

Hadron Spectroscopy with Lattice QCD: From Two Quarks to Six Quarks

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11/08/26 | Talk at IISER Mohali

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Collaborators



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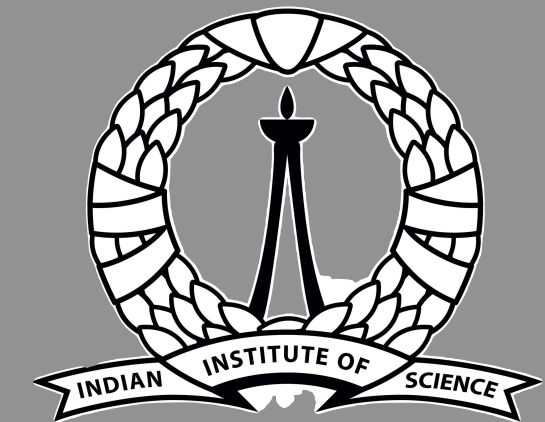
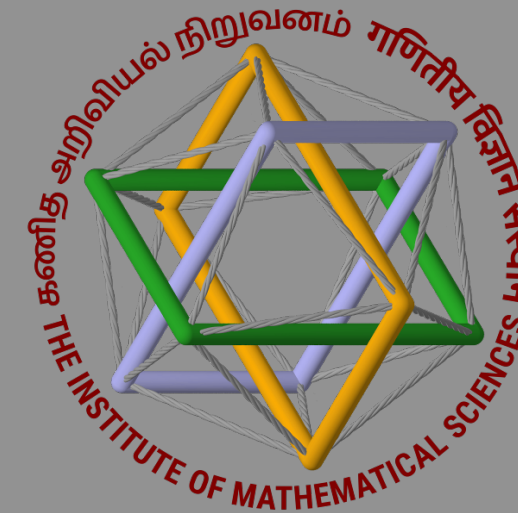
Debsubhra
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BASED ON:

POS LATTICE2024 (2025) 082, PHYS.REV.D 112 (2025) L111501, PHYS.REV.D 112 (2025) 054501,
POS LATTICE2025 (2026) 069, ARXIV:2609:ABCDE, POS LATTICE2026 (2026) ABC



So... Is Lattice QCD Interesting?

► Apparently, there's someone at Empire State University who knows a thing or two about this

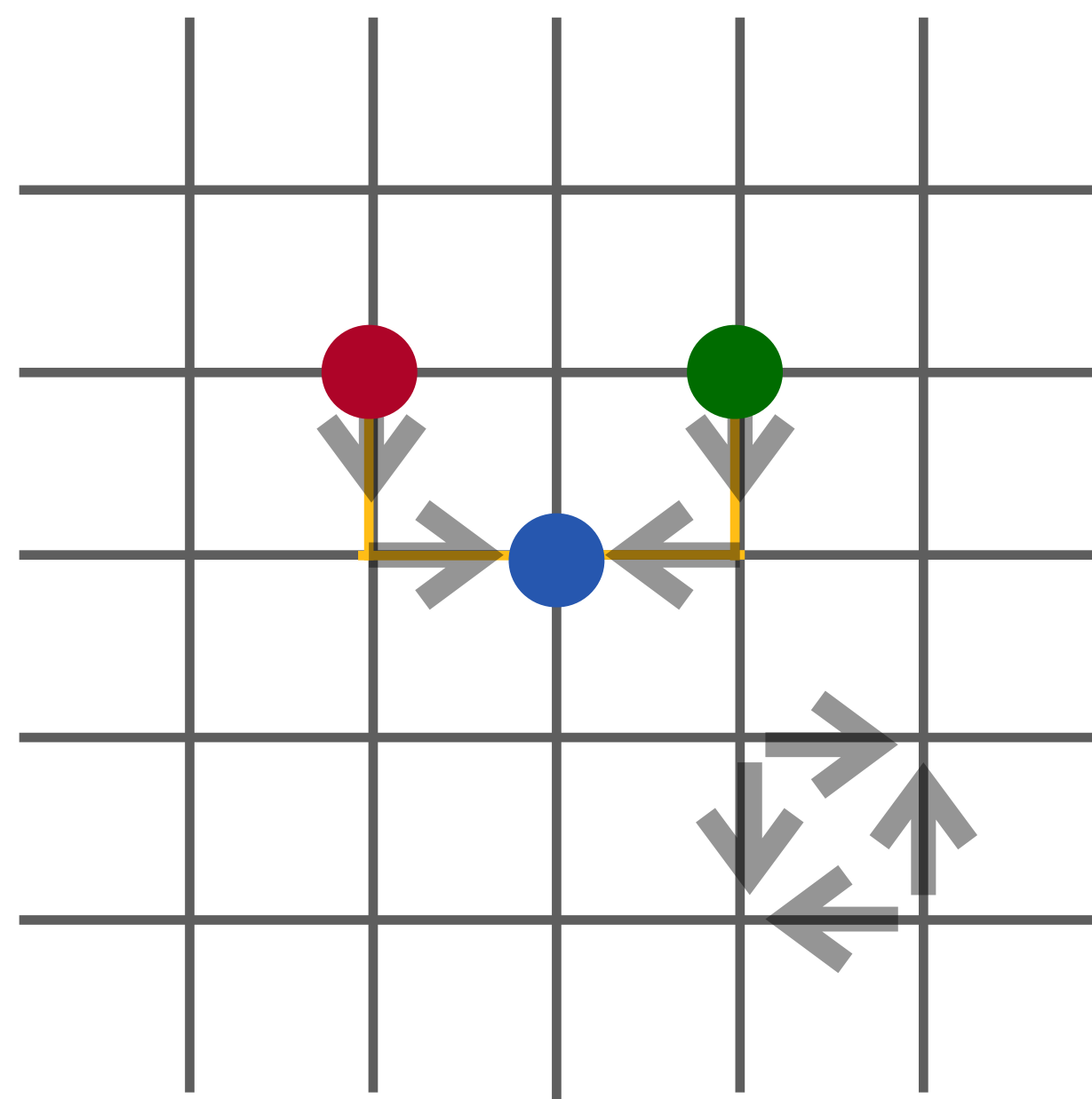


So... Is Lattice QCD Interesting?

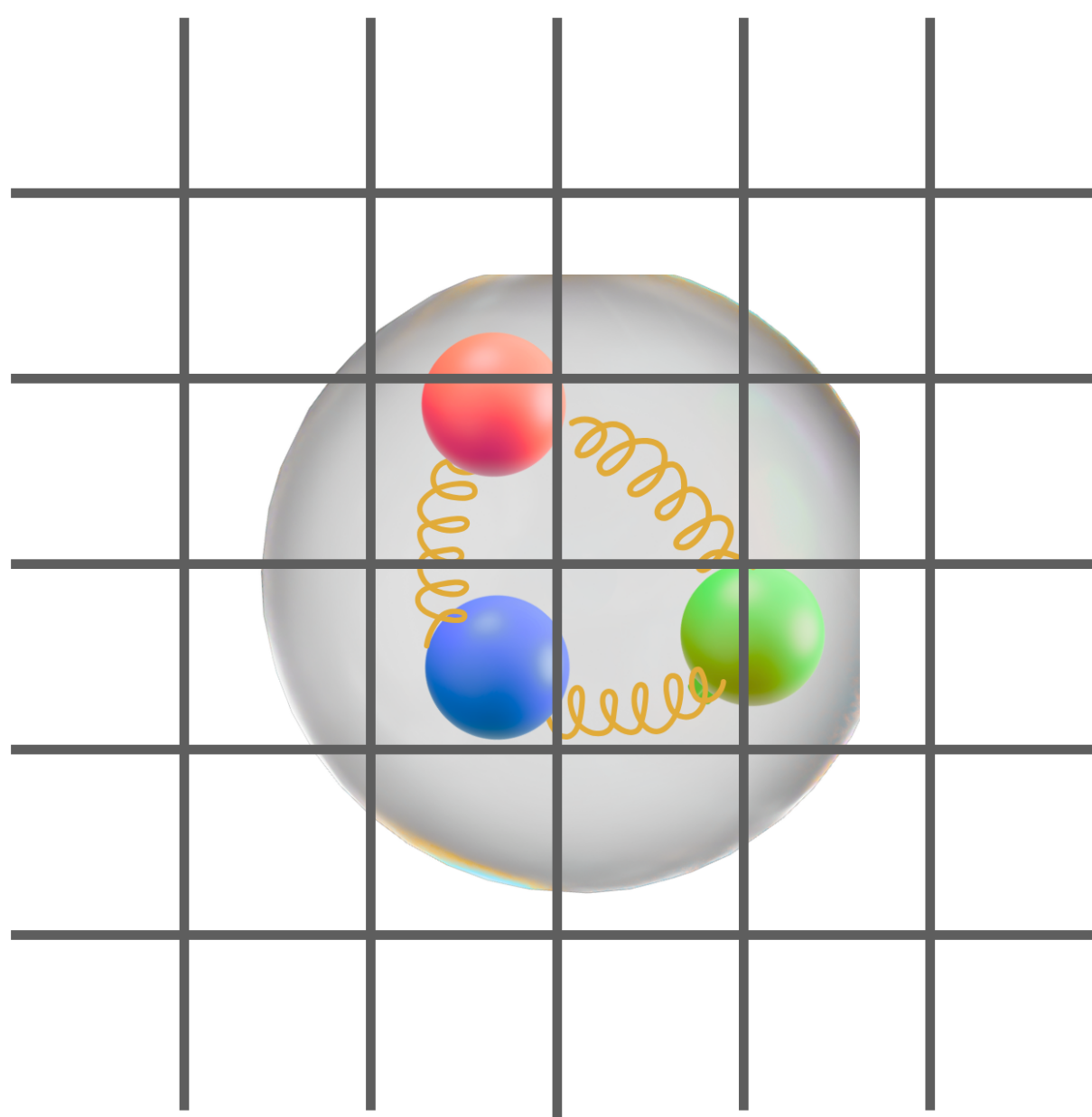




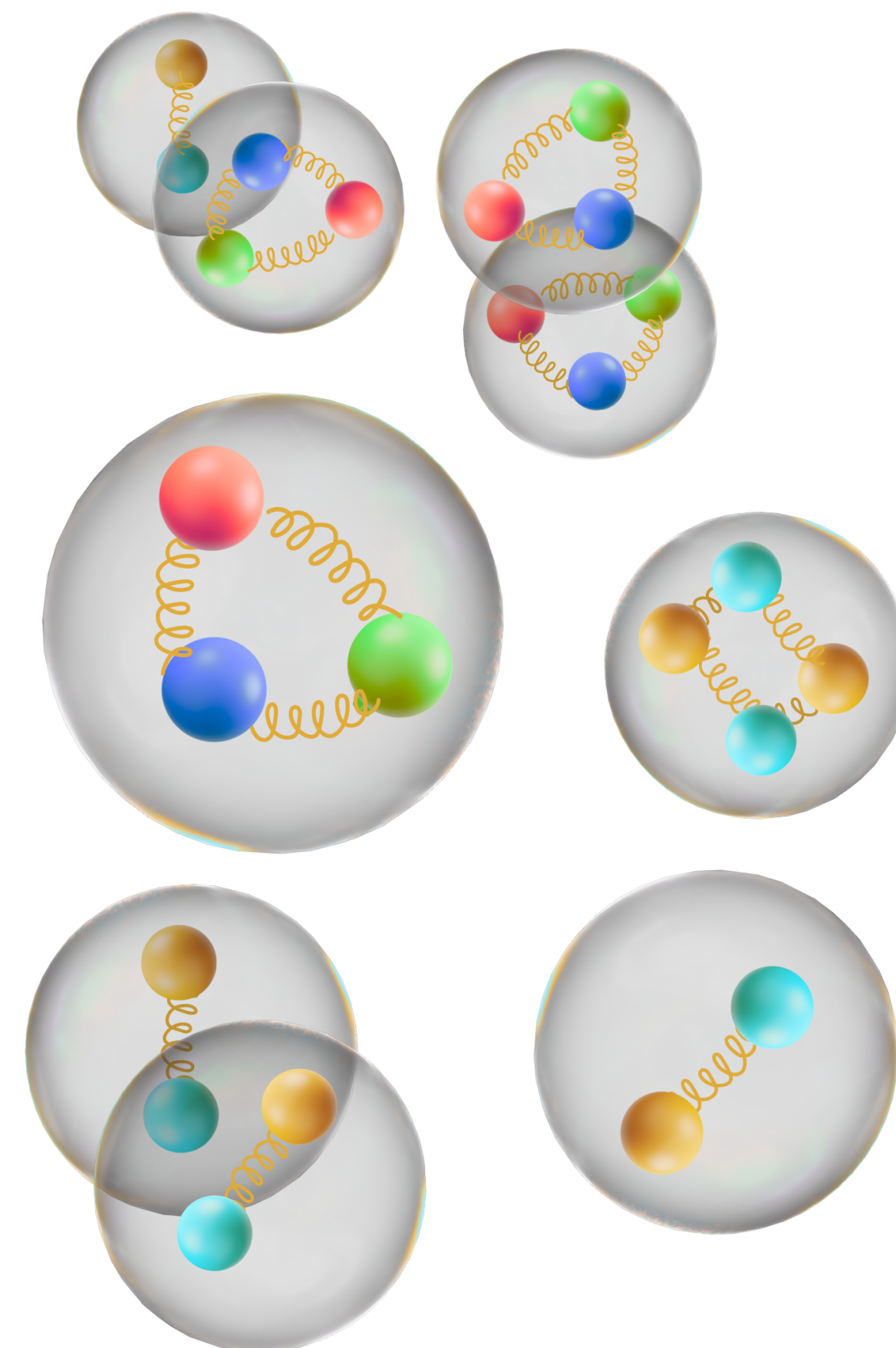
Outline



Lattice QCD



*Hadron Spectroscopy
using Lattice*



*For various
Hadrons*

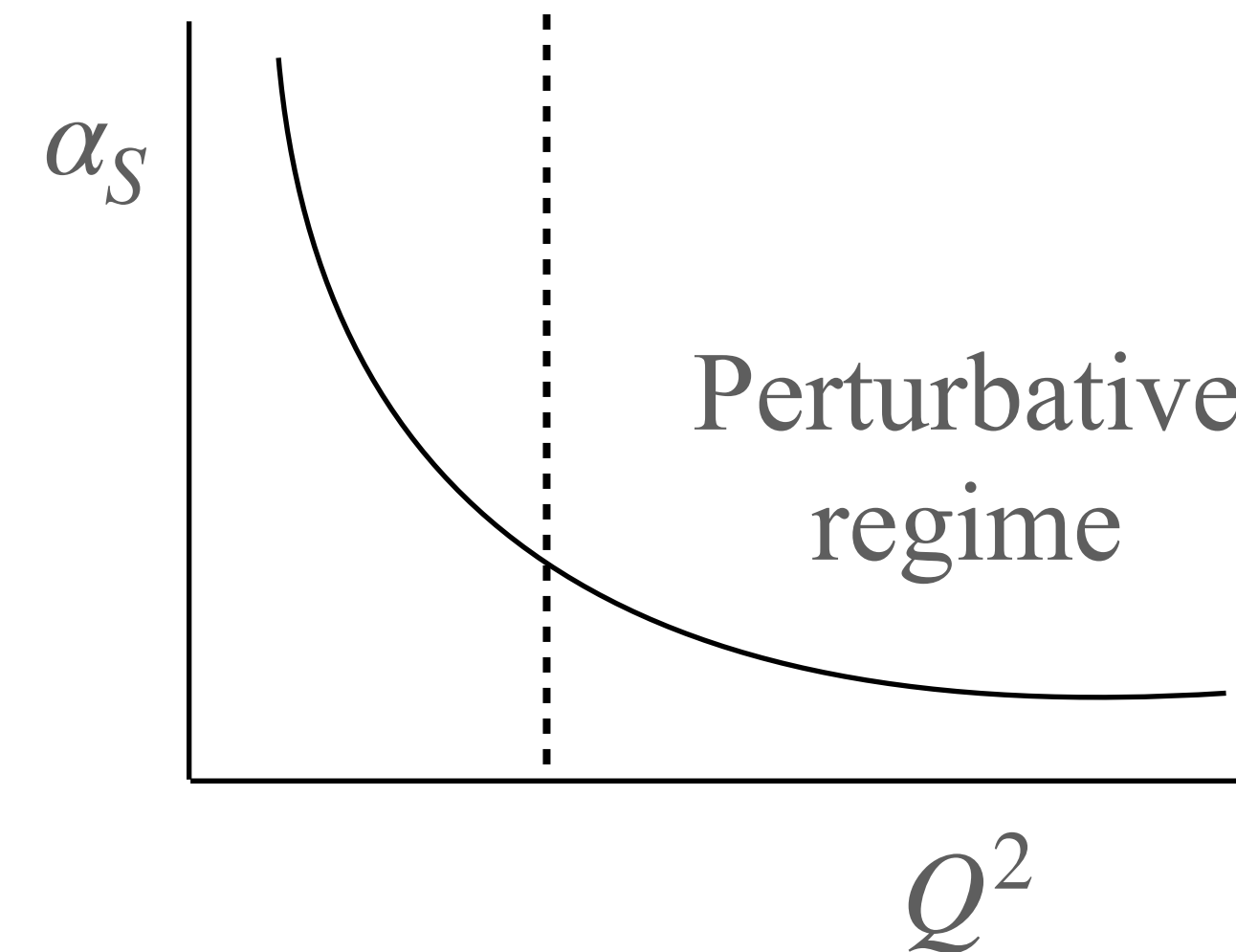
Lattice QCD: **Why?**



■ QCD: theory of strong interactions formulated in terms of quarks and gluons

- ▶ Perturbation theory at higher energies
- ▶ Quark confinement and hadronic d.o.f. at lower energies

Need for non-perturbative approach



Lattice QCD is the first-principles approach for QCD

Only approach where calculations can be made in a manner to achieve complete control over statistical and systematic uncertainties

Lattice QCD: **How?**



Continuum quantum field theory, observables are computed using the path integral formalism. For example, the expectation value of some operator $\mathcal{O}$ is

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}A_\mu \mathcal{D}\psi \mathcal{D}\bar{\psi} \mathcal{O}[A, \psi, \bar{\psi}] e^{iS[A, \psi, \bar{\psi}]}$$

Highly Oscillating

where

$$Z = \int \mathcal{D}A_\mu \mathcal{D}\psi \mathcal{D}\bar{\psi} e^{iS[A, \psi, \bar{\psi}]}$$

Wick rotate $t \rightarrow -i\tau$, to get Euclidean version

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}A_\mu \mathcal{D}\psi \mathcal{D}\bar{\psi} \mathcal{O}[A, \psi, \bar{\psi}] e^{-S_E[A, \psi, \bar{\psi}]}$$

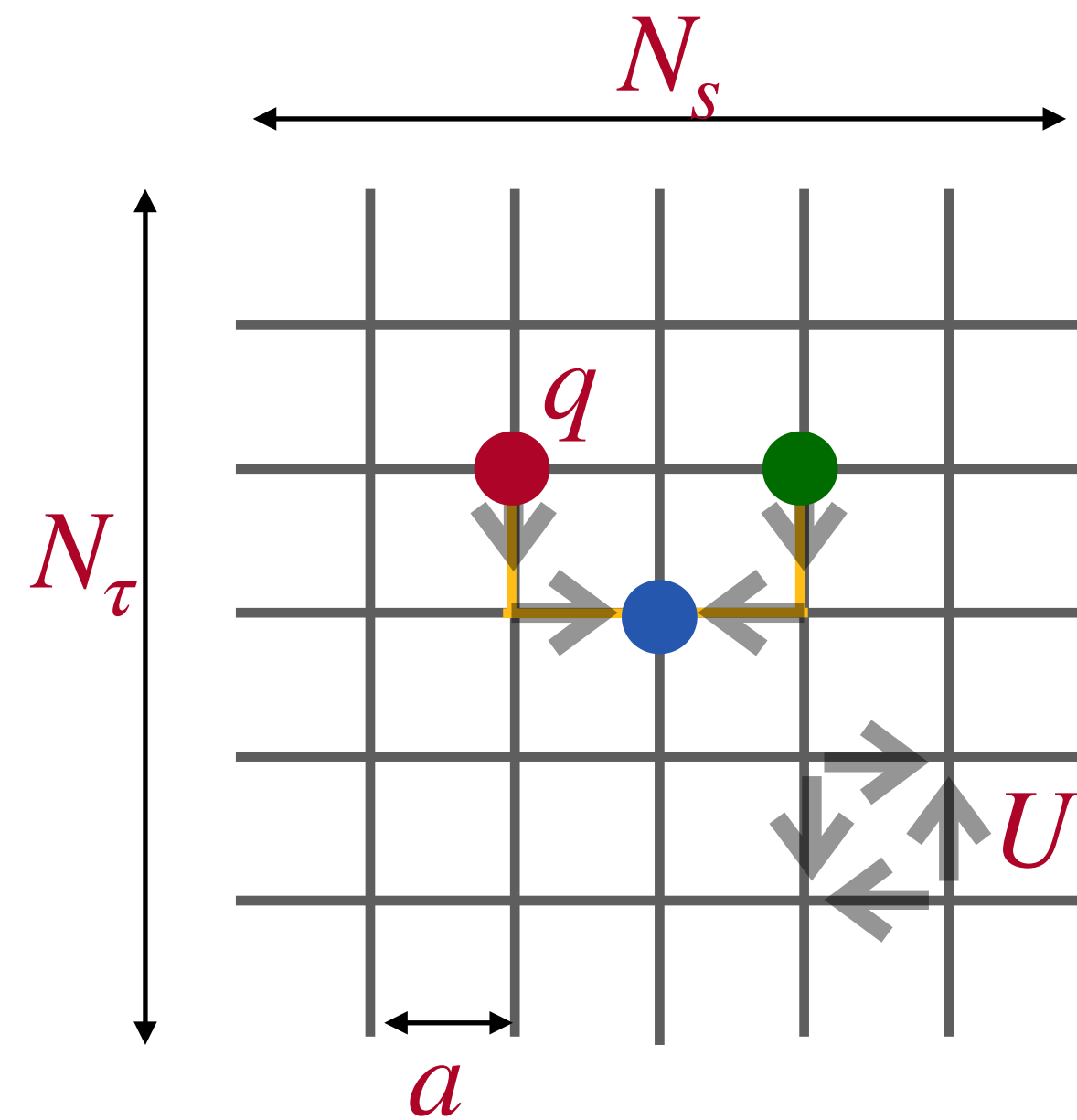
Lattice QCD: How?



► In lattice QCD, we replace continuous spacetime with a discrete 4D Euclidean grid

► Quarks live on the sites

► Gauge fields associated with links



■ Lattice spacing 'a'

Three key parameters

■ Lattice volume $V = N_s^3 \times N_\tau$

■ Pion Mass (simulate at heavier pion mass)

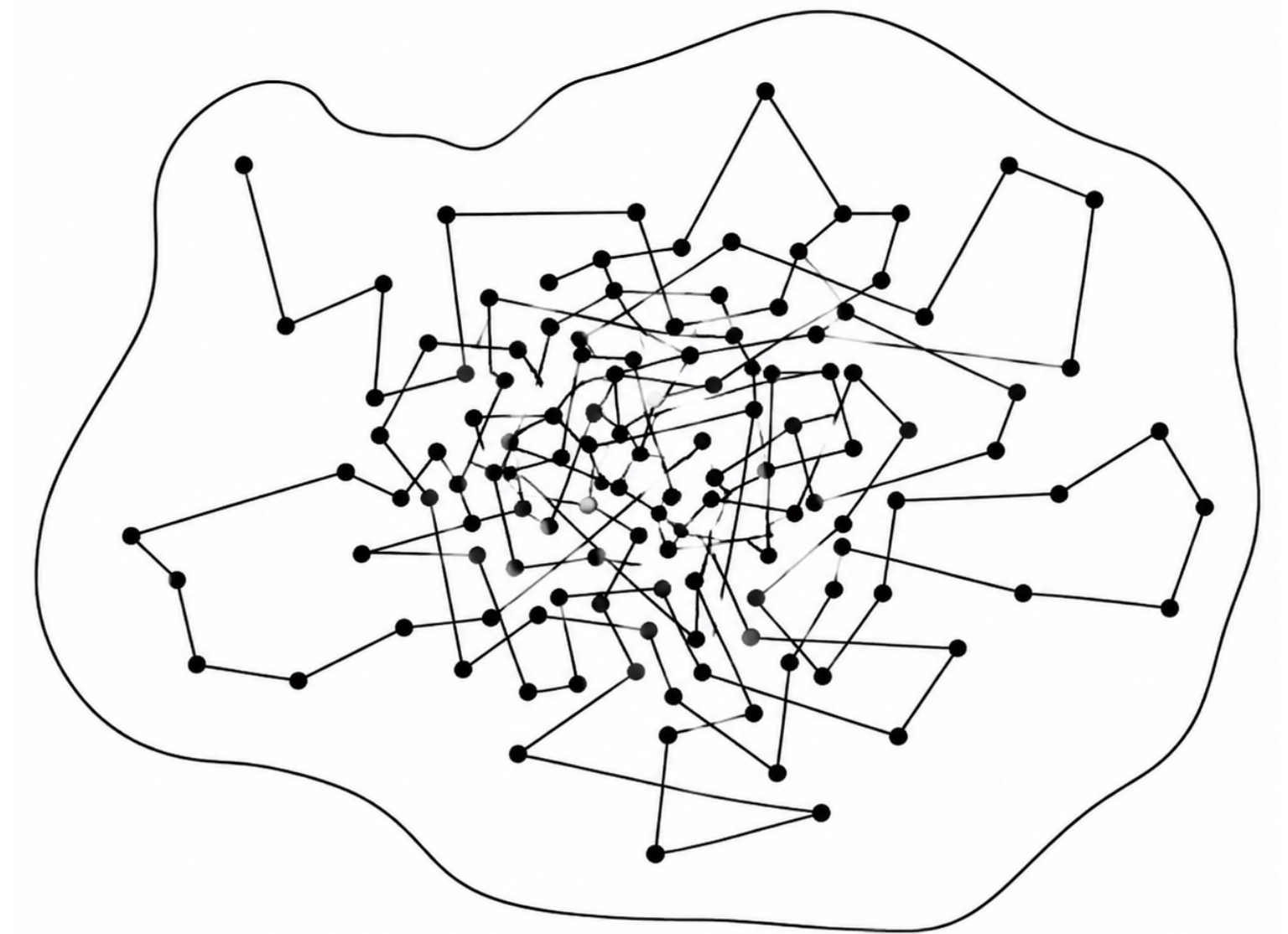
Lattice QCD: How?



