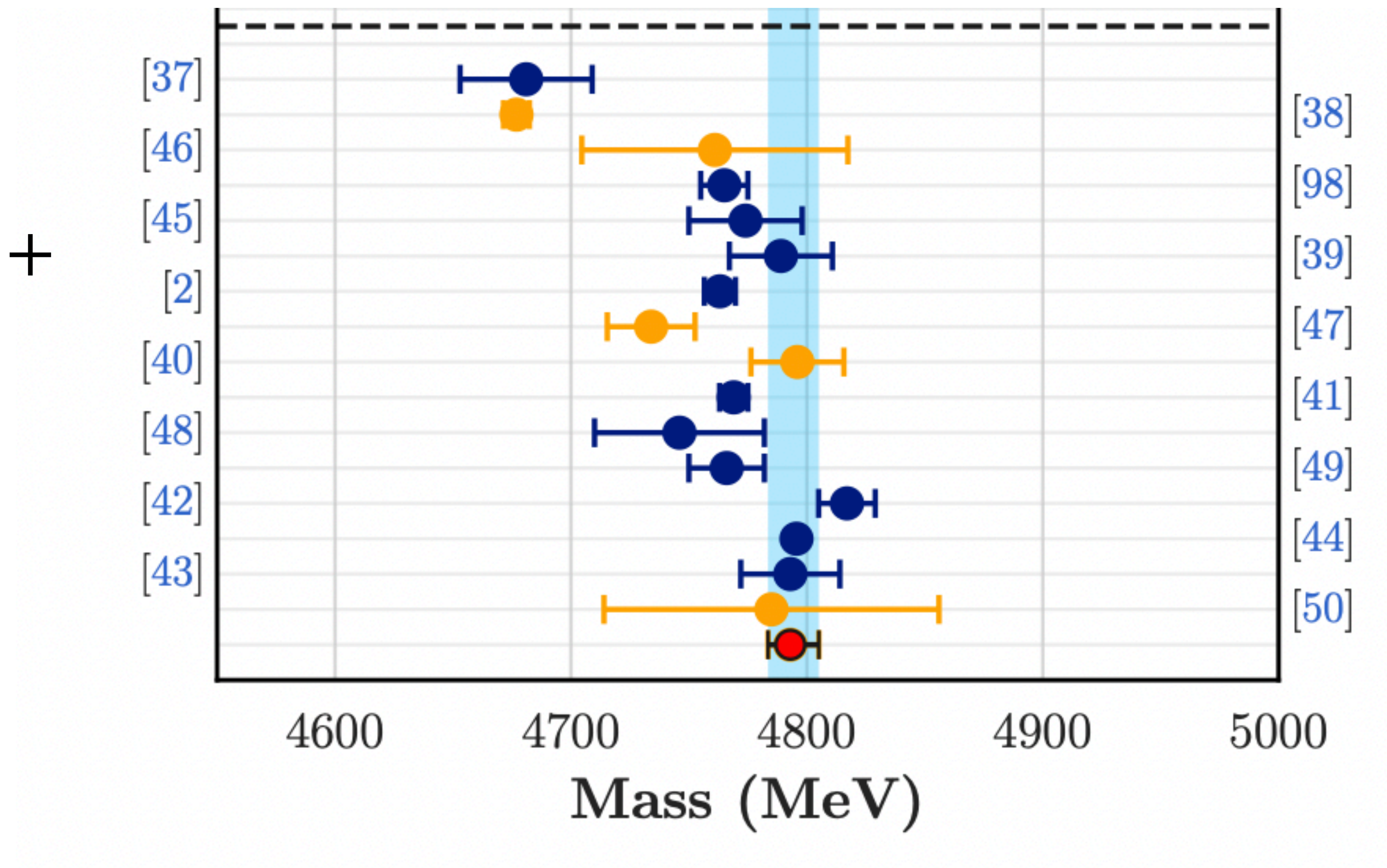
PRD **93** (2016) 094510
Bazavov et al.