Using our lattice action, we can numerically generate a set of gauge field configurations using importance sampling, typically with Markov Chain Monte Carlo methods

■ Each configuration represents a possible QCD vacuum state with gluon fluctuations

■ Once we have an ensemble of such configurations, we can compute expectation values of observables by averaging over the ensemble



$$U_1, U_2, \dots, U_{N_{\text{cfg}}} \implies \langle \mathcal{O} \rangle = \frac{1}{N_{\text{cfg}}} \sum_{i=1}^{N_{\text{cfg}}} \mathcal{O}[U_i]$$

Lattice QCD: **What can be done?**



Finite Temperature QCD

Precision QCD

Hadron Spectroscopy

Lattice 2026 presentation data

■ QCD phase transition

■ Equation of state

■ Quark-gluon plasma

□ Hadronic contribution
to $g-2$

□ Matrix elements

□ Decay constants

▶ Ground and excited states

▶ Resonance

▶ Exotics

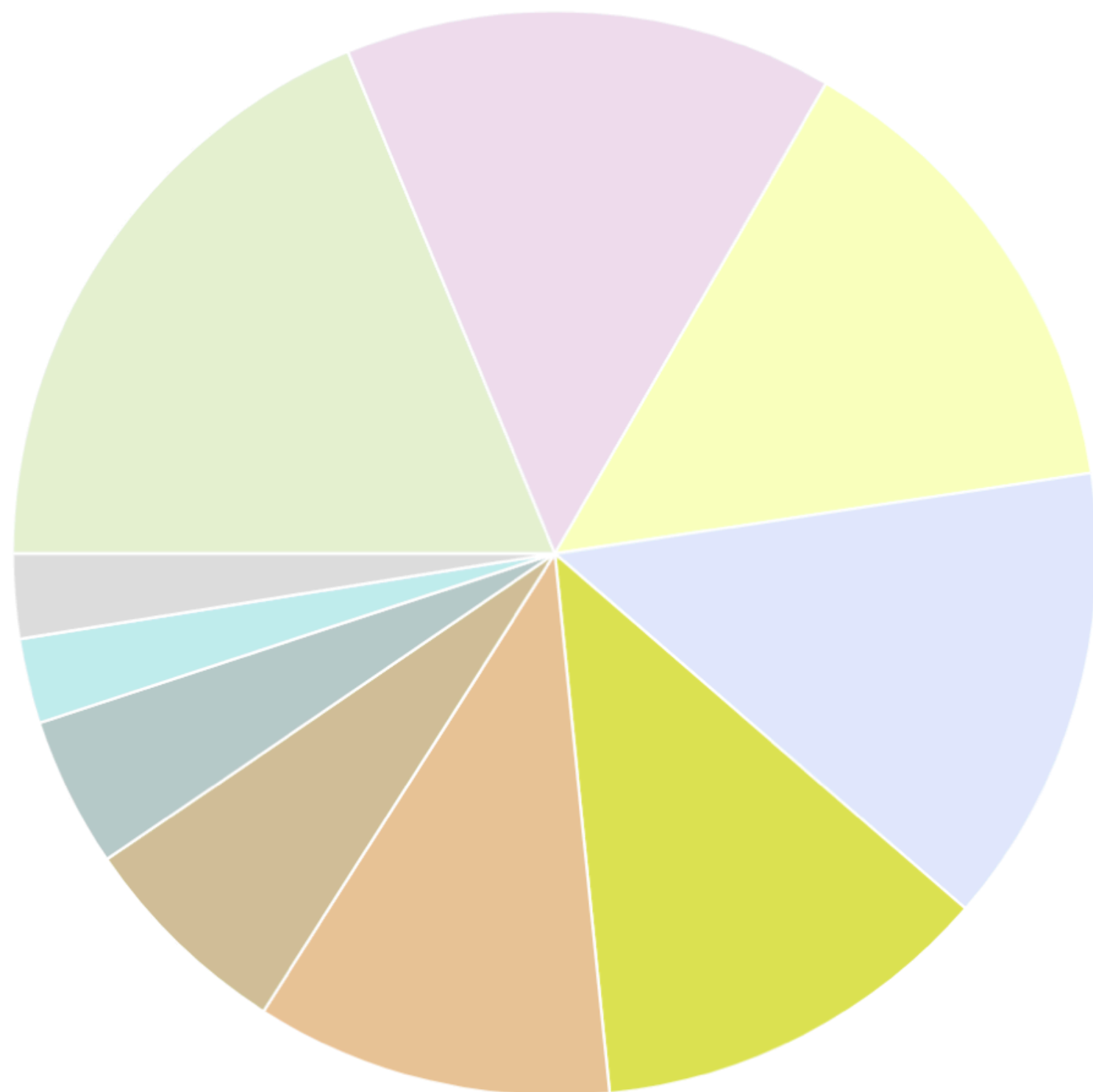
Lattice QCD: **What can be done?**



...and the program spans 10 scientific tracks:

Lattice 2026 presentation data

Q
Ec
Q



- Hadronic/nuclear — 67 • 18.8%
- Algorithms/AI — 52 • 14.6%
- Hadrons/nuclei structure — 51 • 14.3%
- Flavor — 49 • 13.7%
- Quantum/QI — 43 • 12.0%
- Theory BSM — 38 • 10.6%
- QCD T/μ — 23 • 6.4%
- Software/machines — 16 • 4.5%
- SM parameters — 9 • 2.5%
- Vacuum/confinement — 9 • 2.5%

ed states

Lattice QCD: **What we skip?**



- ▶ Fermion discretisation
- ▶ Fermion doubling
- ▶ Sign problem
- ▶ New approaches like Langevin, tensor networks
- ▶ Inverting large sparse matrices
- ▶ RHMC
- ▶ Critical slowing down
- ▶ Softwares MILC, Chroma, Grid..
- ▶ Scattering amplitudes
- ▶ Disconnected diagrams
- ▶ Substantial Computational Resources
- ▶

Correlation functions

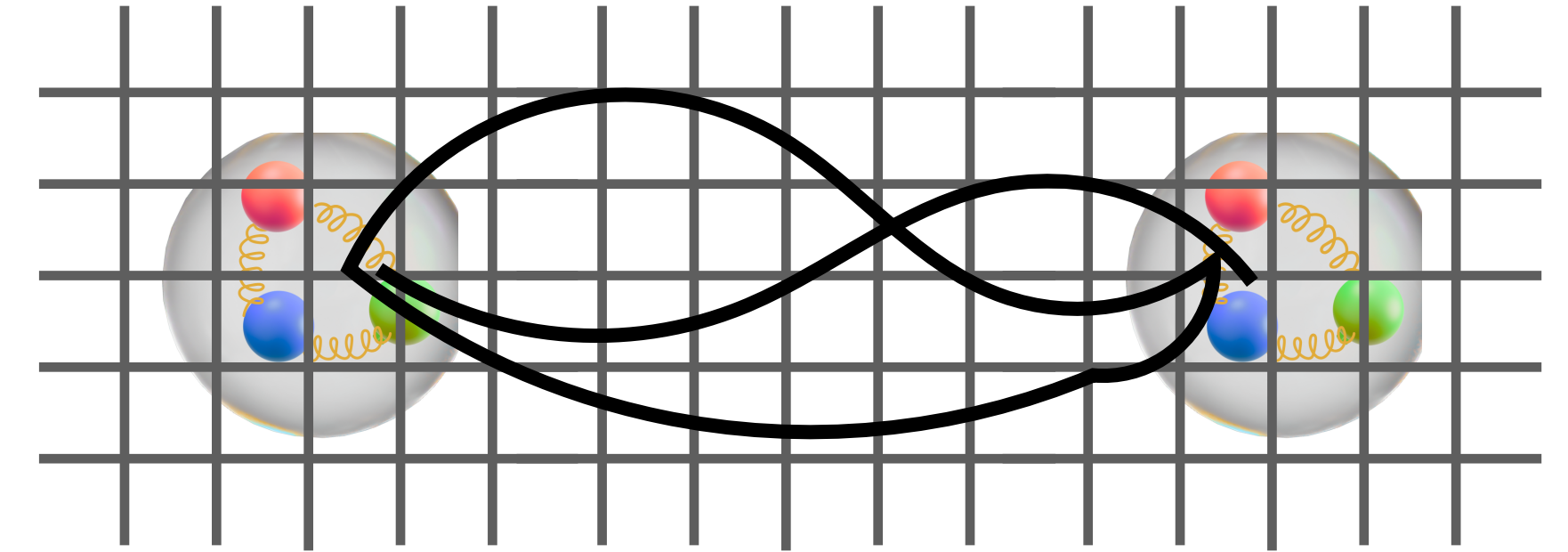


Extracting ground and excited
states

Hadron Spectroscopy: **Contraction**



- ▶ First construct an interpolating operator with the same quantum numbers as the state I'm interested in
- ▶ Create quarks at source and annihilate at sink



- Calculating the quark propagators $G(x, t; y, 0) = M^{-1}(x, t; y, 0)$
- Performing all the required Wick contractions to construct the hadron correlator

$$C(t) = \langle \mathcal{O}(t) \mathcal{O}^\dagger(0) \rangle$$

- ▶ The correlator contains the information about the spectrum. Using the spectral decomposition

$$C(t) = \sum_n |Z_n|^2 e^{-E_n t}$$

Hadron Spectroscopy: **Example**



Let us take an example of pseudoscalar B_c meson, $\mathcal{O}_{B_c}(x) = \bar{b}(x)\gamma_5 c(x)$

$$C_{B_c}(t) = \left\langle \mathcal{O}_{B_c}(t) \mathcal{O}_{B_c}^\dagger(0) \right\rangle$$

Only wick contractions

$$C_{B_c}(t) = \left\langle [\bar{b}\gamma_5 c](x) [\bar{c}\gamma_5 b](0) \right\rangle$$

$$c(x) \longleftrightarrow \bar{c}(0), \quad b(0) \longleftrightarrow \bar{b}(x)$$

$$G_c(x,0) = M_c^{-1}(x,0) \quad G_b(0,x) = M_b^{-1}(0,x)$$

$$C_{B_c}(t) = \sum_{\vec{x}} \left\langle \text{Tr} \left[\gamma_5 G_c(x, t; 0) \gamma_5 G_b(0; x, t) \right] \right\rangle$$

All-to-all propagators: $G(x, t; y, 0) \quad \forall \vec{x}, \vec{y}$ are prohibitively expensive

We instead use different source/sink constructions to access the required contractions

Hadron Spectroscopy: Effective Mass



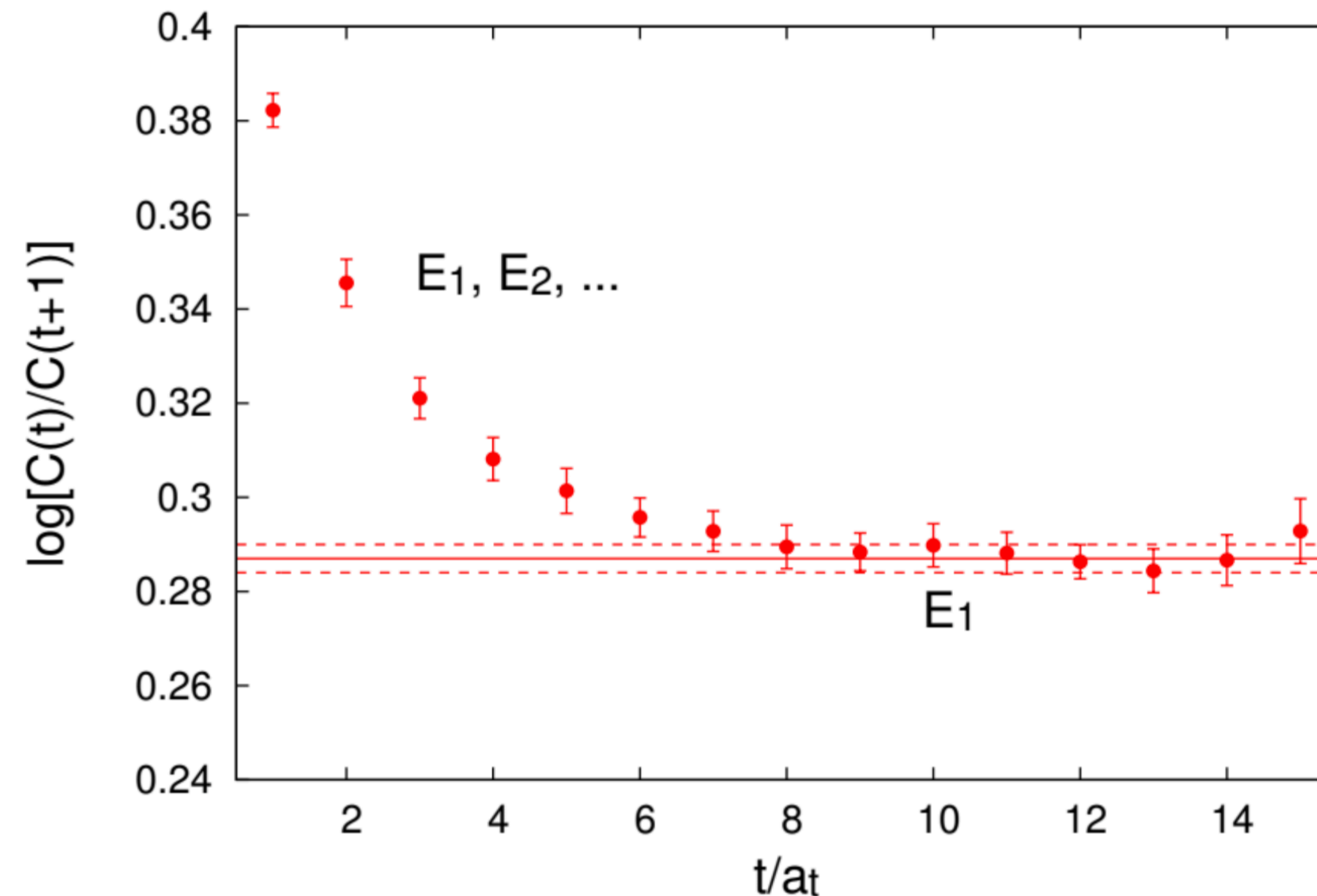
$$C(t) = \sum_n |Z_n|^2 e^{-E_n t}$$

At sufficiently large Euclidean time, the ground state dominates

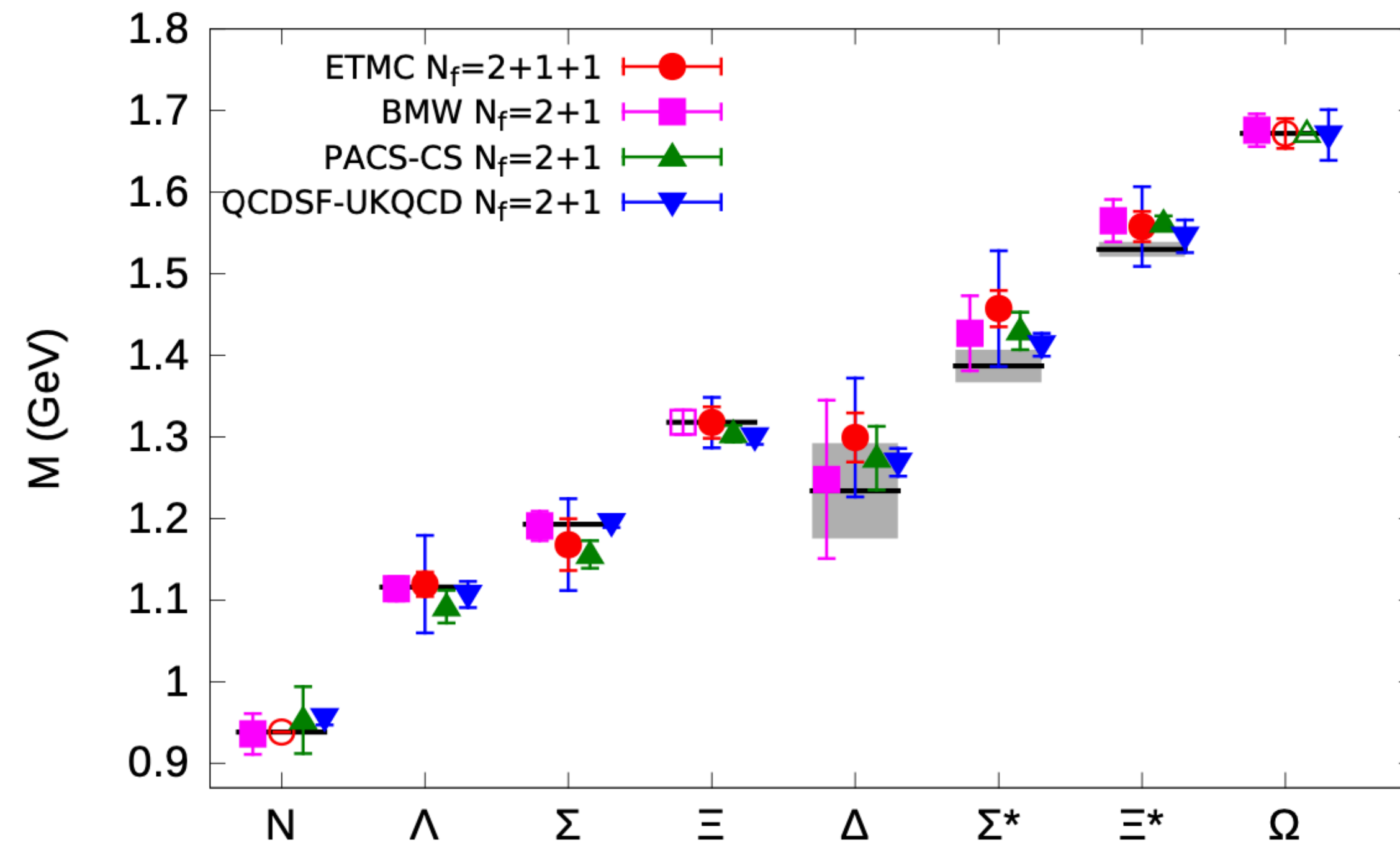
$$C(t) \xrightarrow{t \rightarrow \infty} |Z_0|^2 e^{-E_0 t}$$

Define the effective mass

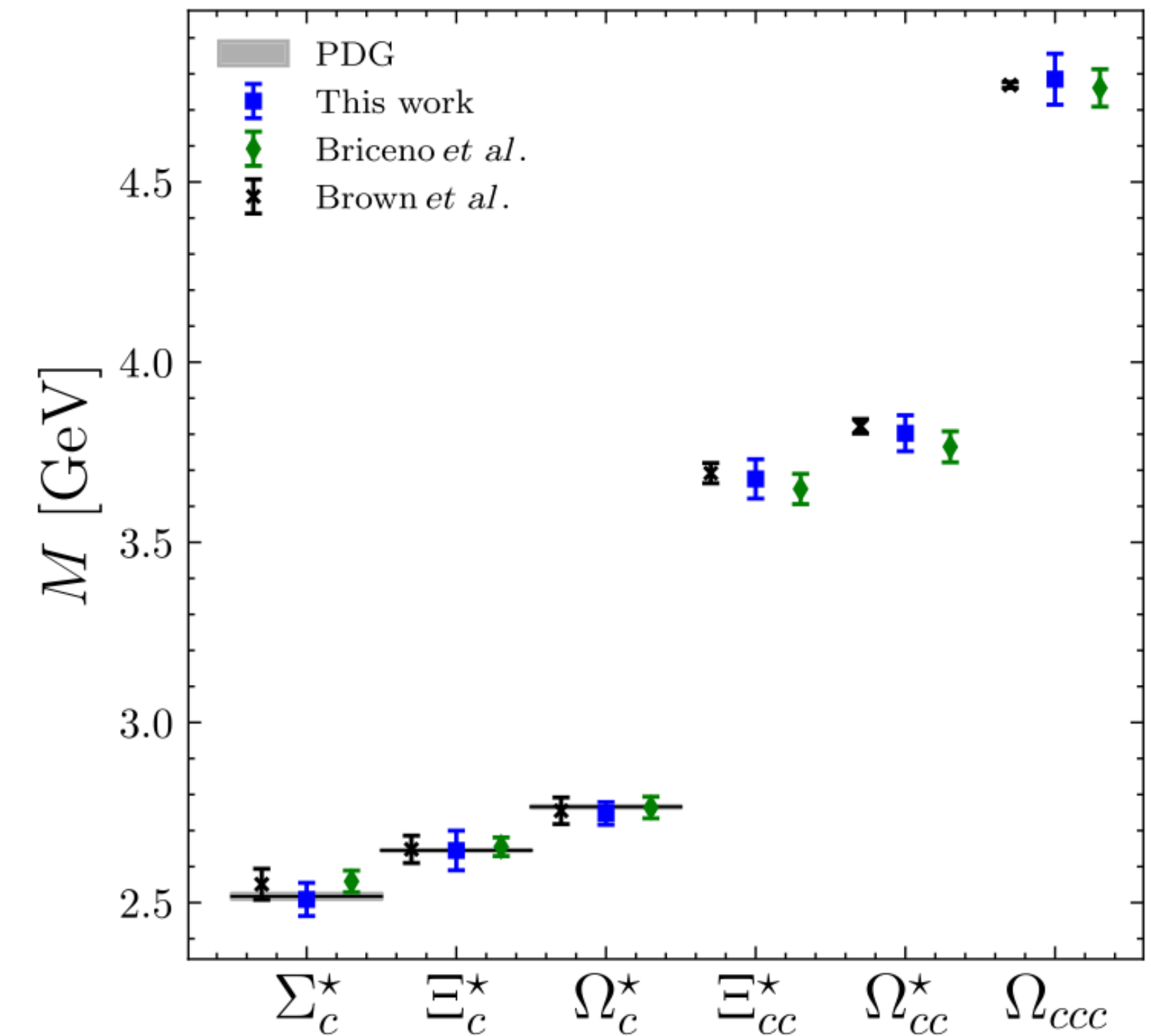
$$m_{\text{eff}}(t) = \frac{1}{d} \ln \left[\frac{C(t)}{C(t+d)} \right]$$



Hadron Spectroscopy: **Lattice** - state of the art

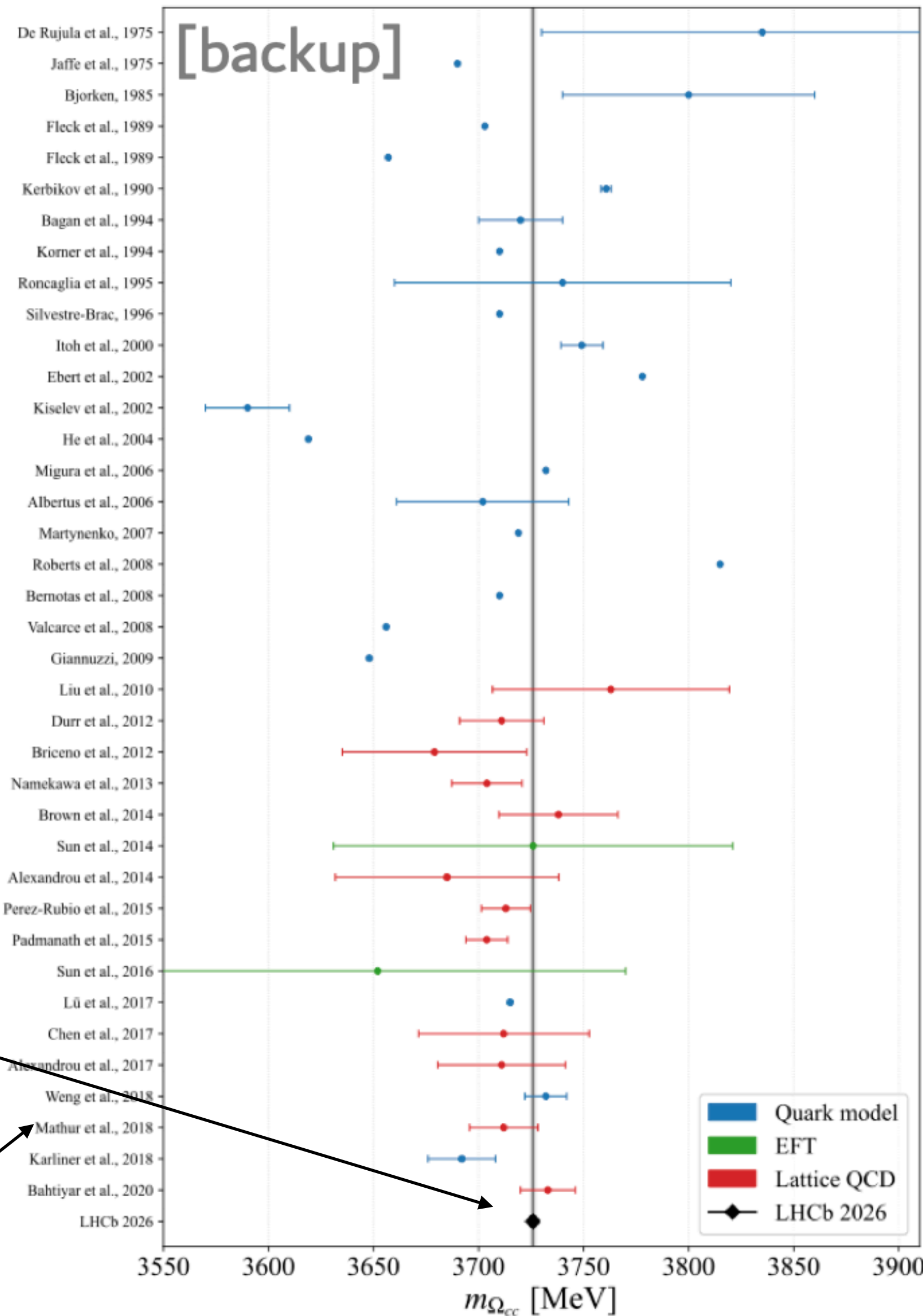
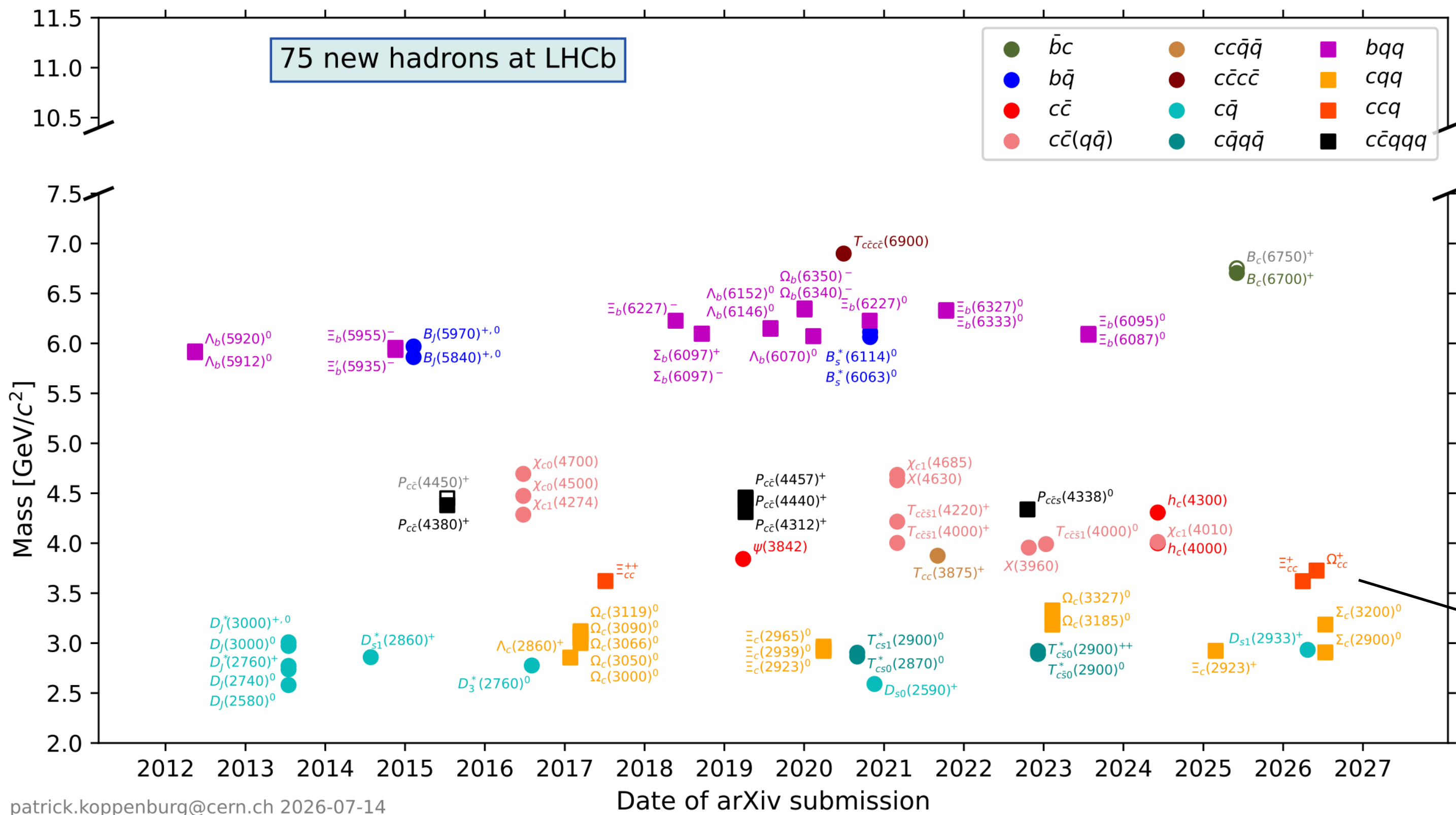


Alexandrou, Drach, Jansen, Kallidonis, Koutsou
PRD 90, 074501 (2014)



Alexandrou, Bacchio, Christou, Finkenrath
PRD 108, 094510 (2023)

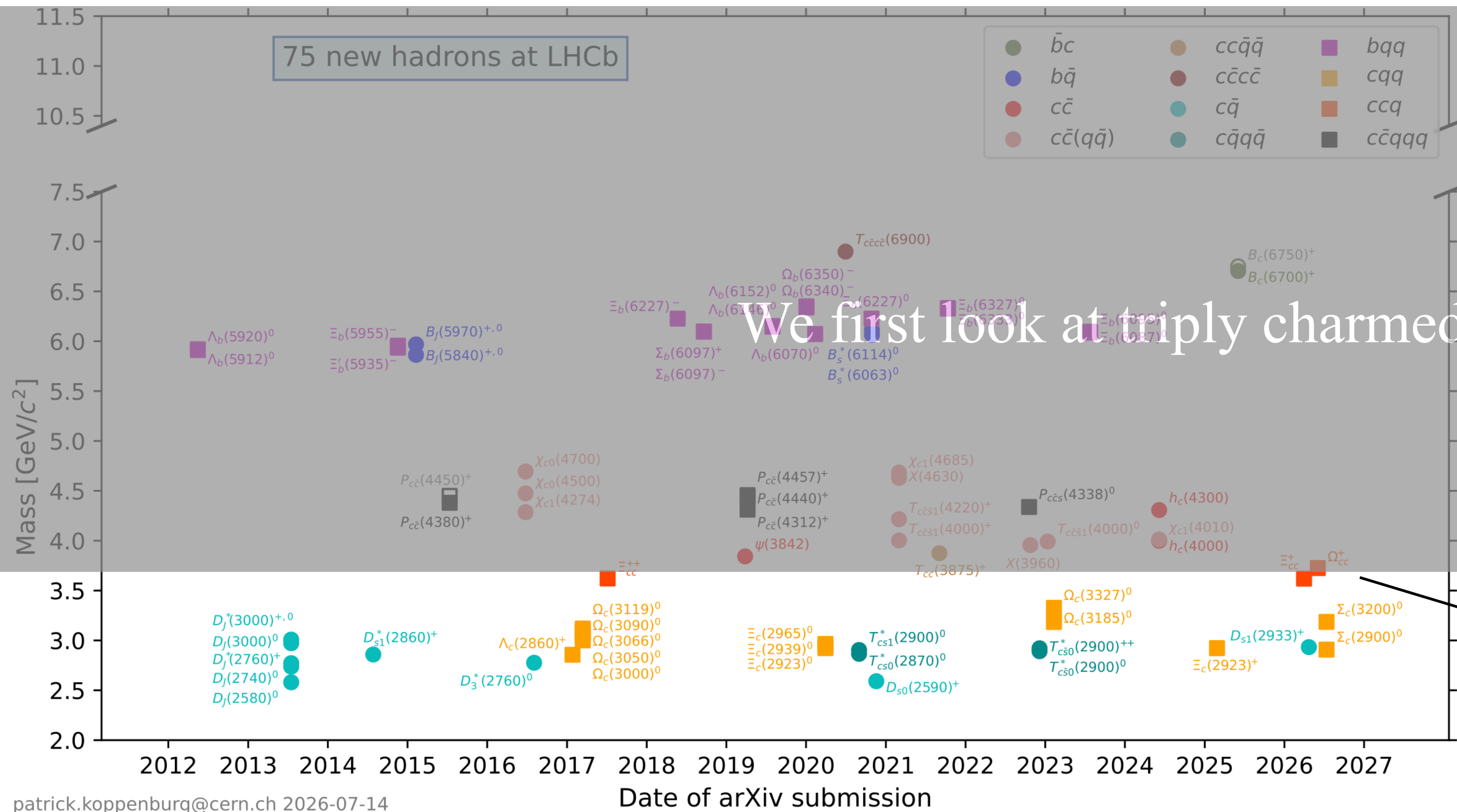
Hadron Spectroscopy: LHCb



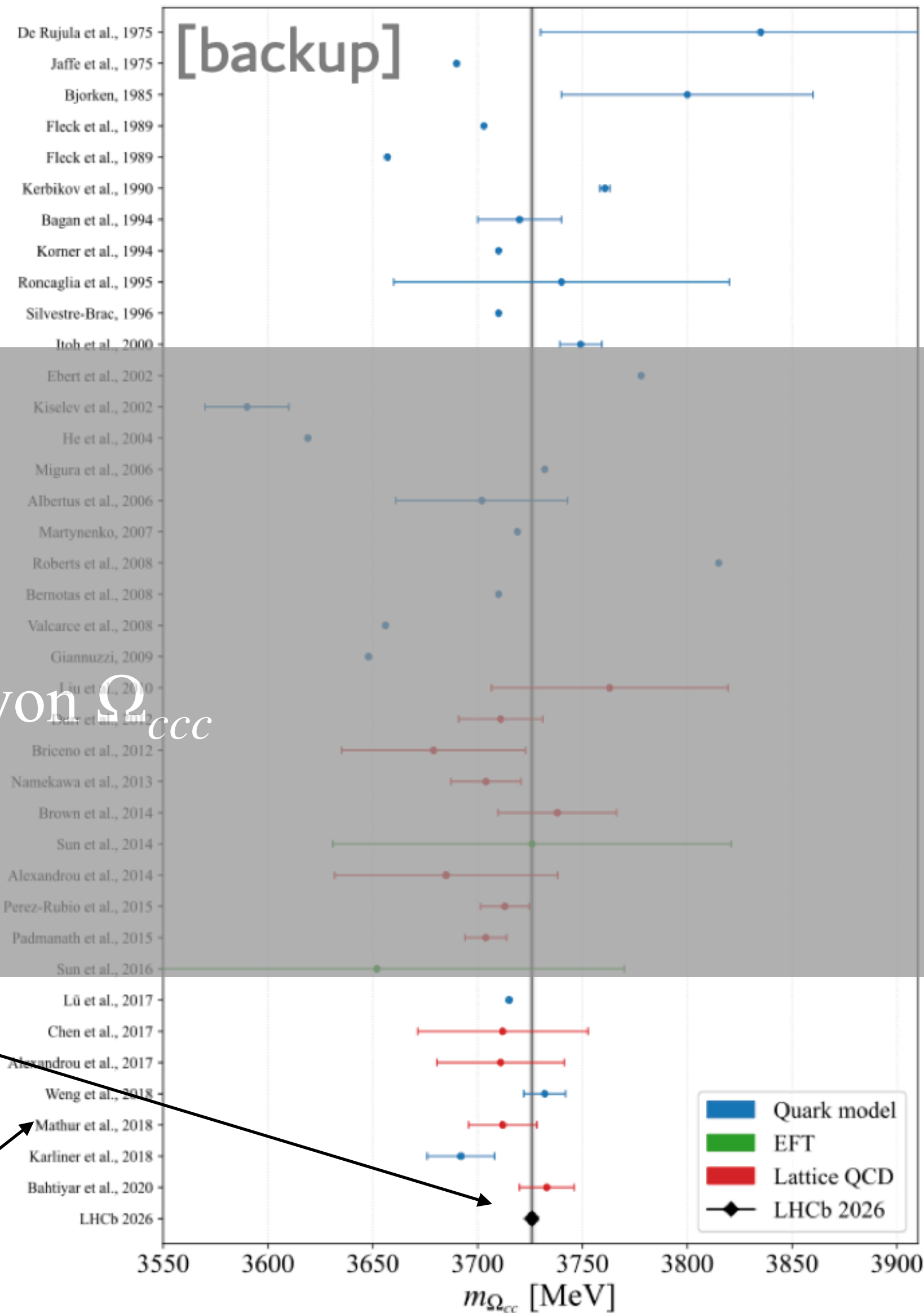
Mathur and Padmanath
(TIFR)

From Yuhao Wang talk
@ Beauty 2026

Hadron Spectroscopy: LHCb



We first look at triply charmed baryon Ω_{ccc}



Mathur and Padmanath
(TIFR)

From Yuhao Wang talk
@ Beauty 2026



Ω_{ccc} : Experimentally relevant!

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

Ω_{ccc} : Experimentally relevant!

NSD, CHAKRABORTY, RADHAKRISHNAN, MATHUR, PADMANATH
PRD 112 (2025) 11, L111501



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 charmed baryon Ω_{ccc}^{++} is explored. The conclusion is that it is 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

■ 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.

■ $\Omega_{ccc} \rightarrow$ clean system to study quark-quark interactions and confinement, free from light-quark complications.

► Even with heavy quarks constituents

⌘ phenomenological models predictions are spread over 400 MeV.

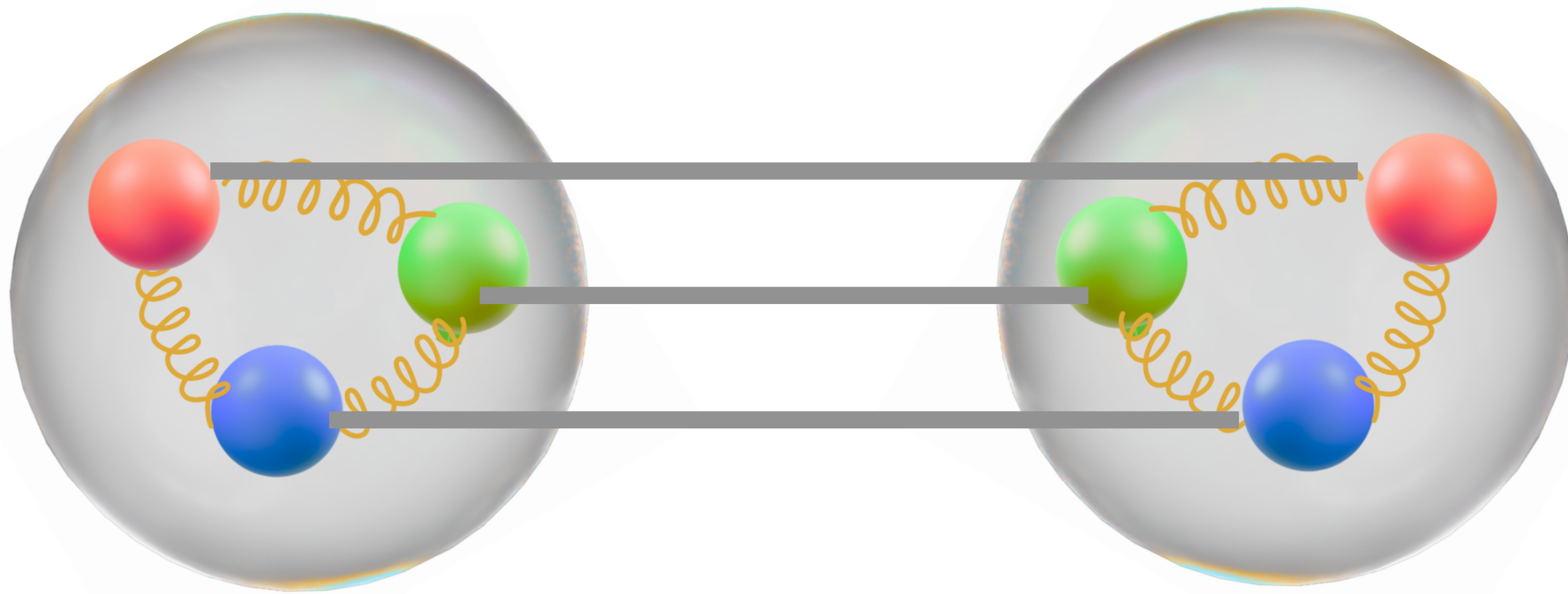
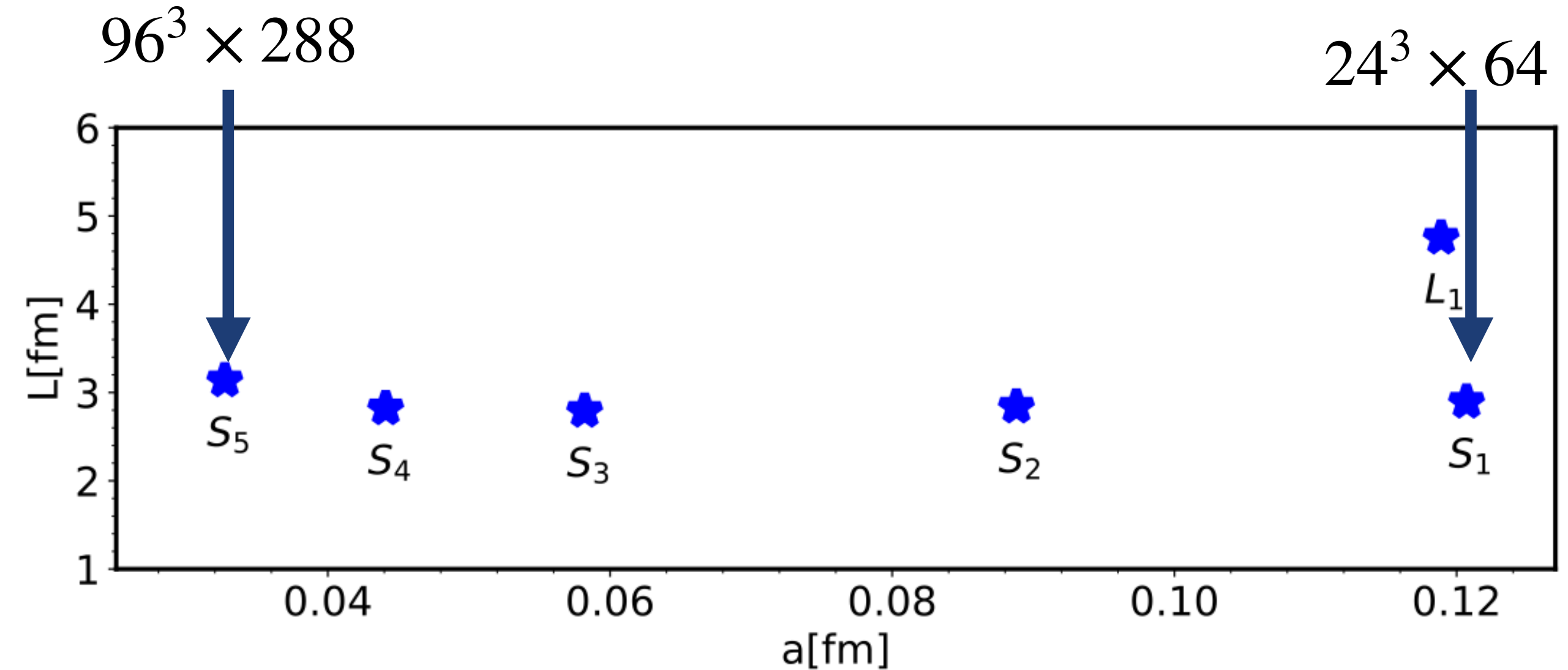
► Lattice predictions as well spread over 100 MeV for $\Omega_{ccc}(3/2^+)$.

Hence this precise study



Ω_{ccc} : Lattice Setup

- 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.



Ω_{ccc} : Valence Quarks

- **Overlap:** Free from $\mathcal{O}(a)$ discretization errors, enabling cleaner continuum extrapolations, good control over operator mixing, suitable for heavy quark systems
- **HISQ:** 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.