Source	Error (MeV)
Statistical	5
Discretization	4
Scale setting	3
m_c tuning	2
unphysical sea-quark	5
Taste-splitting (HISQ)	2
Mixed action (Overlap)	2
Finite size	1
Electromagnetism	$^{+7.8}_{+0.0}$
Total	5 (stat) & $^{+11}_{-8}$ (syst)

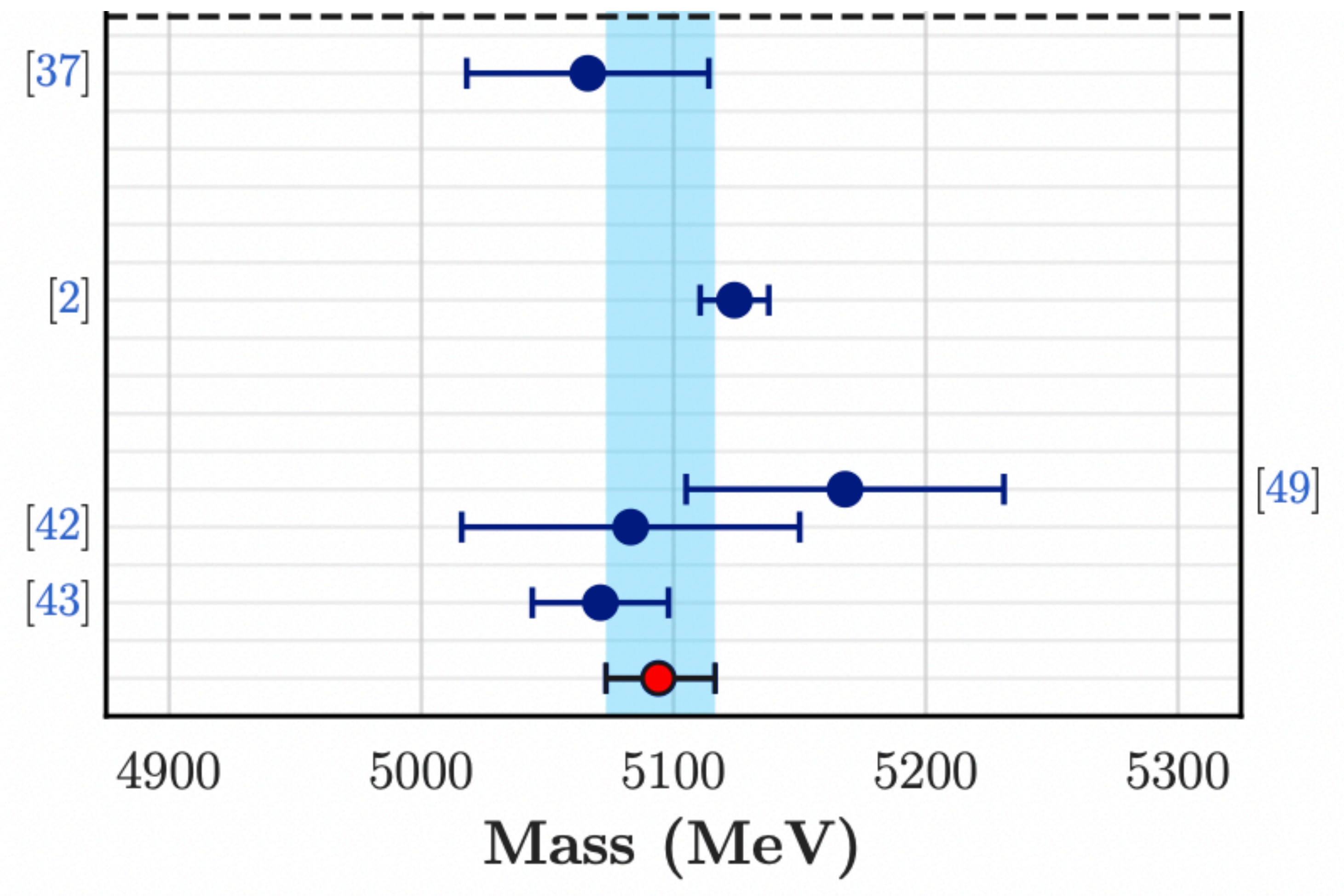
- Larger statistical and systematic (finite size) error in $\left(\frac{3}{2}\right)^{-}$