Overlap operator: Color-Anti, Flavor-Symm $\rightarrow$ Spin-Symm $\rightarrow$ 3/2 $\rightarrow H^+$ irrep

Expanded operator basis

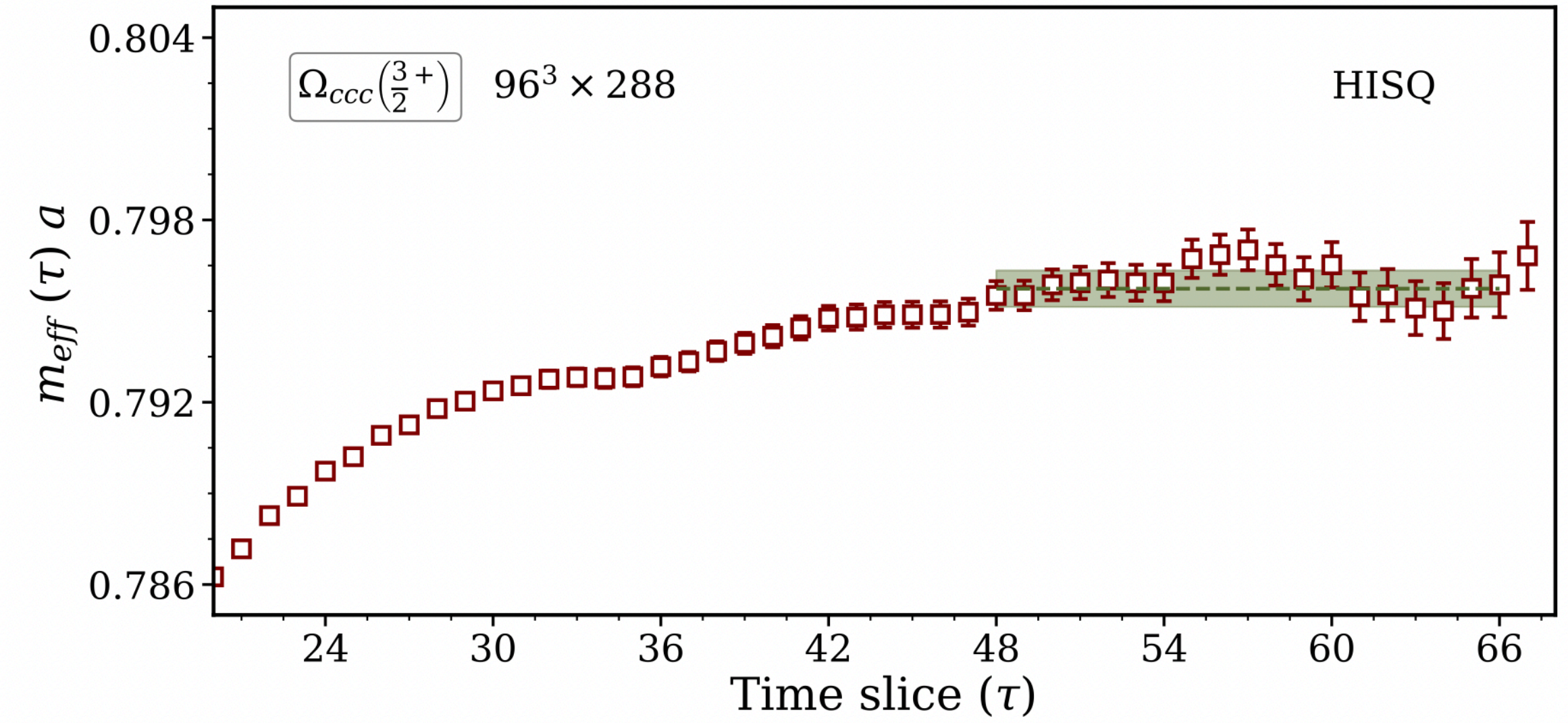
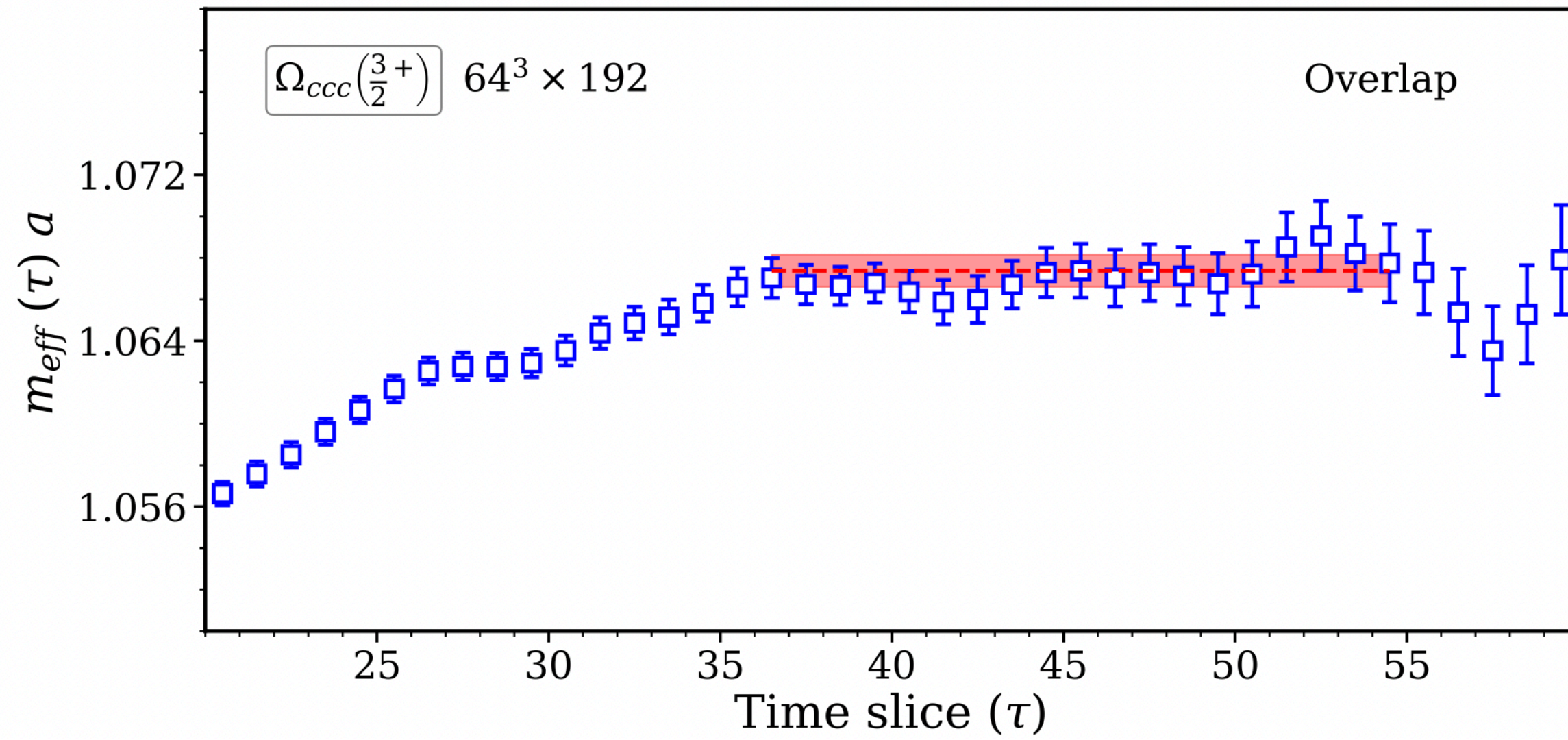
$$C_b(t) = \begin{bmatrix} \mathcal{O}_{b,H}^N \mathcal{O}_{b,H}^N & \mathcal{O}_{b,H}^N \mathcal{O}_{b,H}^R \\ \mathcal{O}_{b,H}^R \mathcal{O}_{b,H}^N & \mathcal{O}_{b,H}^R \mathcal{O}_{b,H}^R \end{bmatrix}$$

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	$^1H_{-3/2}$	$\{222\}_S$	$^2H_{-3/2}$	$\{244\}_S$

$$xyz_S = xyz + yzx + zxy$$

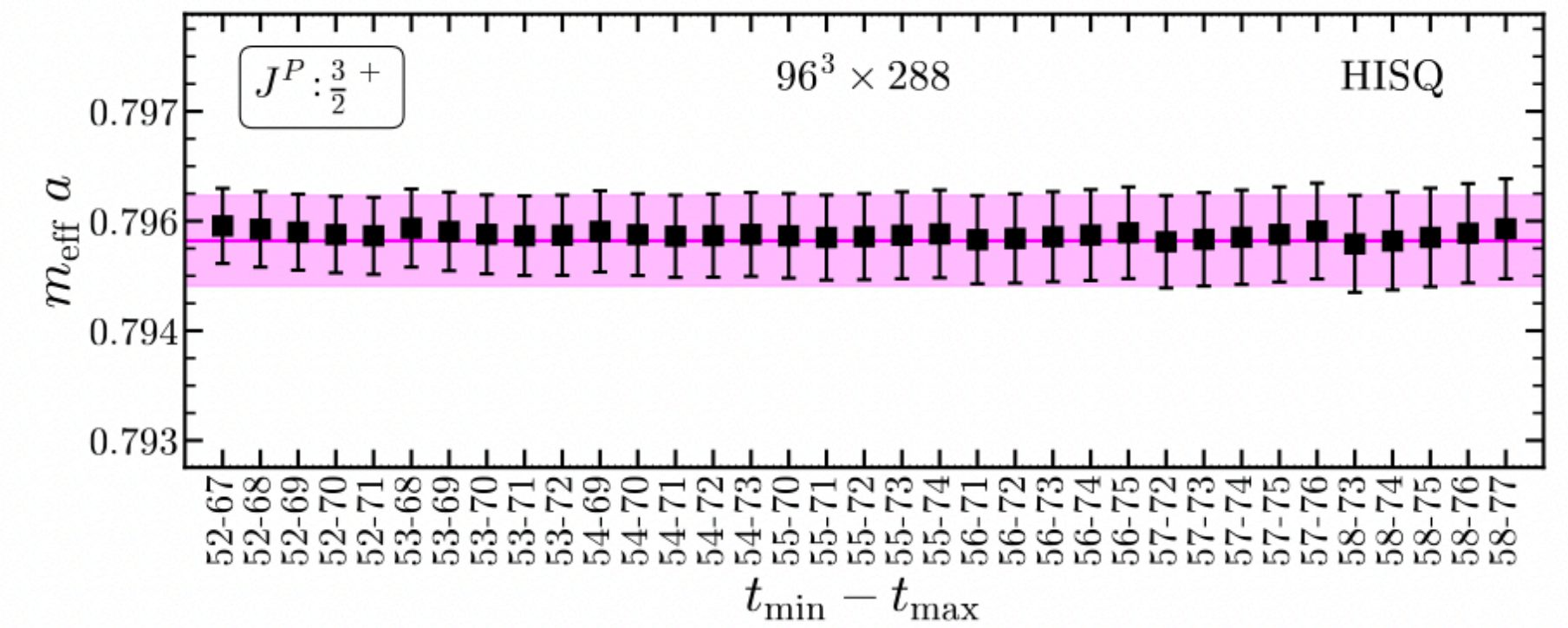
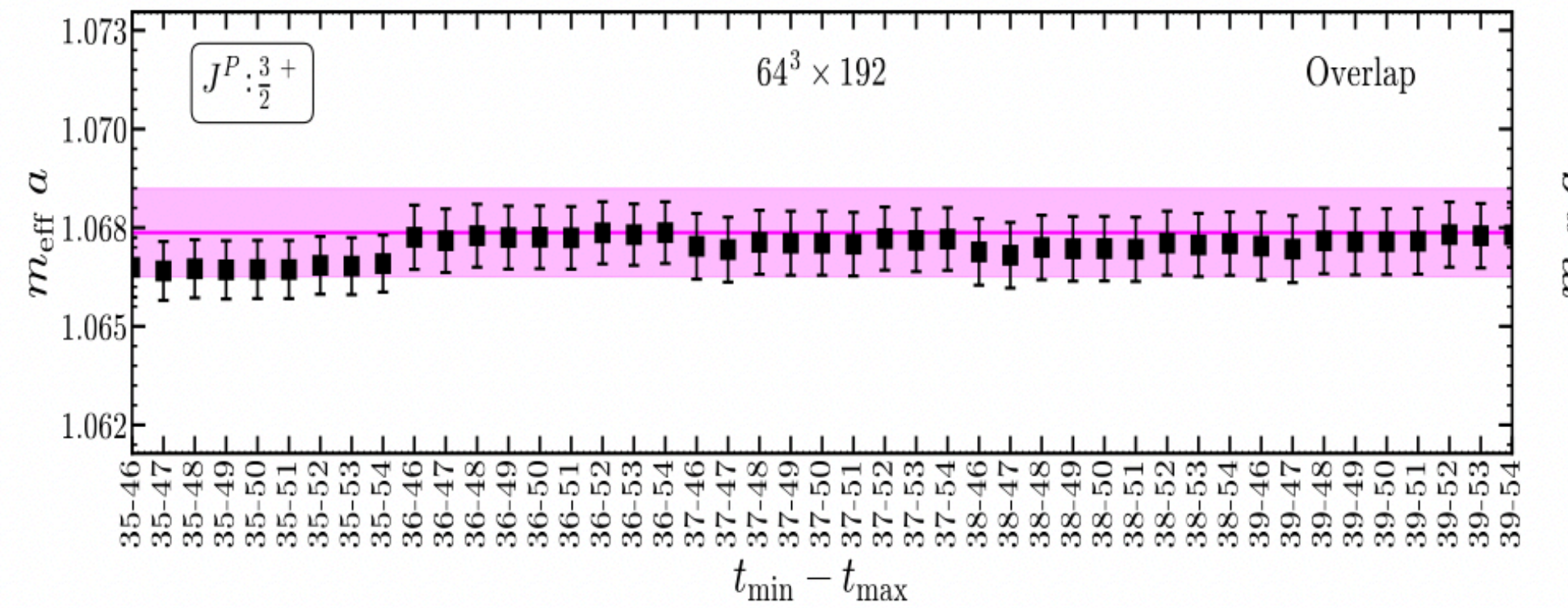


Ω_{ccc} : Signal



■ Using GEVP

■ Single and two exponential fit forms used





Ω_{ccc} : Discretisation

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

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

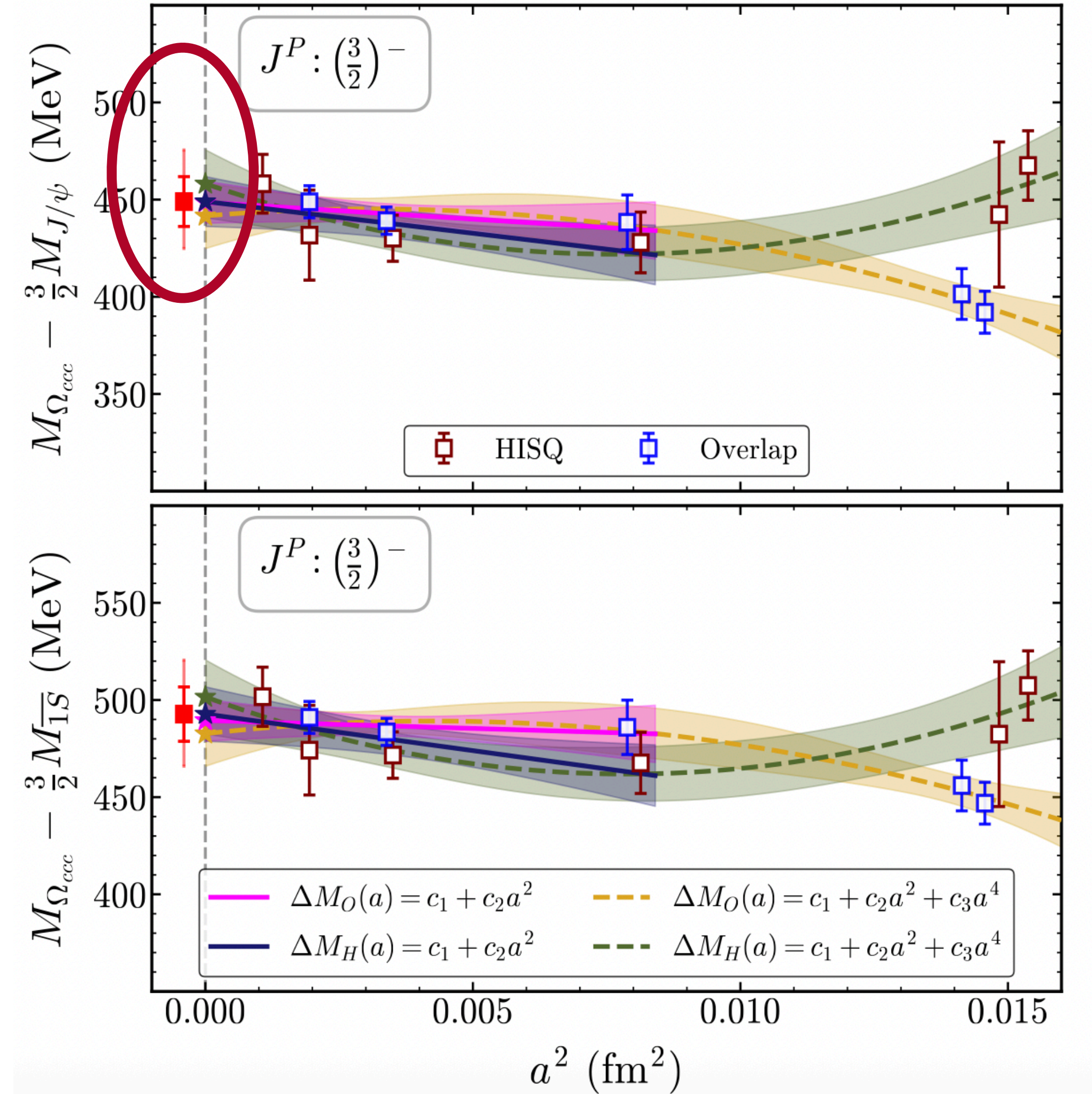
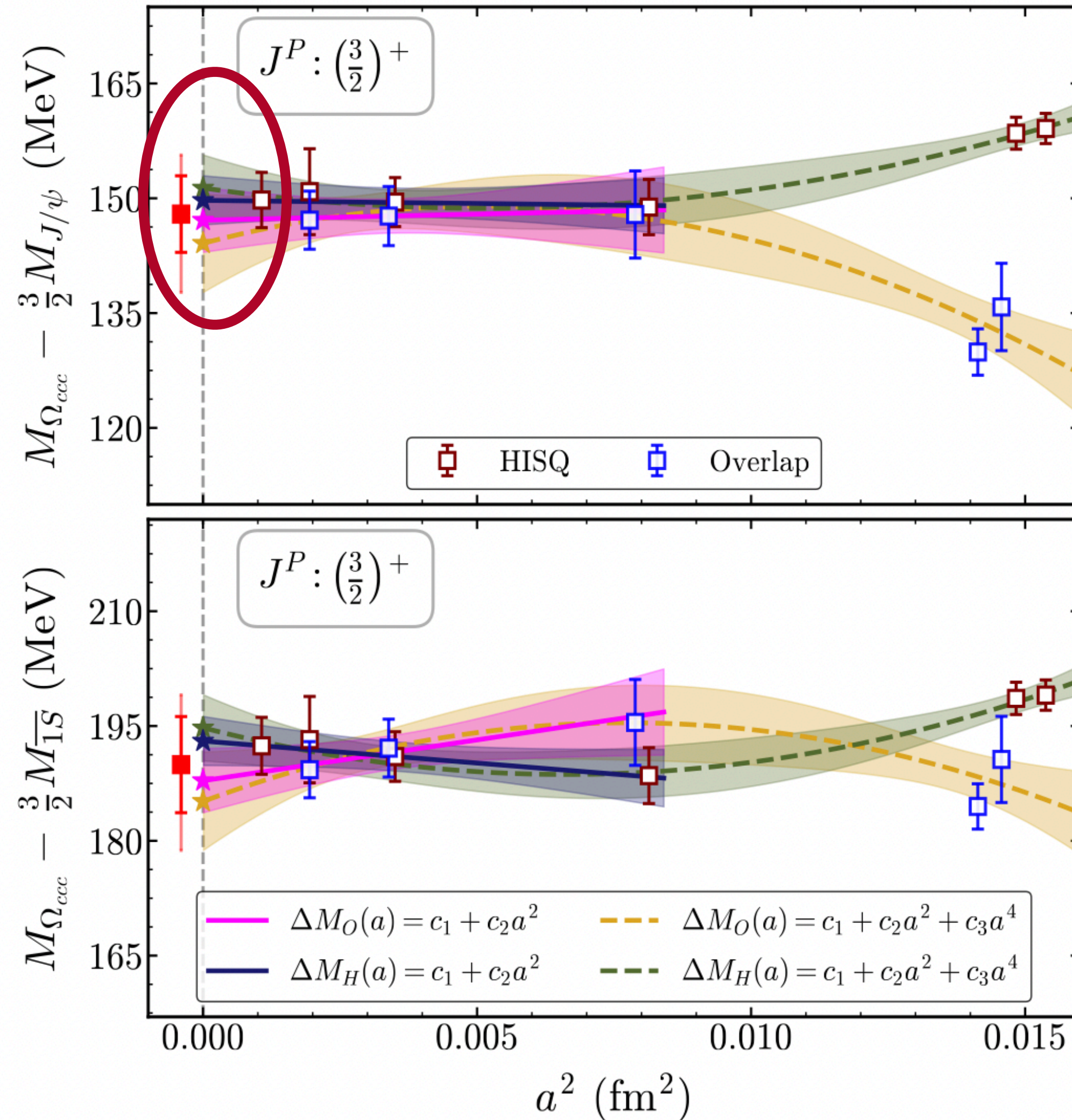
- ▶ Two choices- J/ψ and spin-averaged $\overline{1S}$.
- ▶ J/ψ masses on lattice closer to continuum value on each lattice.
- ▶ Spin-averaged $\overline{1S}$ - Charm quark mass tuned using this.



Ω_{ccc} : Splitting

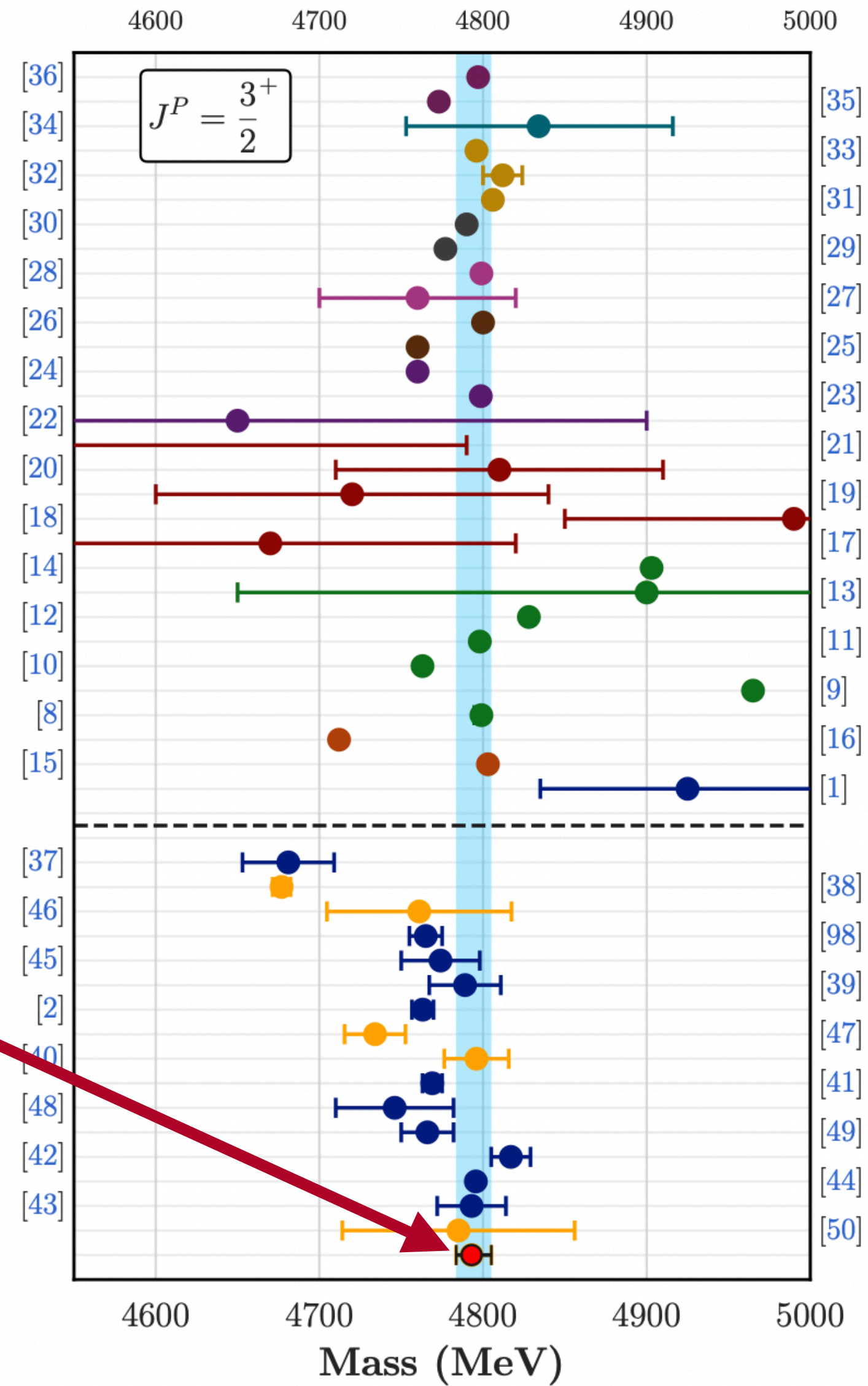
$4793(5)^{(+11}_{-8}) \text{ MeV}$

$5094(12)^{(+19}_{-17}) \text{ MeV}$



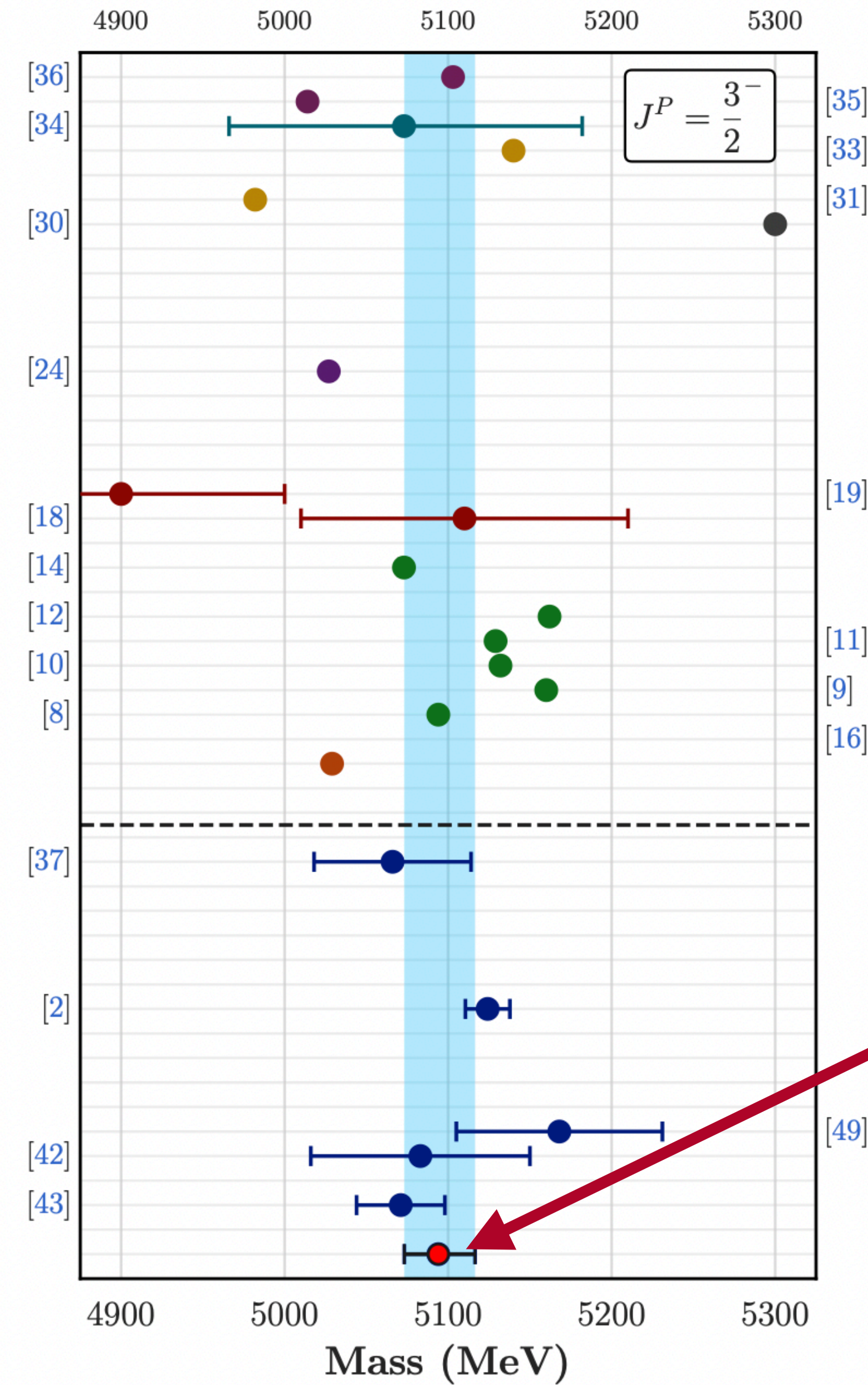
Not discussing error budget but we accounted for all systematic errors as well NAVDEEP | PAGE 22

Ω_{ccc} : Precise Result

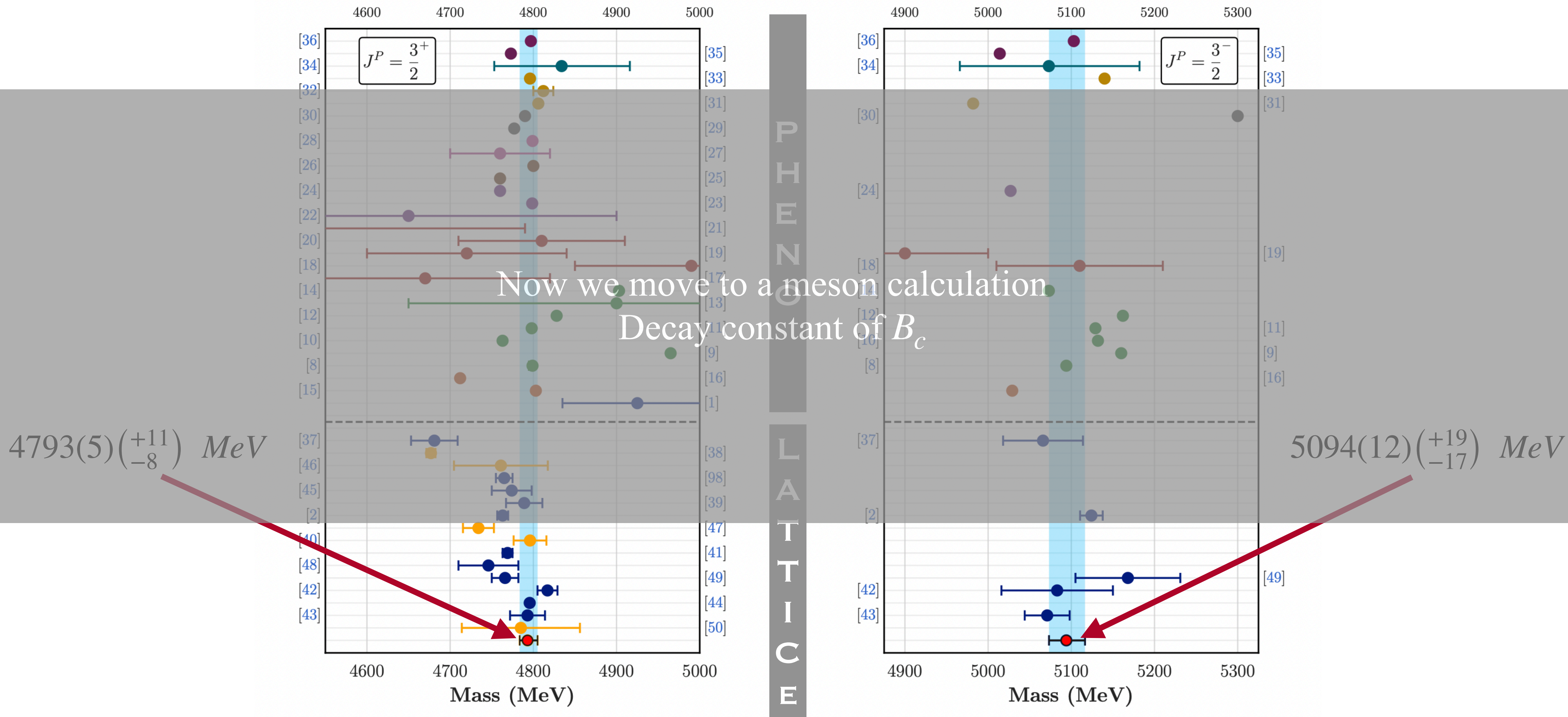


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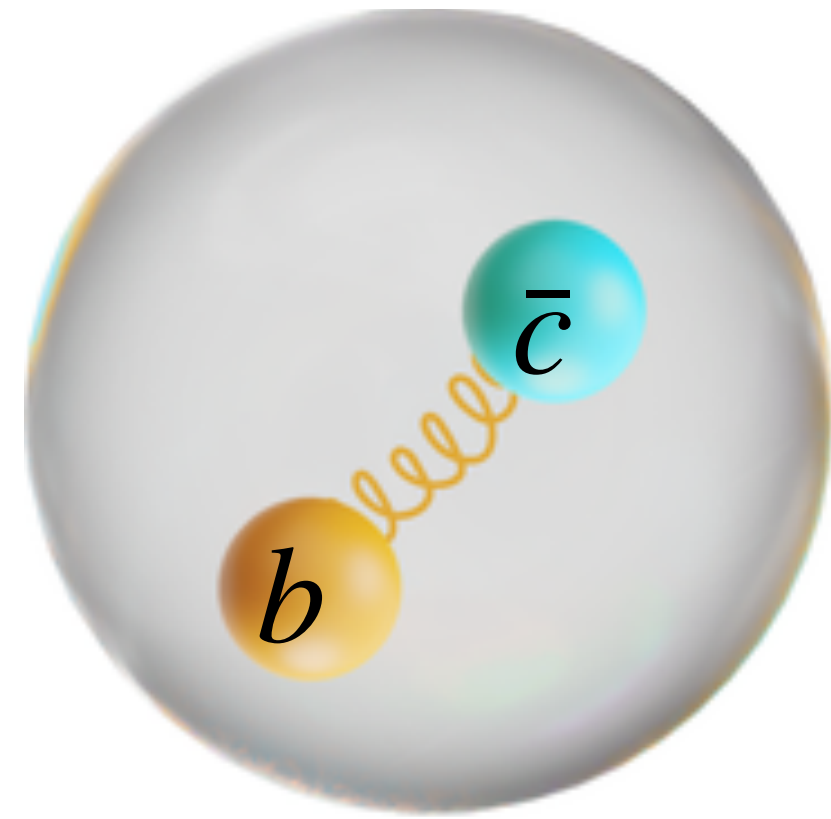


Ω_{ccc} : Precise Result



B_c meson

NSD, CHAKRABORTY, MATHUR
UNDER PREPARATION

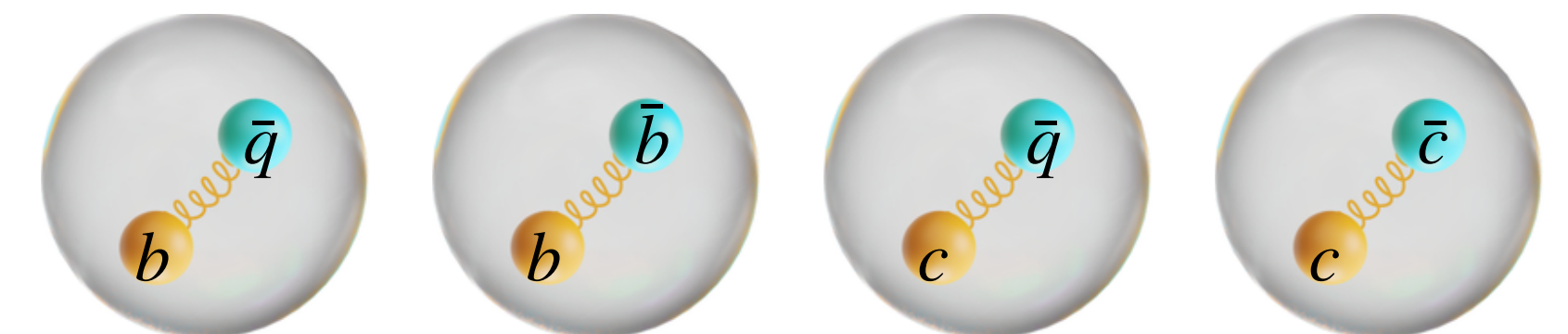


- Only meson composed of two different heavy quarks
- Unique laboratory for two-scale heavy-quark dynamics

- Large B_c samples at the LHC (More in future LHC, FCC)
- Precision studies of leptonic decays becoming feasible

- Purely leptonic decay, $\bar{B}_c \rightarrow l\bar{\nu}$, all hadronic effects encoded in a single decay constant
- Useful in accurate determinations of $|V_{cb}|$ (next slide)

Combines features of heavy-light mesons and heavy quarkonia
A unique heavy-heavy system connecting precision flavour physics
and lattice QCD



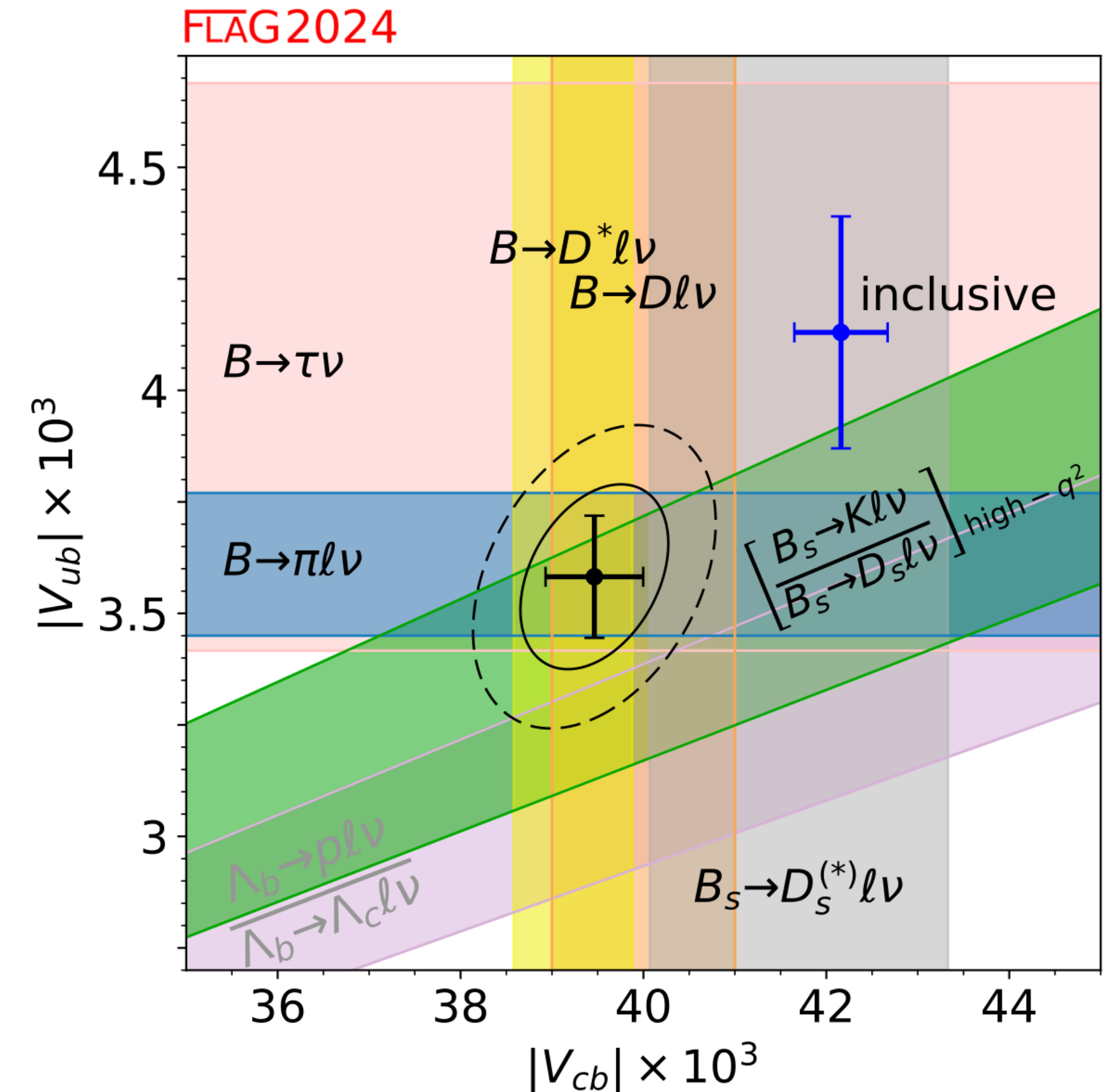
Why f_{B_c} ?

NSD, CHAKRABORTY, MATHUR
UNDER PREPARATION



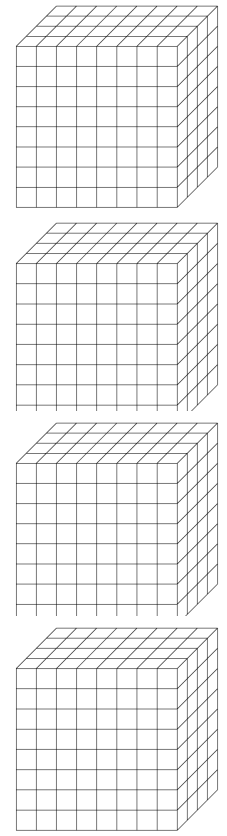
A precise determination of $|V_{cb}|$ is a central goal of precision flavor physics.

- Determined from inclusive and exclusive semileptonic B-meson decays
- A longstanding $2 - 3\sigma$ tension exists between the two determinations
- Exclusive determinations require precise hadronic form factors, making lattice QCD an essential theoretical input.
- A precise f_{B_c} strengthens unitarity bounds, leading to improved $B \rightarrow D^{(*)}$ form factors and a more precise exclusive determination of $|V_{cb}|$





Our Setup



$N_f = 2 + 1 + 1$ MILC HISQ ensemble, $96^3 \times 288$ lattice, $a \sim 0.0327$ fm

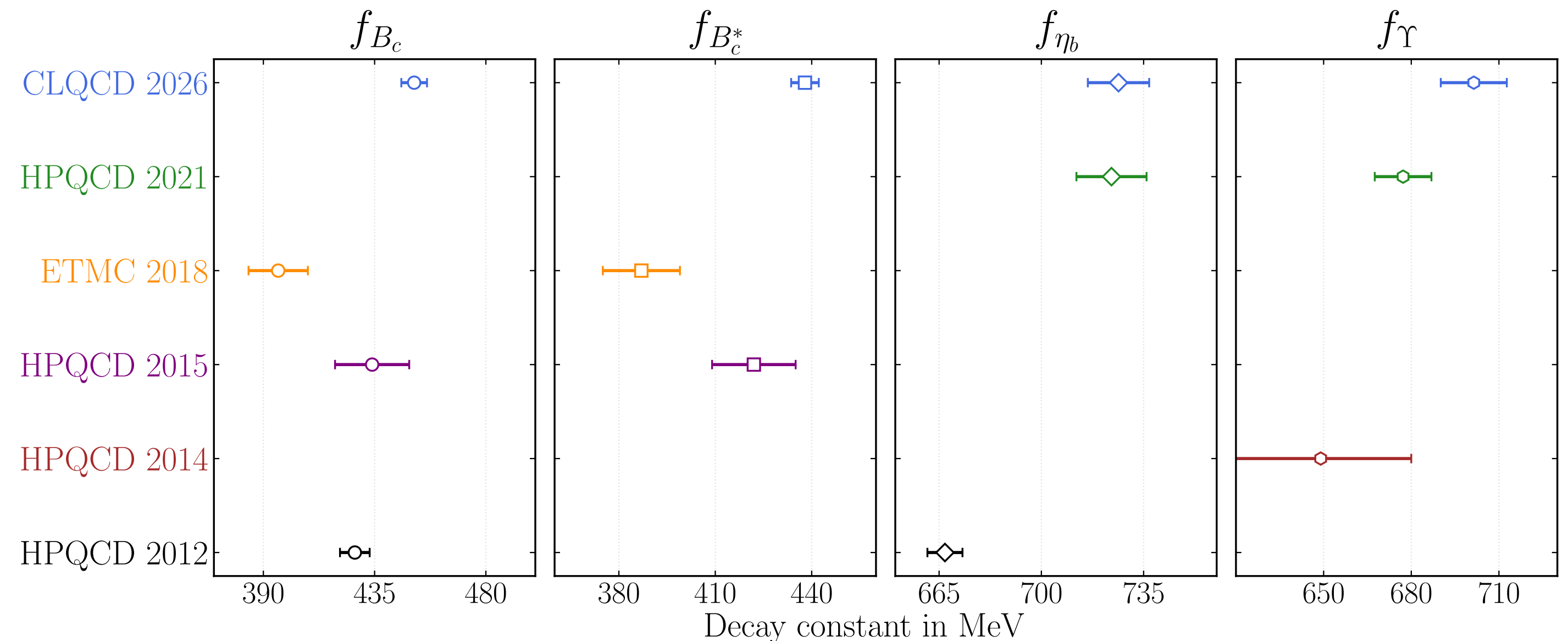
HISQ action for valence quarks as well

Charm tuned to physical spin-averaged charmonium, bottom tuned to physical Υ

400 gauge configurations (so far), random color wall source to point sink setup

Targets of the work:

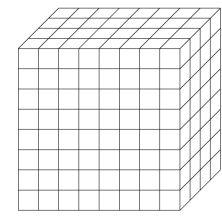
- Precise determination of f_{B_c} and $f_{B_c^*}$
- Results for tensor decay constant $f_{B_c^*}^T$
- Excited states using TGEVP (later part of the talk)



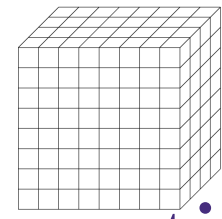
Lattice results so far

Why HISQ?

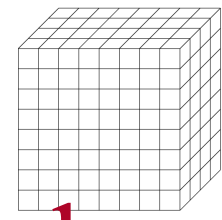
NSD, CHAKRABORTY, MATHUR
UNDER PREPARATION



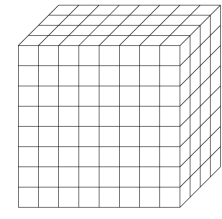
Ultrafine lattice spacing ($a \sim 0.0327 \text{ fm}$) allows a fully relativistic treatment of the bottom quark, $am_b = 0.6223$, (also $am_c = 0.137$)



Unlike coarser lattices, which often require specialized heavy-quark actions (e.g., NRQCD or RHQA), our ultrafine lattice allows the bottom quark to be simulated directly with the HISQ action



Highly Improved Staggered Quark (HISQ) action significantly reduces heavy-quark discretization errors through higher-order improvement.



Staggered fermions retain four continuum tastes per quark flavor, with meson operators classified by their spin–taste structure

$$\begin{array}{c} \bar{\psi} \Gamma \psi \\ \downarrow \\ \bar{\chi} (\Gamma_S \otimes \Gamma_T) \chi \end{array}$$

- ▶ Taste splitting effects suppressed (HISQ), ultrafine lattice spacing taste splitting expected to be small
- ▶ No mixed action effects, enables high-precision lattice calculations with controlled discretization errors

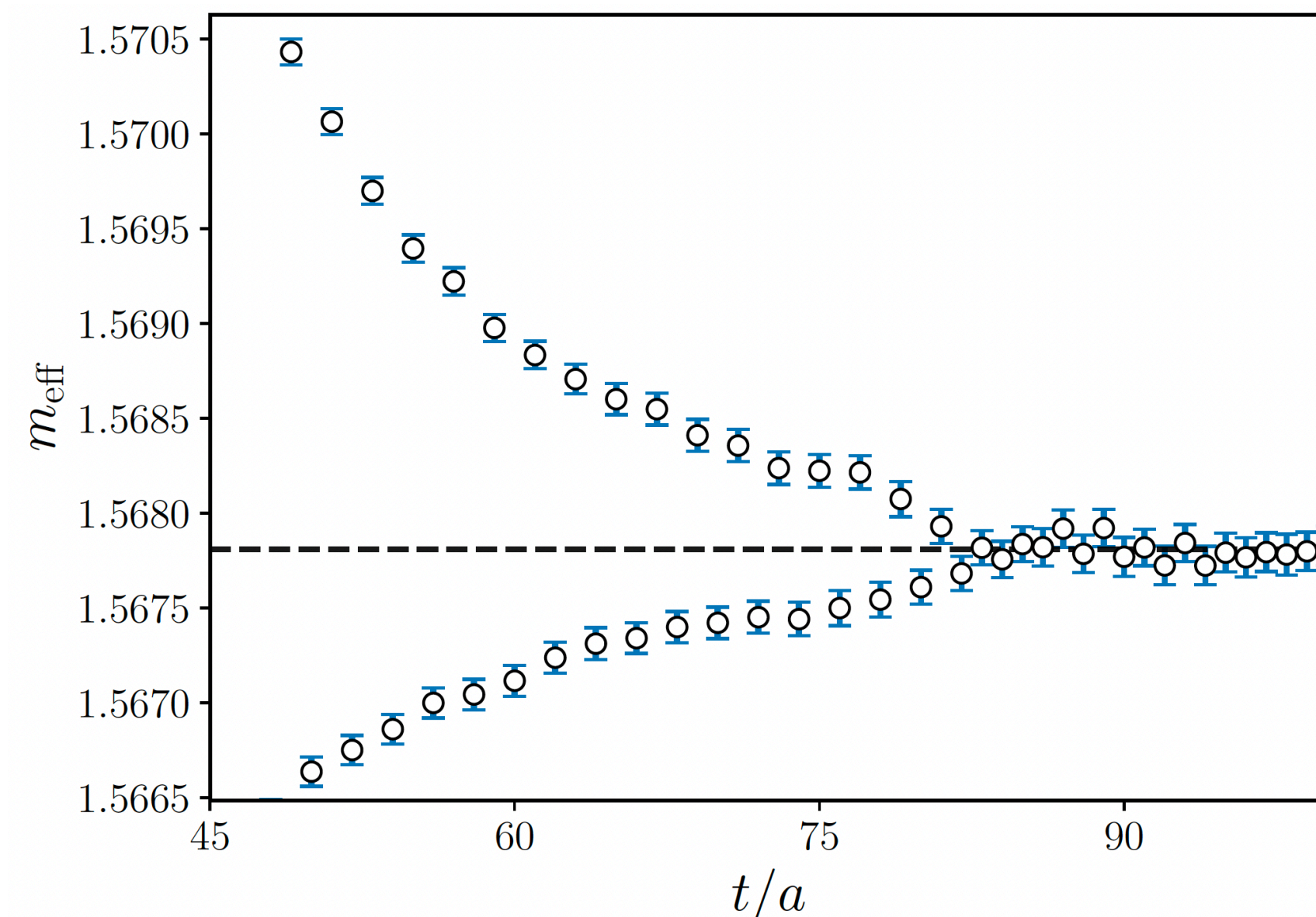


Oscillating Correlators

- ▶ Staggered meson operators couple to both the desired state and its opposite-parity partner
- ▶ Consequently, the two-point correlation function contains oscillating contributions