PRECISION ACHIEVED

$$\left(\frac{3}{2}\right)^{+}$$



$$\left(\frac{3}{2}\right)^{-}$$

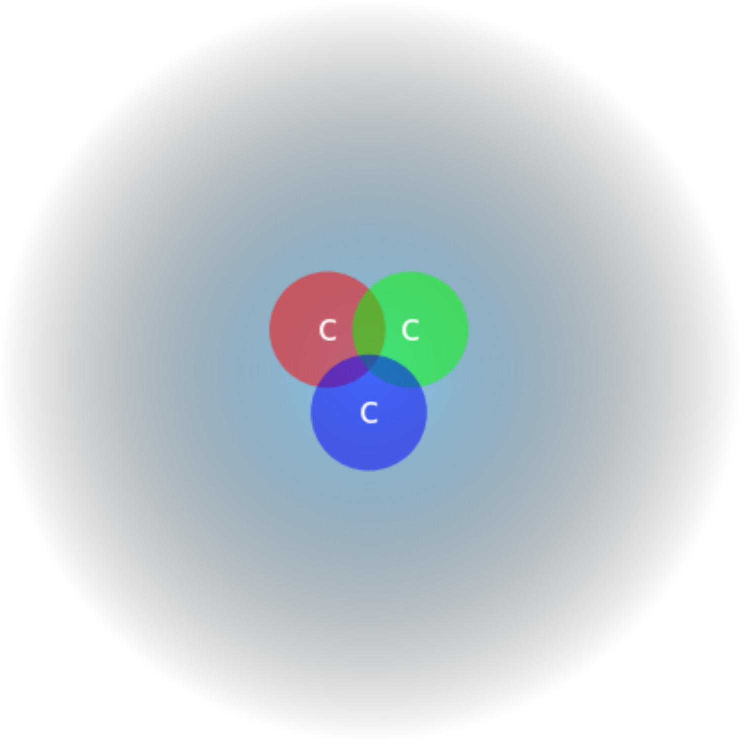


(Year)	N_f	$a(fm)$	m_π (MeV)	S_q^{sea}	S_c^{val}	Continuum Extrapolation
(2005)	quench	0.0882	-	Wilson	DW	**No**
(2012)	2,2+1	0.056-0.089	260-470	TM	OS	**Yes** (3)
(2012)	2+1+1	0.06-0.12	220-310	HISQ	RHQA	**Yes** (3)
(2012)	2+1+1	0.06-0.09	316-329	HISQ	Overlap	**No**
(2012)	2	0.0728	280	Clover	Brillouin	**No**
(2013)	2+1	0.0899	135	Clover	RHQA	**No**
(2013)	2+1	0.0351	390	Clover	Clover	**No**
(2014)	2+1+1	0.065-0.094	210-430	TM	OS	**Yes** (3)
(2014)	2+1	0.085-0.11	227-419	DW	RHQA	**Yes** (2)
(2015)	2+1	0.0907	156	Wilson	Clover	**No**
(2017)	2	0.0938	130	TM Clover	OS	**No**
(2017)	2+1+1	0.063	280	DW	DW	**No**
(2020)	2+1	0.0907	156	Clover	Clover	**No**
(2021)	2+1	0.0846	146	Clover	RHQA	**No**
(2022)	2+1	0.0711-0.0828	278-300	DW	Overlap	**No**
(2023)	2+1+1	0.057-0.080	137-141	TM Clover	OS	**Yes** (3)
This work	2+1+1	0.0327-0.1207	216-329 [2]	HISQ	HISQ, Overlap	**Yes** (5)

MOST ROBUST DETERMINATIONS OF THE Ω_{ccc} GROUND-STATE MASS

SUMMARY

- Most precise study of Ω_{ccc}, providing robust predictions for the ground-state mass.
- Controlled systematics using five lattice spacings and two valence actions (overlap and HISQ).
- Multiple fitting strategies for effective masses and varied continuum extrapolations to ensure reliability.
- Thorough error analysis to quantify statistical and systematic uncertainties.
- Sets a benchmark for future experimental searches.



THANK YOU

Lattice 2025

MUMBAI

Navdeep Singh Dhindsa

03/11/25