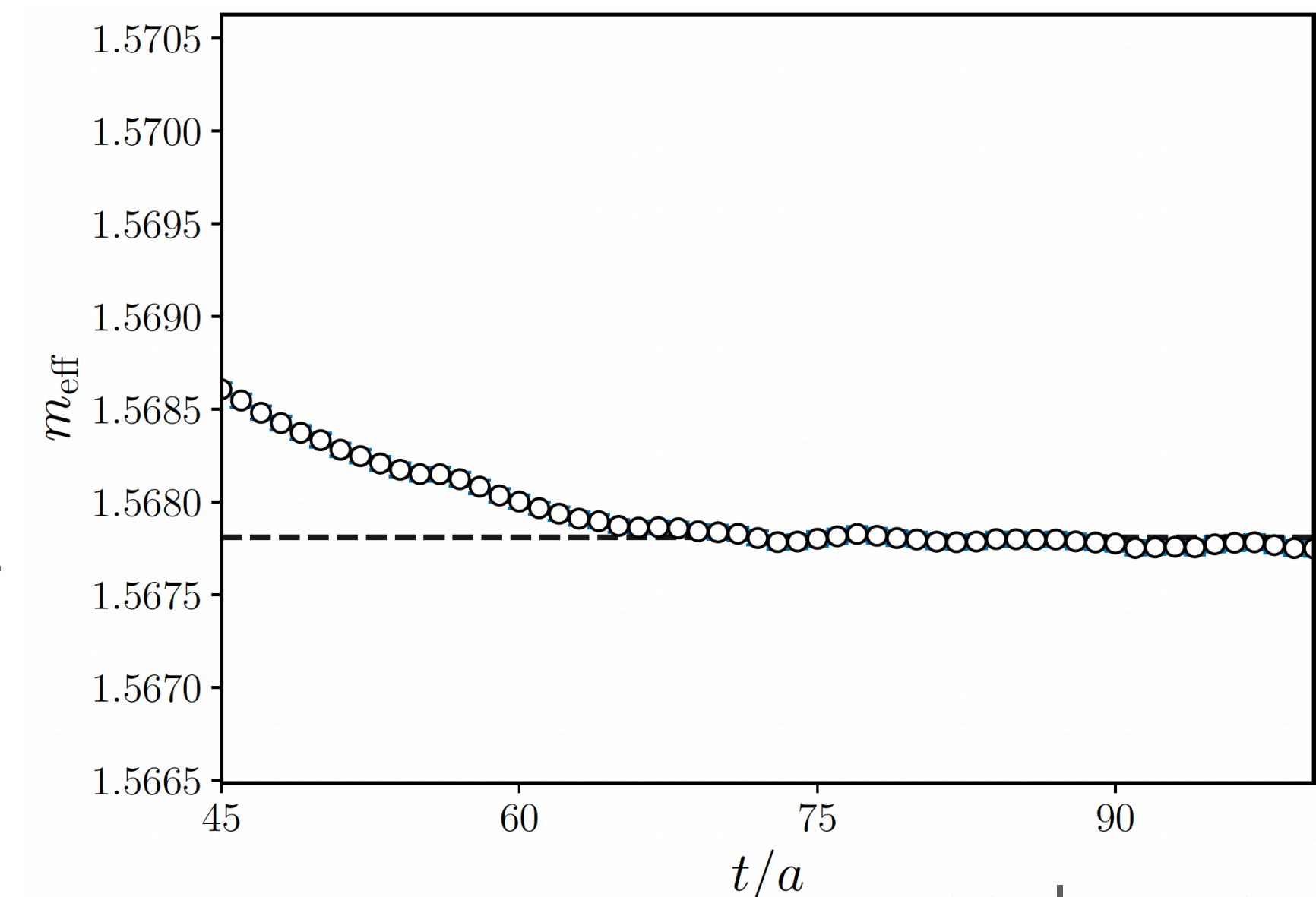
$$C(t) = \sum_n A_n \left(\exp(-E_n t) + \exp(-E_n(T - t)) \right) - (-1)^t \sum_n B_n \left(\exp(-E_n^o t) + \exp(-E_n^o(T - t)) \right)$$

Oscillating contributions produce an even-odd time-slice pattern



A three-point smoothing is applied to reduce these oscillations

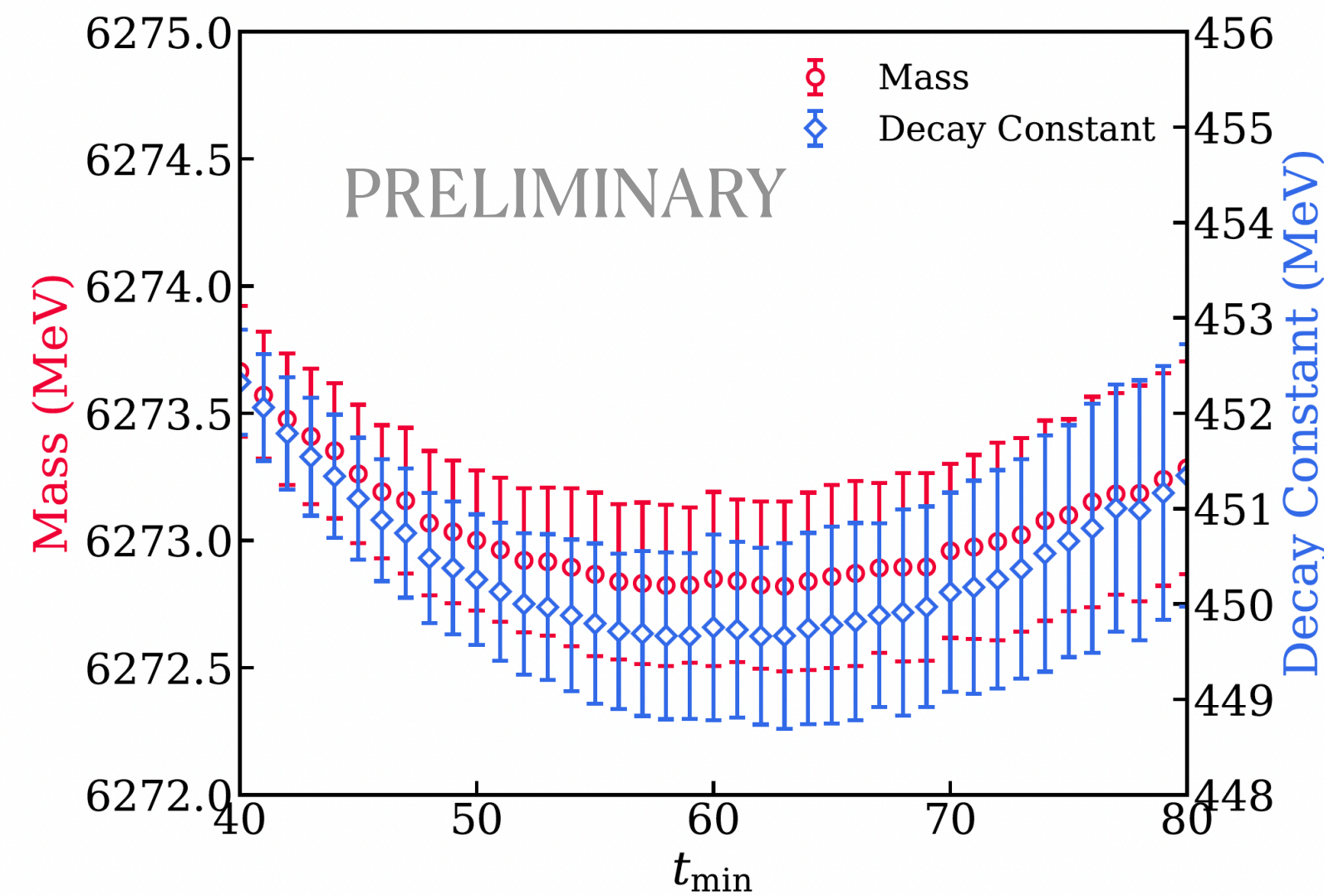
$$C(t) = \sqrt{C(t) \sqrt{C(t-1) C(t+1)}}$$



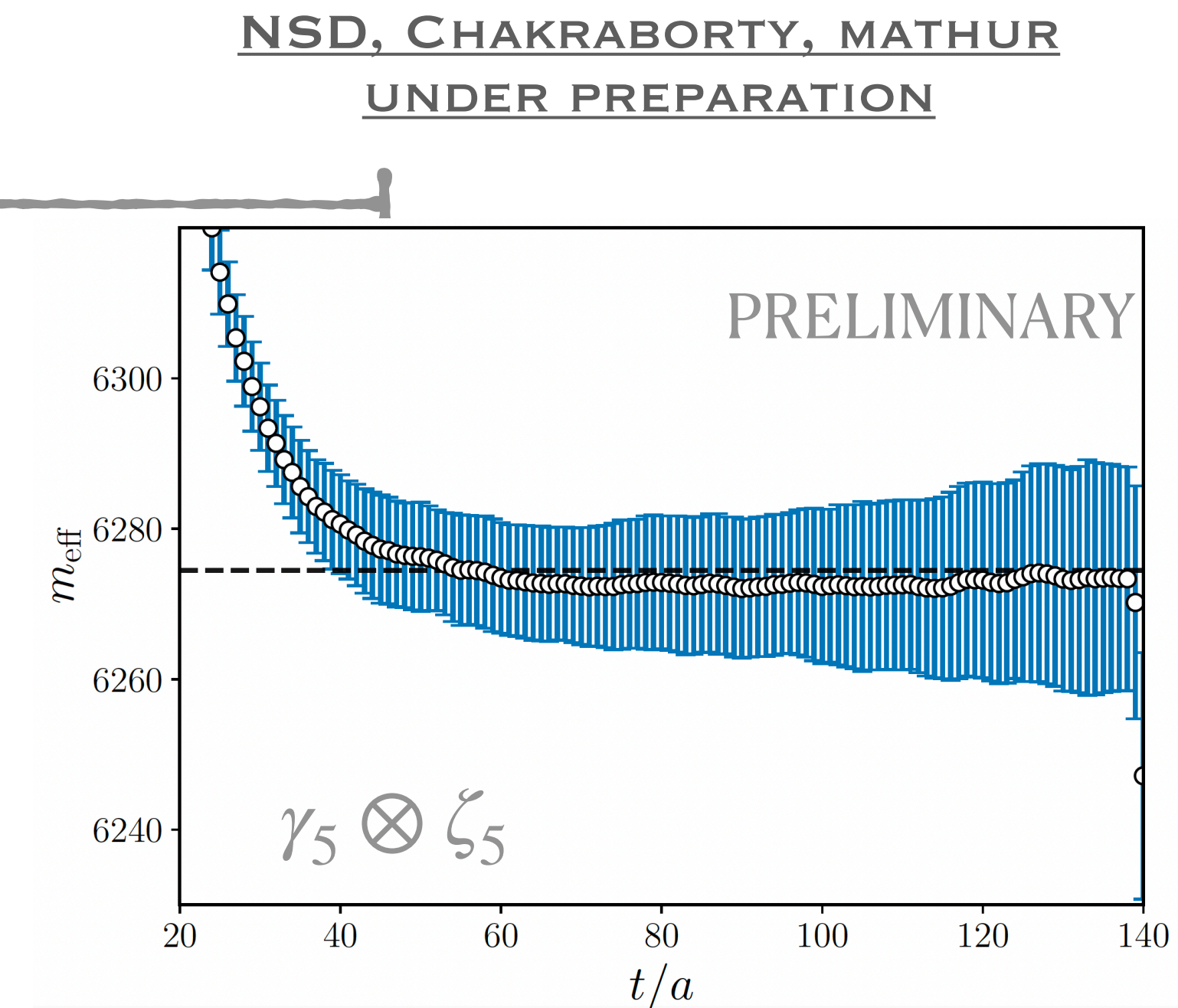
B_c signal

Effective mass constructed from smoothed correlators and shown without bootstrap/jackknife uncertainties to highlight the signal quality

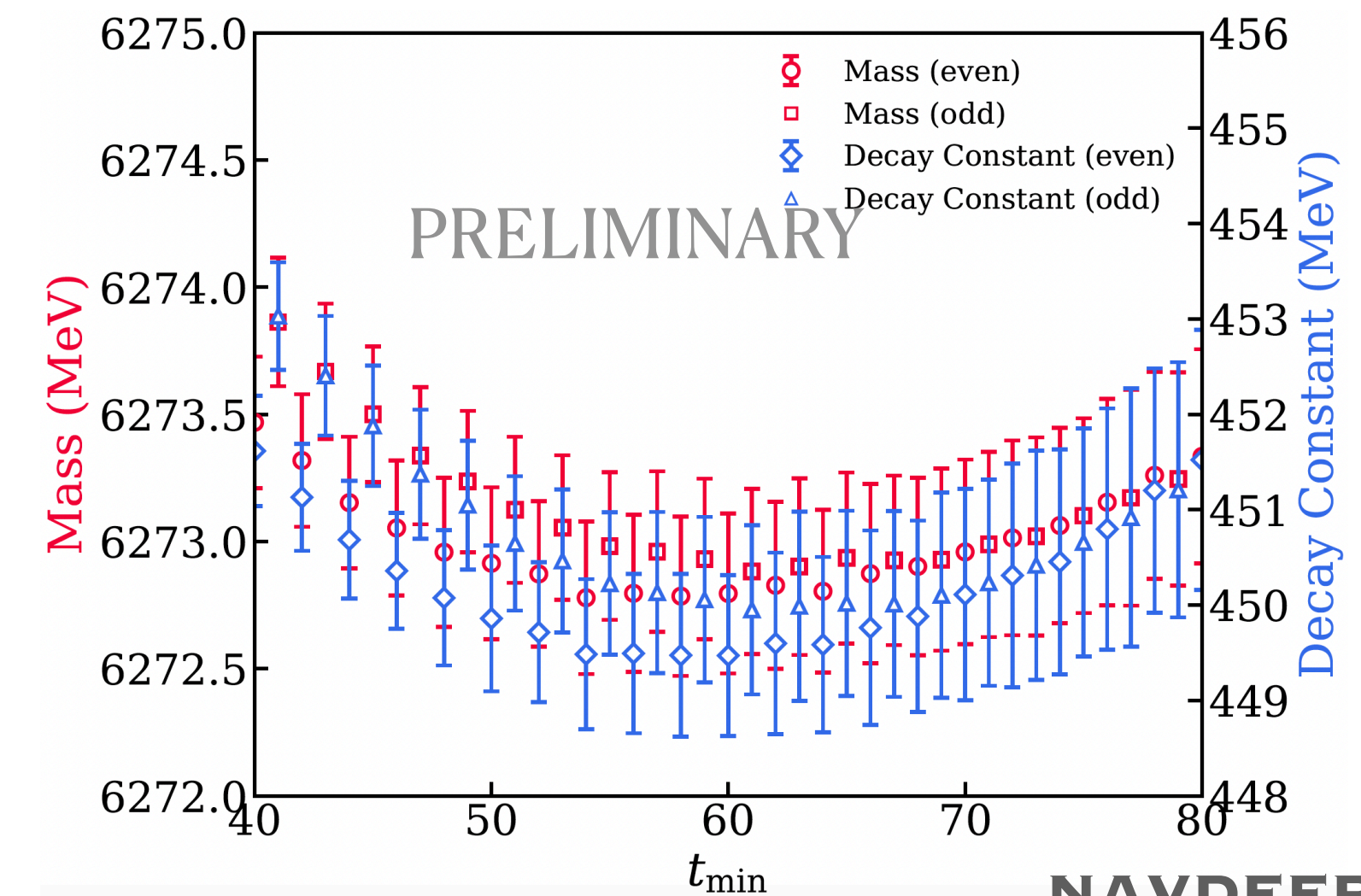
$$f_{ps} = \left(m_{q_1} + m_{q_2} \right) \sqrt{\frac{2A}{E^3}}$$



Oscillating ansatz becomes increasingly noisy at large Euclidean times, single exponential fits to smooth data

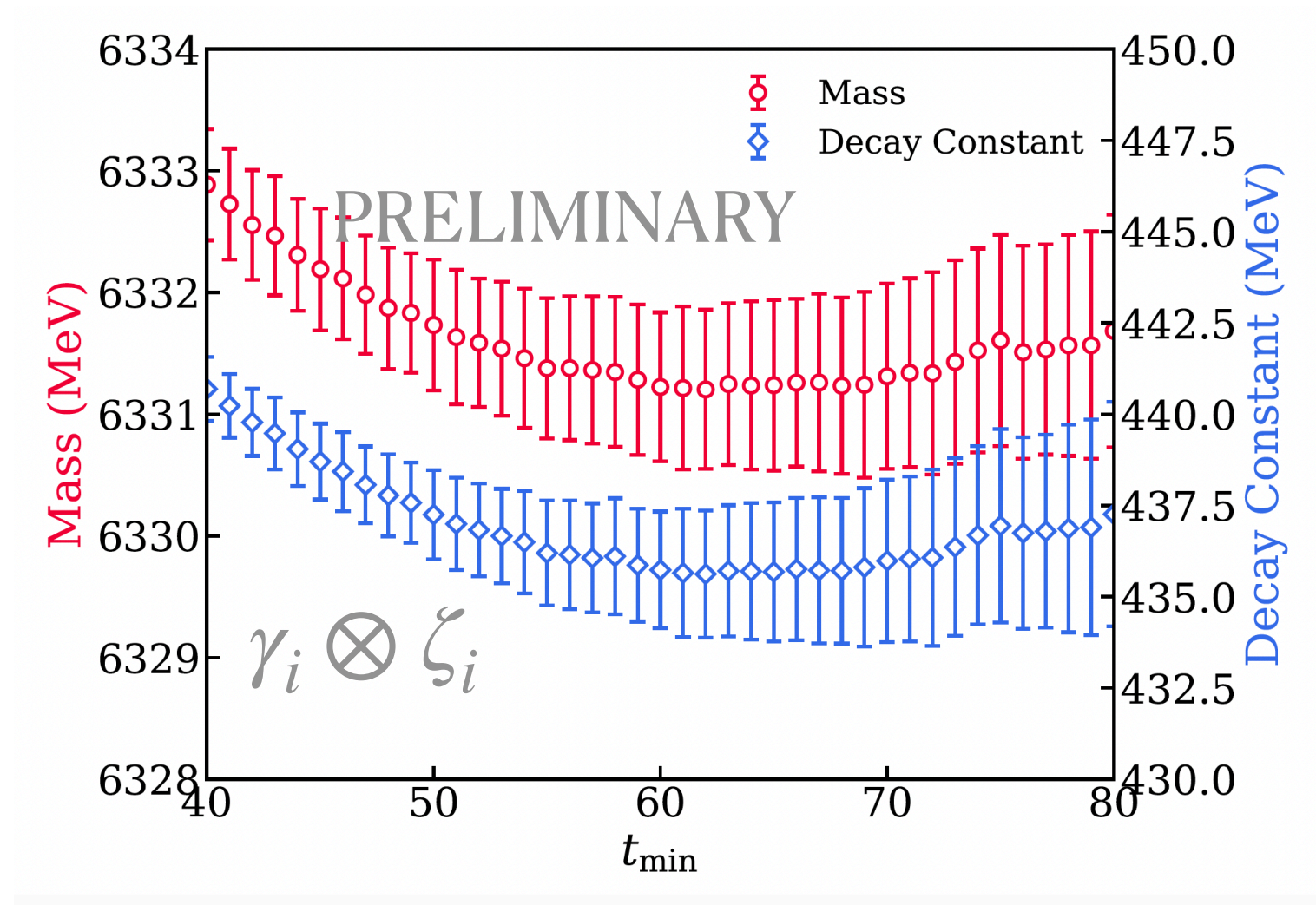


A naive check to verify that no information is lost through smoothing





B_c^* signal

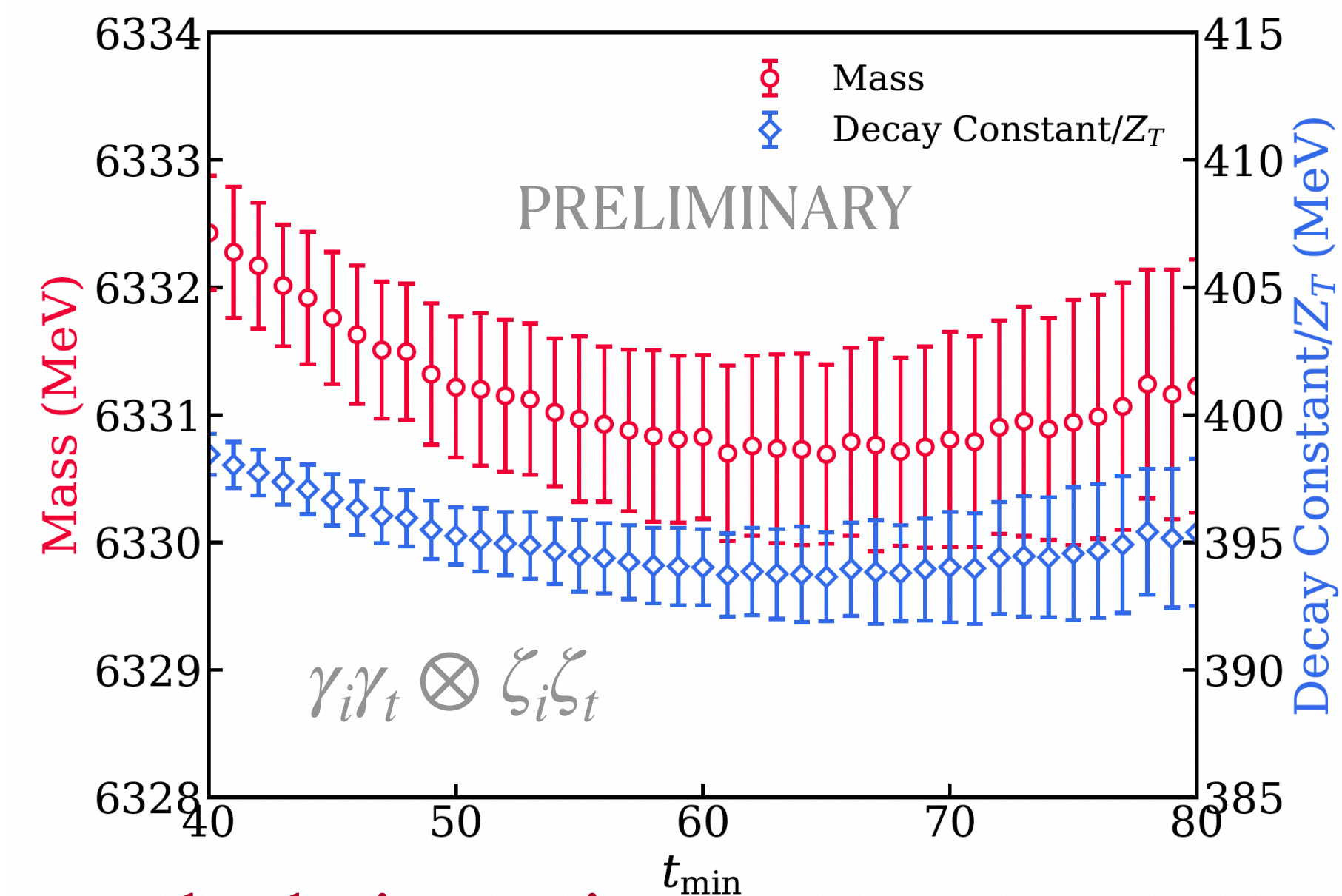


$$f_V = Z_V \sqrt{\frac{2A}{E}}$$

Z_V : PRD 102, 054511 (2020) HPQCD

We are currently investigating the determination of Z_V

- Preliminary $B_c^* - B_c$ splitting (through ratio): 59.07(30) MeV
- We also report B_c^* using tensor interpolating operators
- Tensor currents, absent at tree level in the Standard Model, provide a sensitive probe of physics beyond the Standard Model



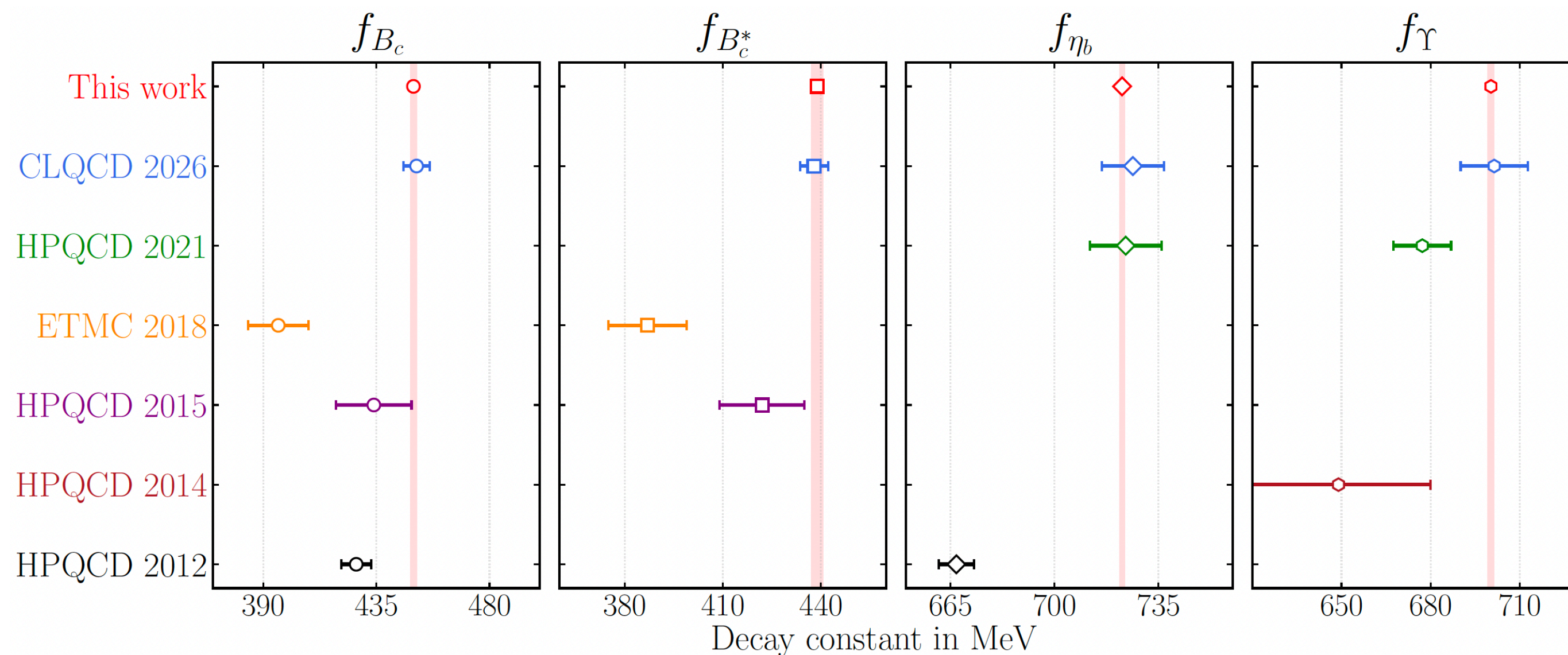
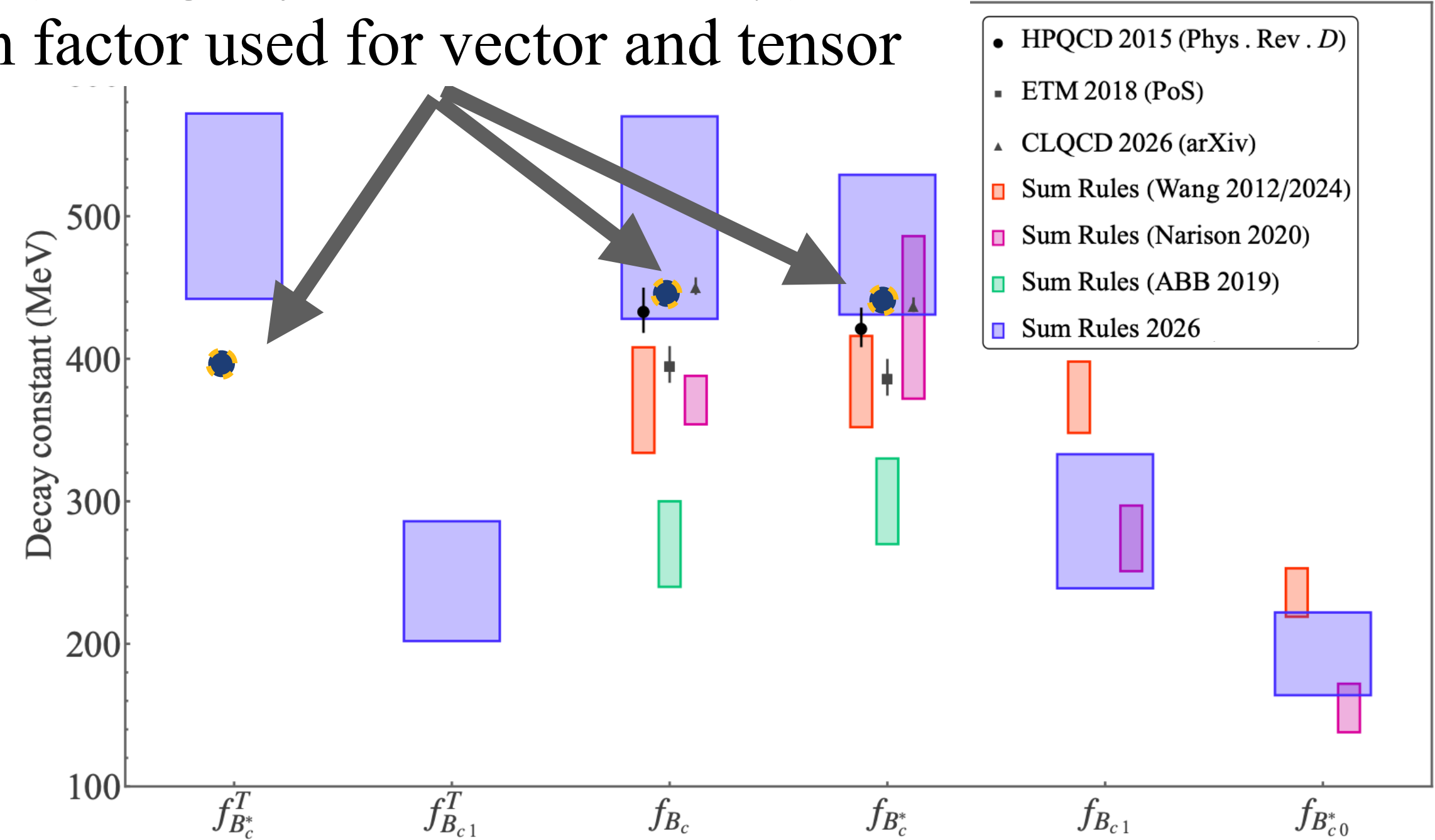
First lattice calculation using tensor operators;
currently investigating renormalisation factor

Results



Our data points (*enlarged for better visibility*)
No renormalisation factor used for vector and tensor

Hadron	Mass [in MeV]	f/Z [in MeV]
η_c	2983.55(30)	396.41(81)
η_b	9404.07(14)	722.76(68)
B_c	6272.85(34)	449.76(97)
B_c^*	6331.22(61)	438.82(161)
B_c^* (tensor)	6330.82(64)	394.02(150)
Υ	9458.14(18)	700.30(79)
Υ (tensor)	9458.27(17)	646.47(70)



A recent pheno calculation
arXiv:2606.25733[hep-ph]
Reina, Gubernari, Wüthrich

No renormalisation factor used here
for B_c^* , Υ

No systematics yet!!

Extracting More ...



So far, we have focused on single-exponential fits to extract the ground-state properties



However, correlation functions contain richer spectral information



Can be accessed using advanced spectral extraction techniques

Using these methods, we



get a validation of our ground states numbers



can validate the impact of excited-state contamination



get faster convergence and improved numerical stability



We use TGEVP for further analysis

- Lanczos, **Wagman**
(PRL 134 (2025) 24, 241901)
- Prony GEVM, **Ostmeyer, Sen, Urbach**
(EPJA 61, 26 (2025))
- Transfer Matrix GEVP, **Chakraborty, Sood, Radhakrishnan, Mathur**
(PRD 112 (2025) 7, 074506)



Truncated Krylov Subspace $\mathcal{K}_m$

$$\mathcal{K}_m \equiv \{ |\chi\rangle, \hat{\mathcal{T}} |\chi\rangle, \hat{\mathcal{T}}^2 |\chi\rangle, \dots, \hat{\mathcal{T}}^m |\chi\rangle \},$$

for $2m - 1 \leq n_T$

Transfer Matrix T_{ij}^m

$$T_{ij}^m = \langle v_i | \hat{\mathcal{T}} | v_j \rangle = C(i + j + 1) / \sqrt{C(2i) \times C(2j)}$$

One time step ahead, encodes transfer matrix action on Krylov basis

Overlap Matrix V_{ij}^m

$$V_{ij}^m = \langle v_i | v_j \rangle = C(i + j) / \sqrt{C(2i) \times C(2j)}$$

Encodes overlaps between the Krylov basis states using correlator values

Solve the Generalised Eigenvalue Problem

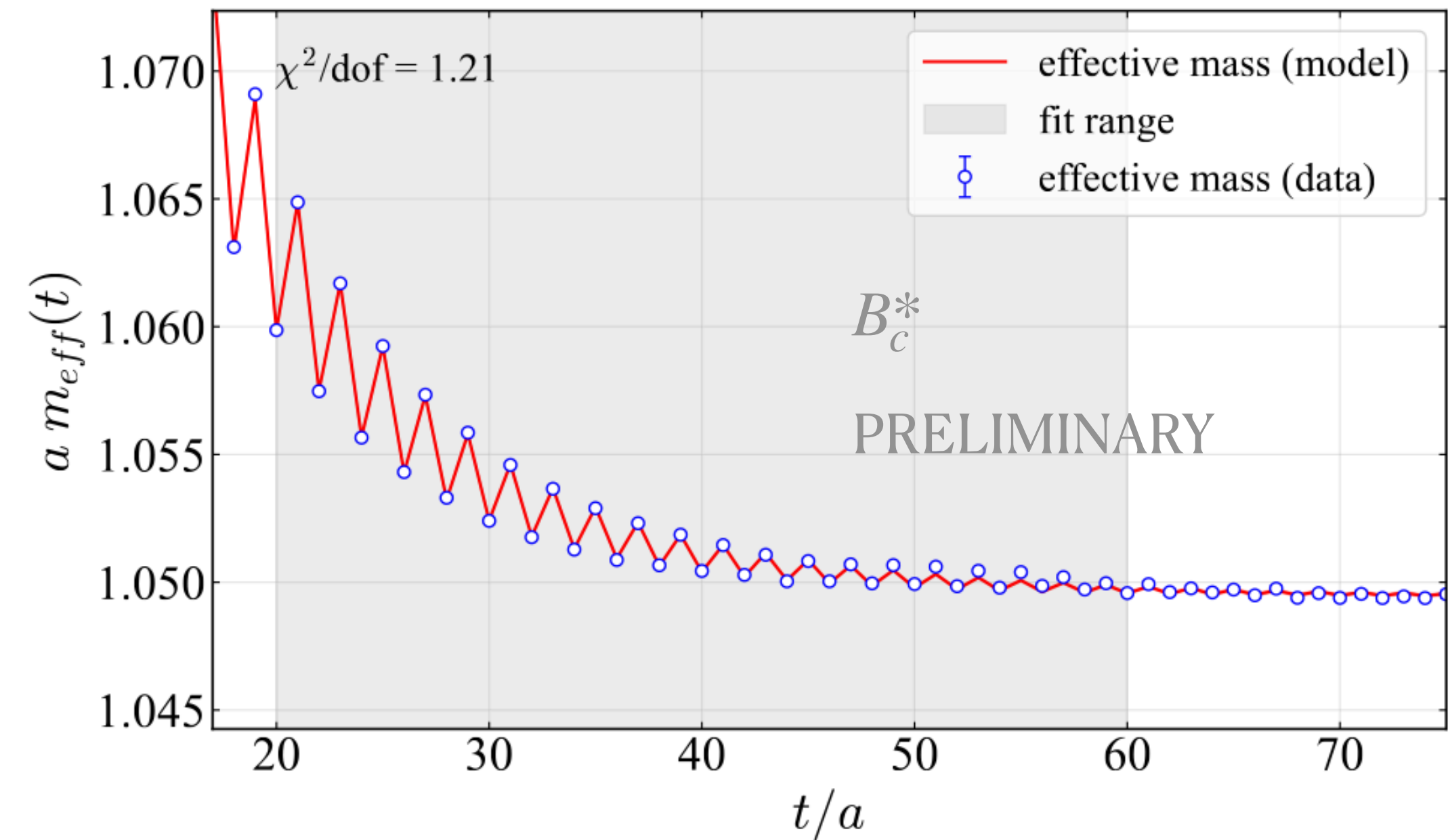
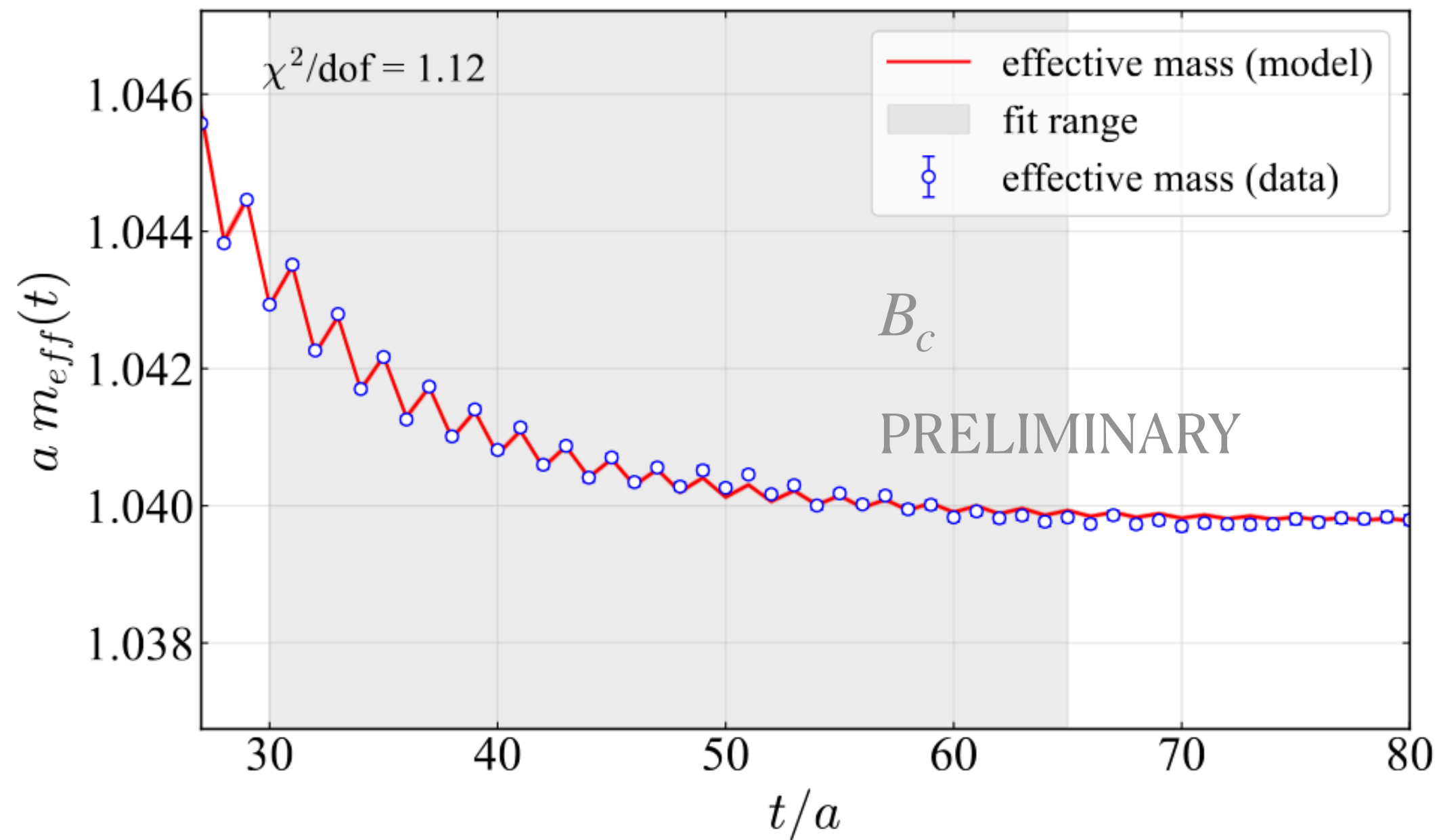
$$T^m x_n^m = \lambda_n^m V^m x_n^m \quad E_n^m = -\log \lambda_n^m$$

T^m and V^m are positive definite $\rightarrow \lambda_n$'s are real and positive $0 < \lambda_n^m \leq 1$

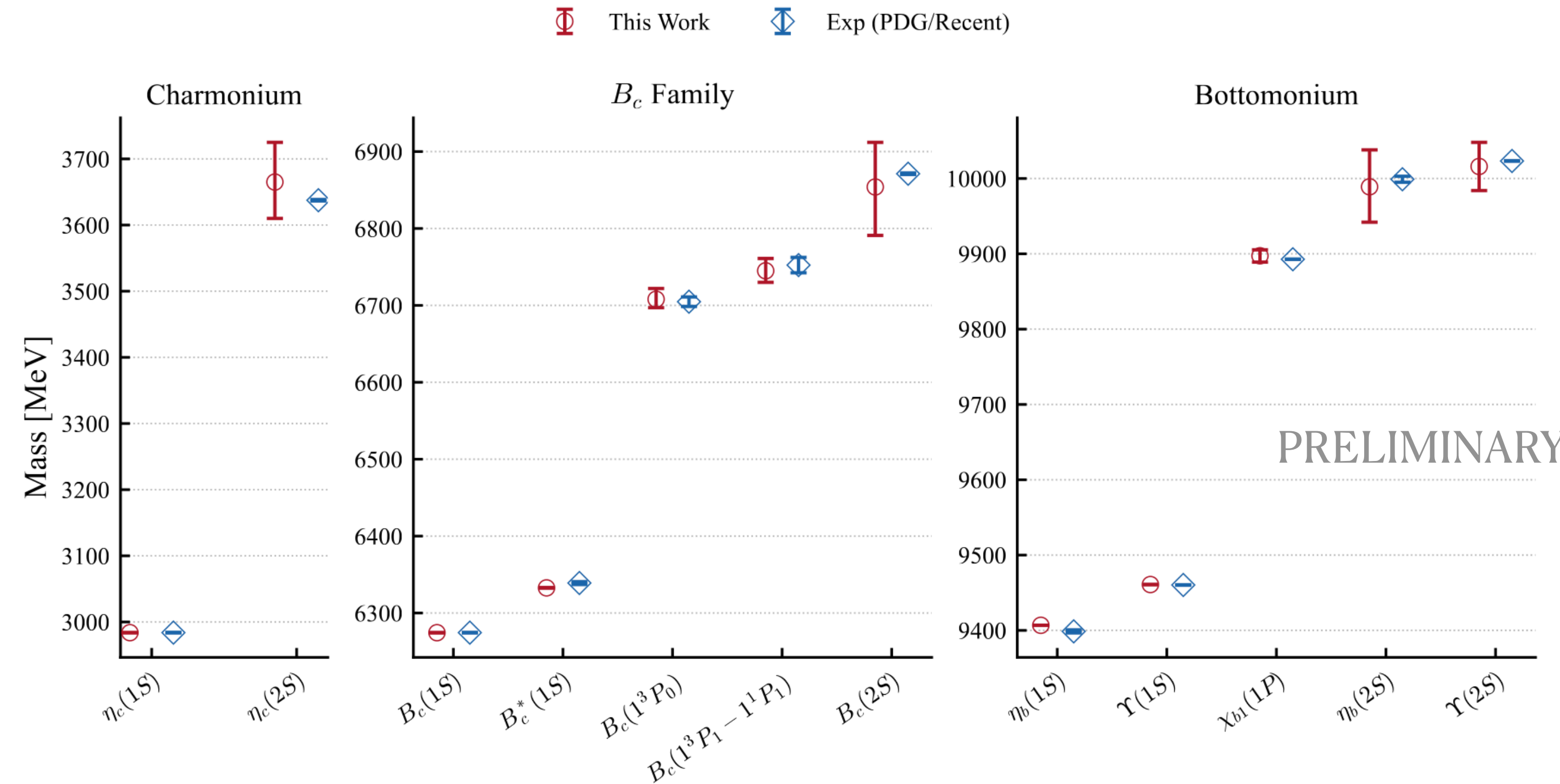


$$C(t) = \sum_n A_n \left(\exp(-E_n t) + \exp(-E_n(T - t)) \right) - (-1)^t \sum_n B_n \left(\exp(-E_n^o t) + \exp(-E_n^o(T - t)) \right)$$

Ansatz incorporates four non-oscillating and three oscillating states



Ground-state information obtained from the late-time region is used to constrain fits at early times, where excited-state contributions are significant

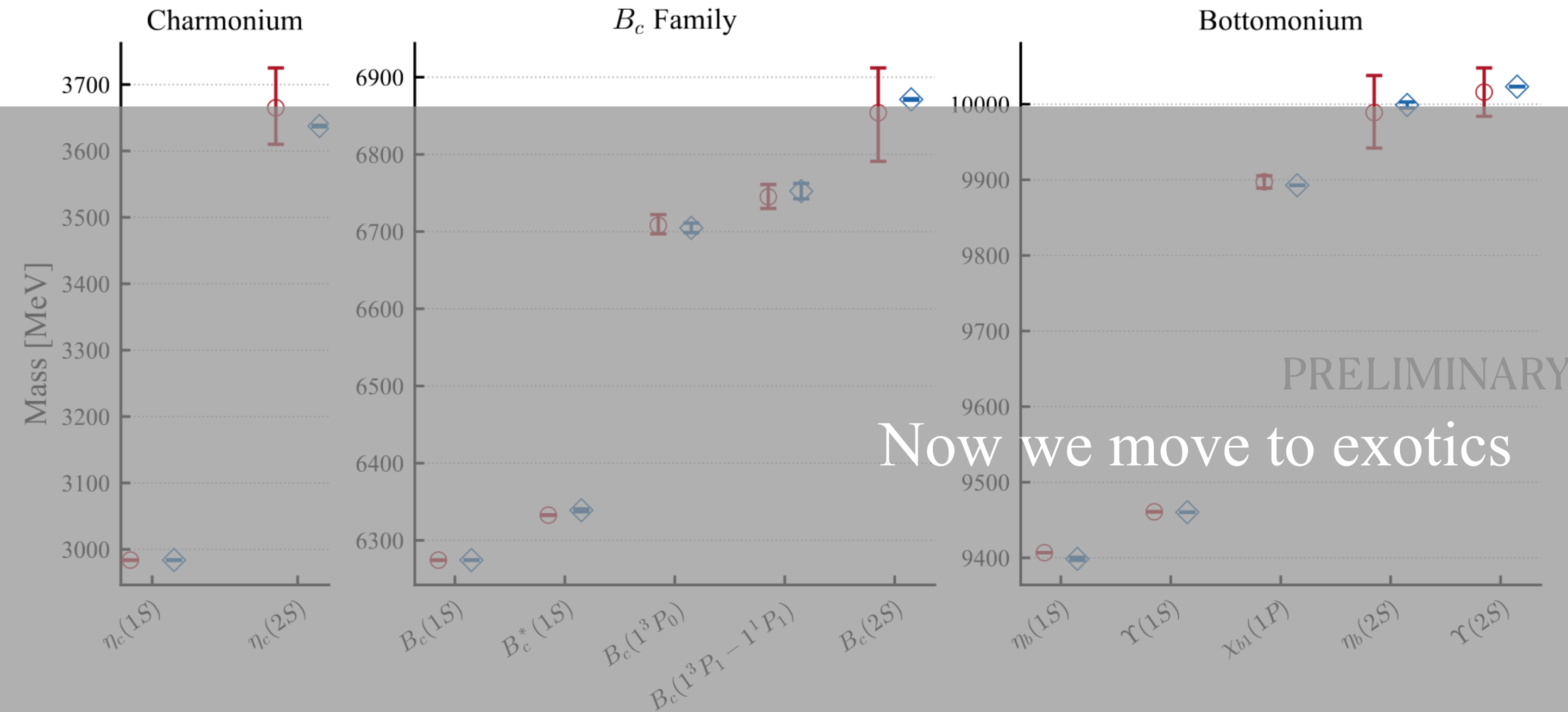


► Excited-state decay constants:
work in progress (more statistics
and systematics underway)

- Excited-state spectrum is well established in lattice QCD
- Single-operator TGEVP provides a complementary cross-check of excited-state contamination and extraction



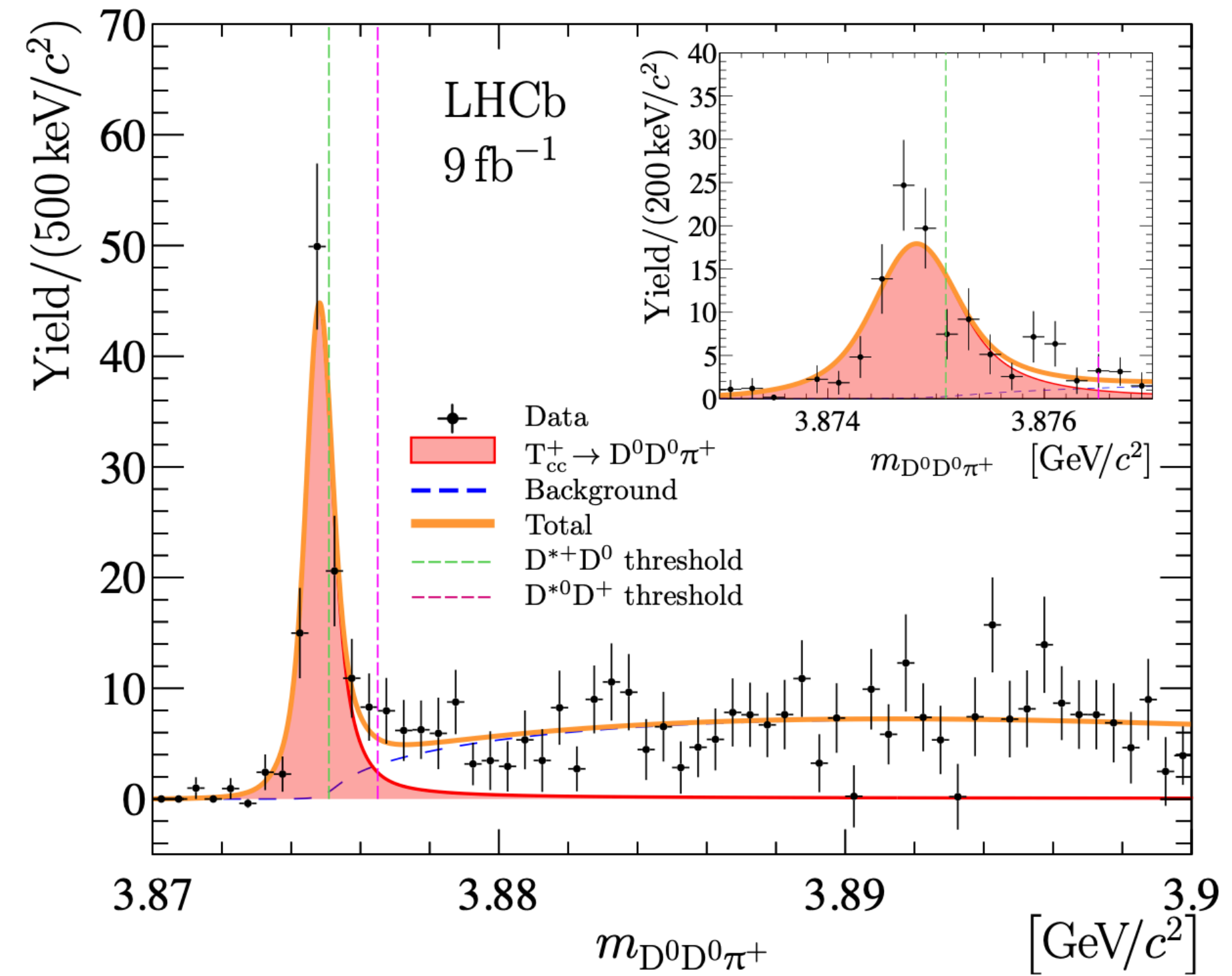
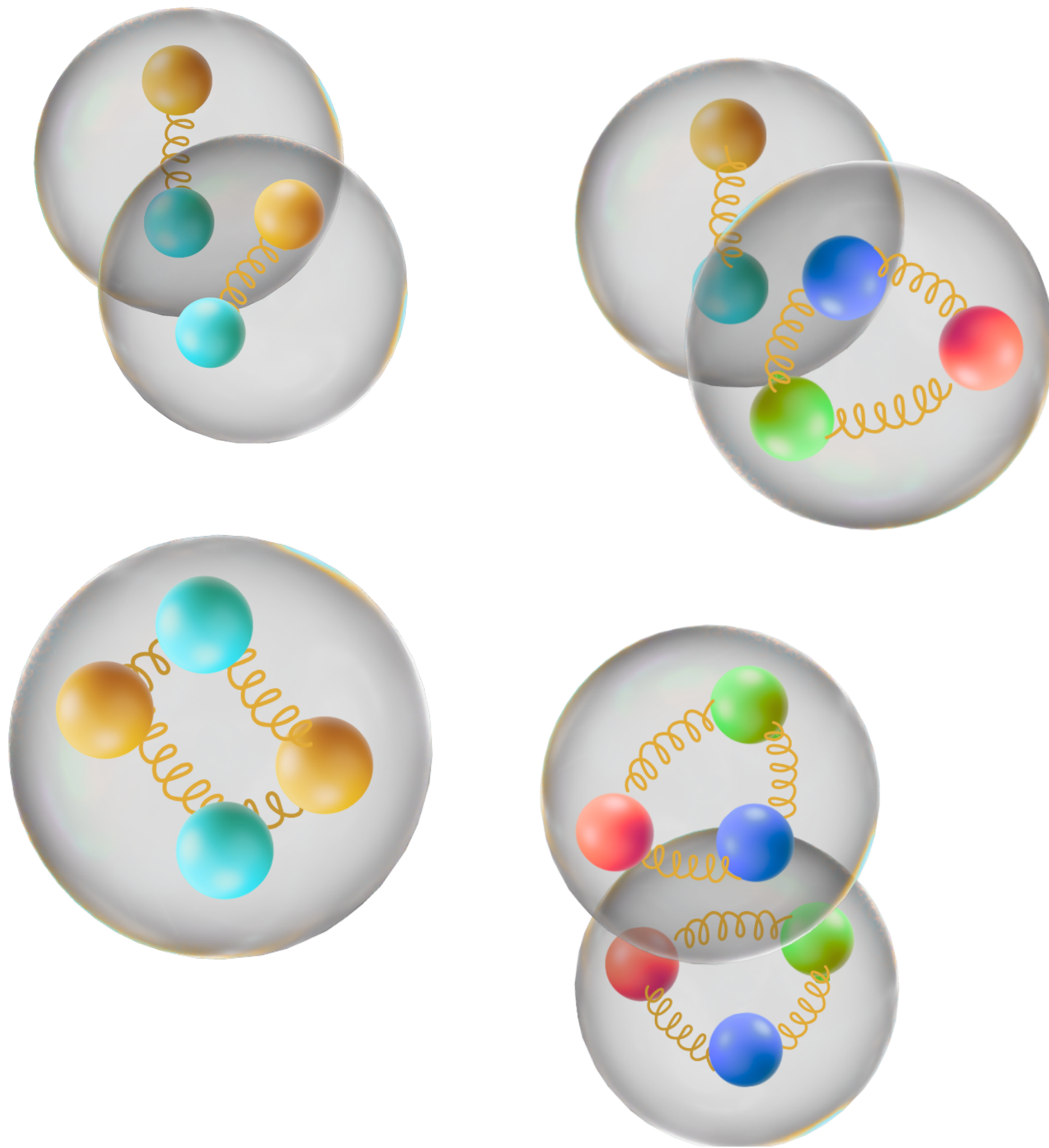
⬮ This Work
 ⬮ Exp (PDG/Recent)



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Beyond Baryons and Mesons



Nature Physics (2022) LHCb

Beyond conventional hadrons, there is significant interest in exotics spectroscopy in the community

Many other discovered recently, more expected in near future

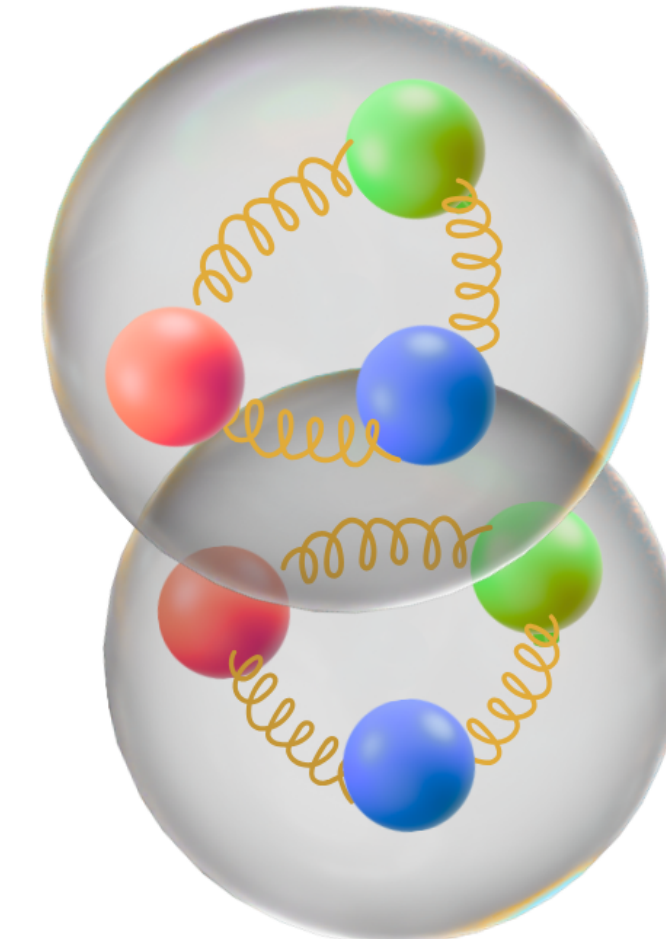


- ▶ Deuteron only stable dibaryon
- ▶ 1950's - Many predictions of various dibaryon states but failed experimental checks
- ▶ Experimental evidence of existence of d^*

Based on theory of strong interactions, we cannot rule out more dibaryons in nature.

Review by Clement
PPNP (2016)

Hexaquark - Any object with Baryon number 2
Composed of six valence quarks
Can be molecular or compact



Dineutron, Diproton, NN scattering experiments indicates absence of bound state

Tension between lattice results due to poor signal to noise ratio

Dibaryons: **fully strange and charm**

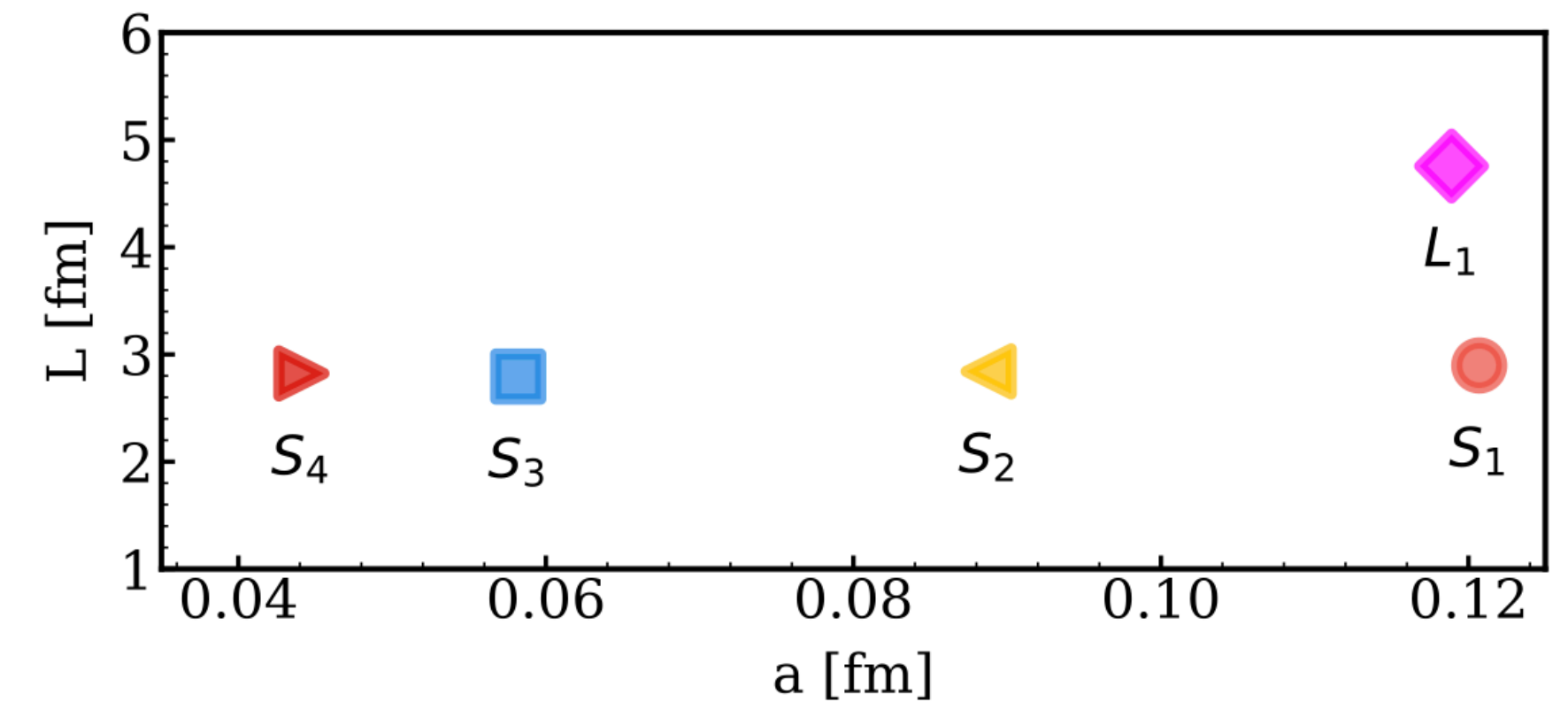
NSD, MATHUR, PADMANATH
PRD 112 (2025) 5, 054501



We work with single flavored dibaryons composed of strange and charm quarks named as $\mathcal{D}_{6s}$ and $\mathcal{D}_{6c}$ respectively

Better signals

- Overlap action on background of Highly Improved Staggered Quark (HISQ) gauge configurations
- Strange and charm masses set at physical values
- Up and down set as degenerate masses heavier than physical values
- Finest lattice used $a \approx 0.044 \text{ fm}$ with Volume as $64^3 \times 192$



Dibaryons: **fully strange and charm**

NSD, MATHUR, PADMANATH
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$$\mathcal{O} = \epsilon_{abc} q_{\mu_1}^a q_{\mu_2}^b q_{\mu_3}^c$$

► Wall source to point sink

► Cross checked results with boxsink

$$\mathcal{O}_d = \mathcal{O}_1 \cdot CG \cdot \mathcal{O}_2$$

- Total wave function anti-symmetric under exchange of baryons.
- Single flavor baryons (symmetric).
- Assume only s wave interactions (symmetric) in dibaryon system.
- Color singlet baryons (symmetric)
- Hence Spin must be anti-symmetric which is in case of even spin (Spin 0 and 2)

- Use reduction coefficients to project continuum based operators to suitable octahedral group.
- $S = 0$ continuum spin subduces to one dimensional A_1^+ irrep.
- $S = 2$ continuum spin subduces to two dimensional E^+ and three dimensional T_2^+ irrep.



Dibaryons: Operators

a,b - different embeddings

$$\mathcal{O}_{d,A_1,1}^{[0]} = \frac{1}{2} \left({}^a H_{3/2} {}^b H_{-3/2} - {}^a H_{1/2} {}^b H_{-1/2} + {}^a H_{-1/2} {}^b H_{1/2} - {}^a H_{-3/2} {}^b H_{3/2} \right)$$

For Spin 0, dibaryon operator corresponding to one dimensional A_1^+ irrep.

For Spin 2, 5 such operators corresponding to E^+ and T_2^+ irrep.

S_z	Operator	State
3/2	${}^1 H_{3/2}$	111
1/2	${}^1 H_{1/2}$	112+121+211
-1/2	${}^1 H_{-1/2}$	122+212+221
-3/2	${}^1 H_{-3/2}$	222

Non Relativistic Embedding

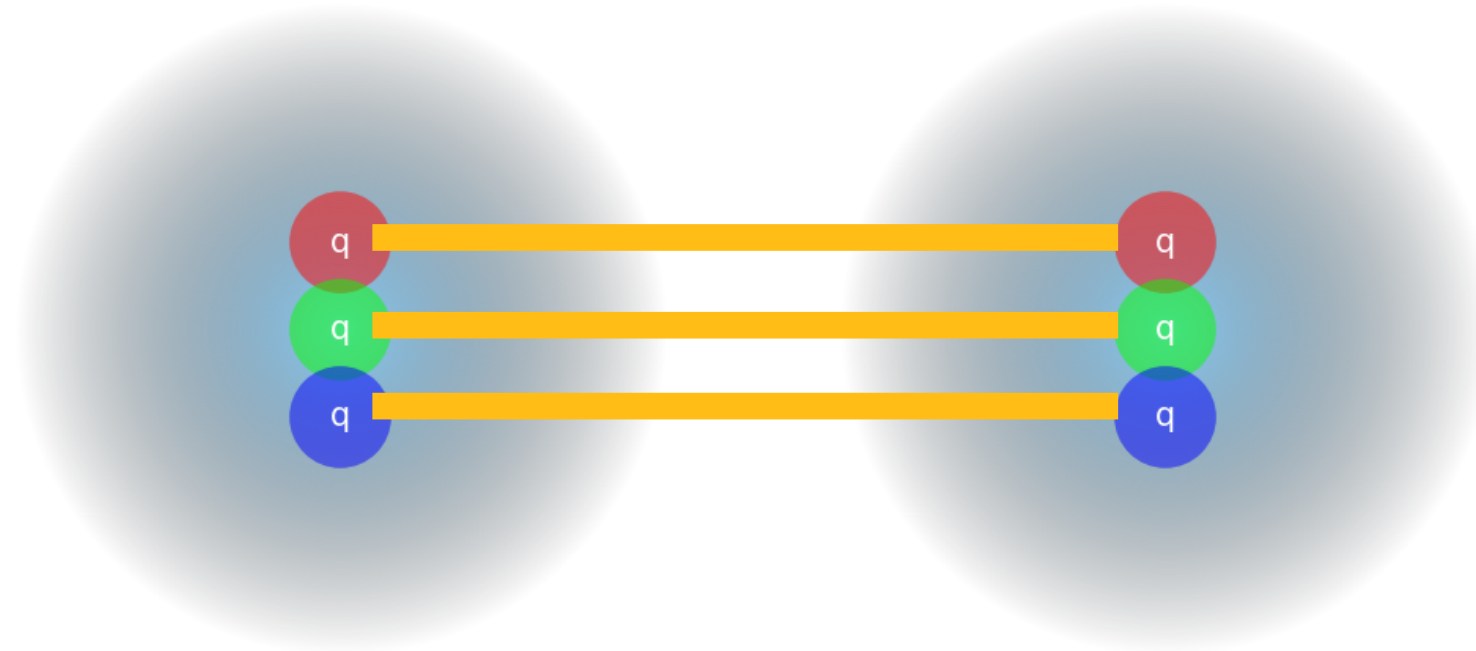
S_z	Operator	State
3/2	${}^2 H_{3/2}$	133+313+331
1/2	${}^2 H_{1/2}$	233+323+332+134+341+413+143+431+314
-1/2	${}^2 H_{-1/2}$	144+414+441+234+342+423+243+432+324
-3/2	${}^2 H_{-3/2}$	244+424+442

Relativistic Embedding

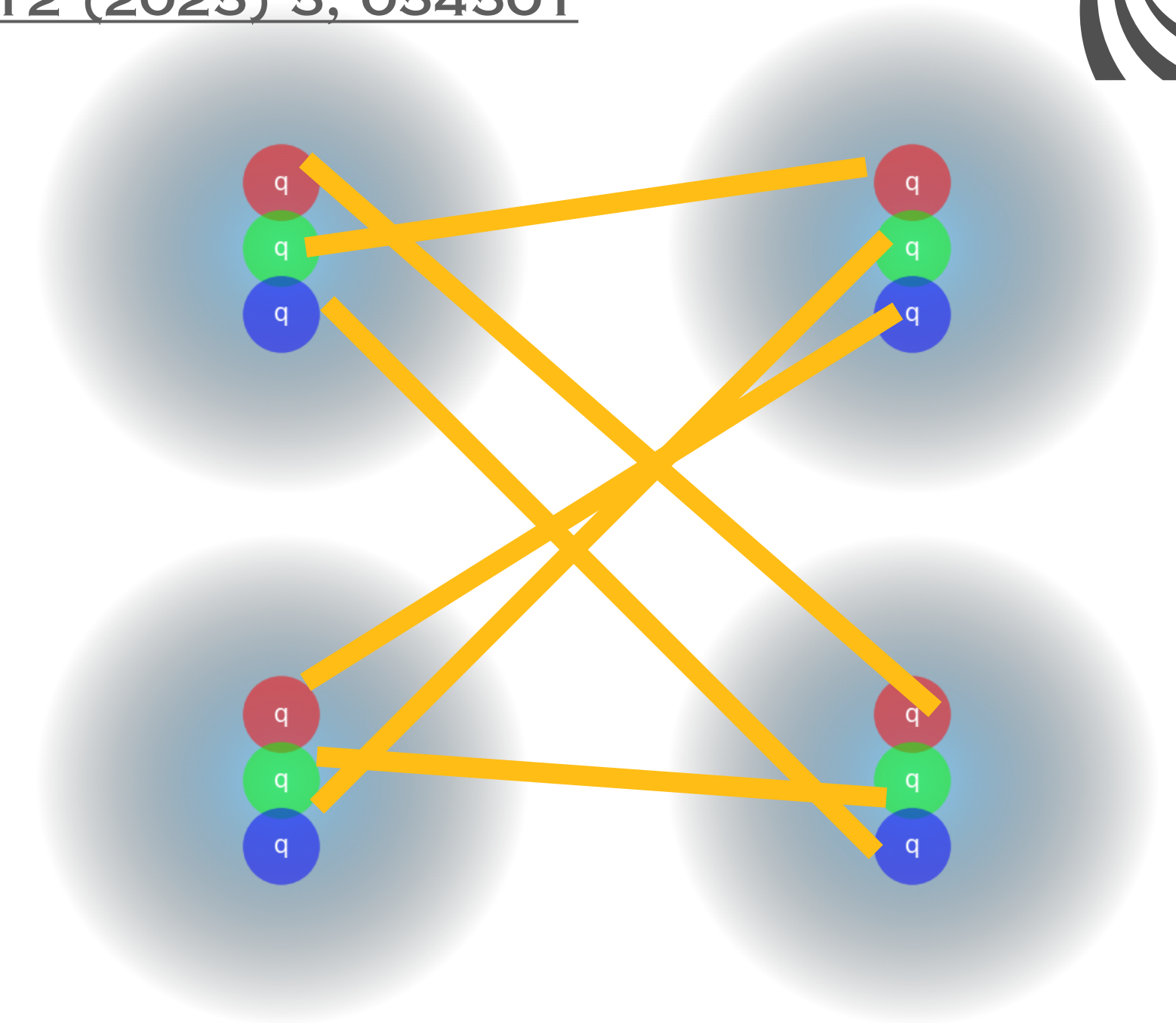
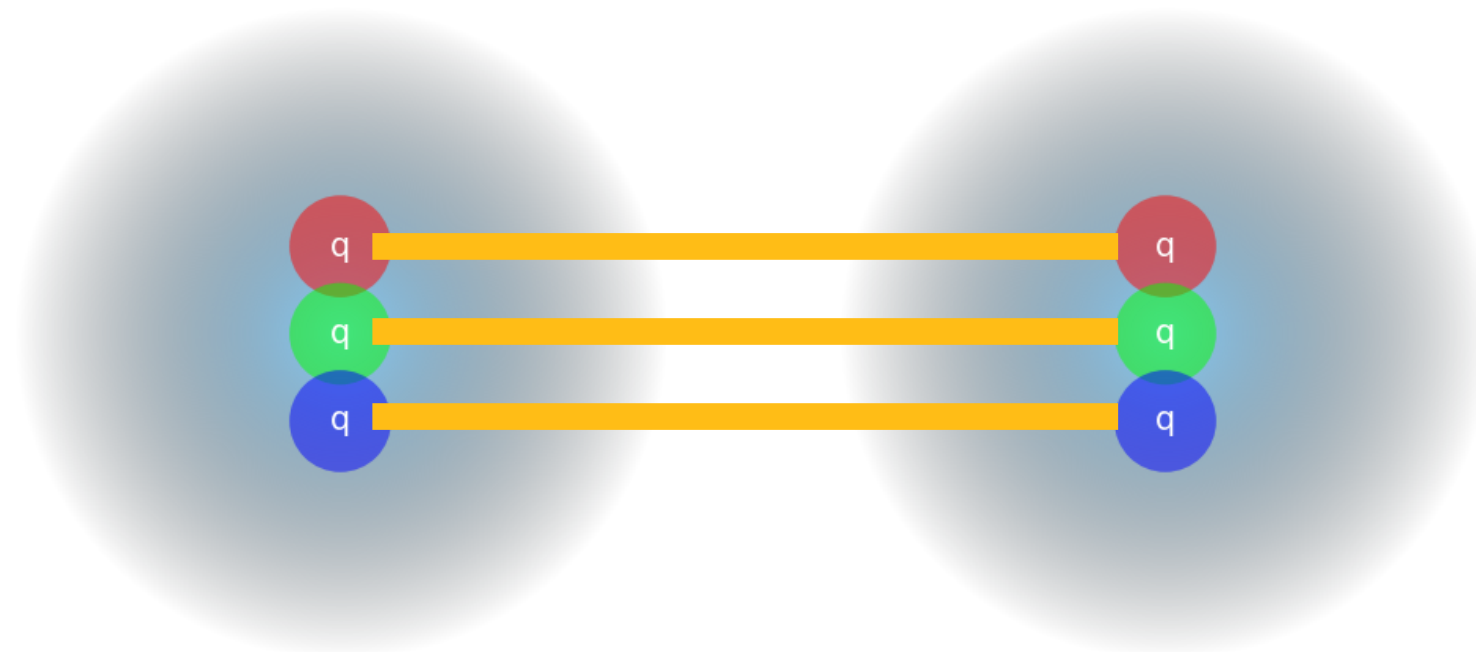


Dibaryons: Contractions

Two baryons at source and two at sink



$6! = 720$ contraction possibilities



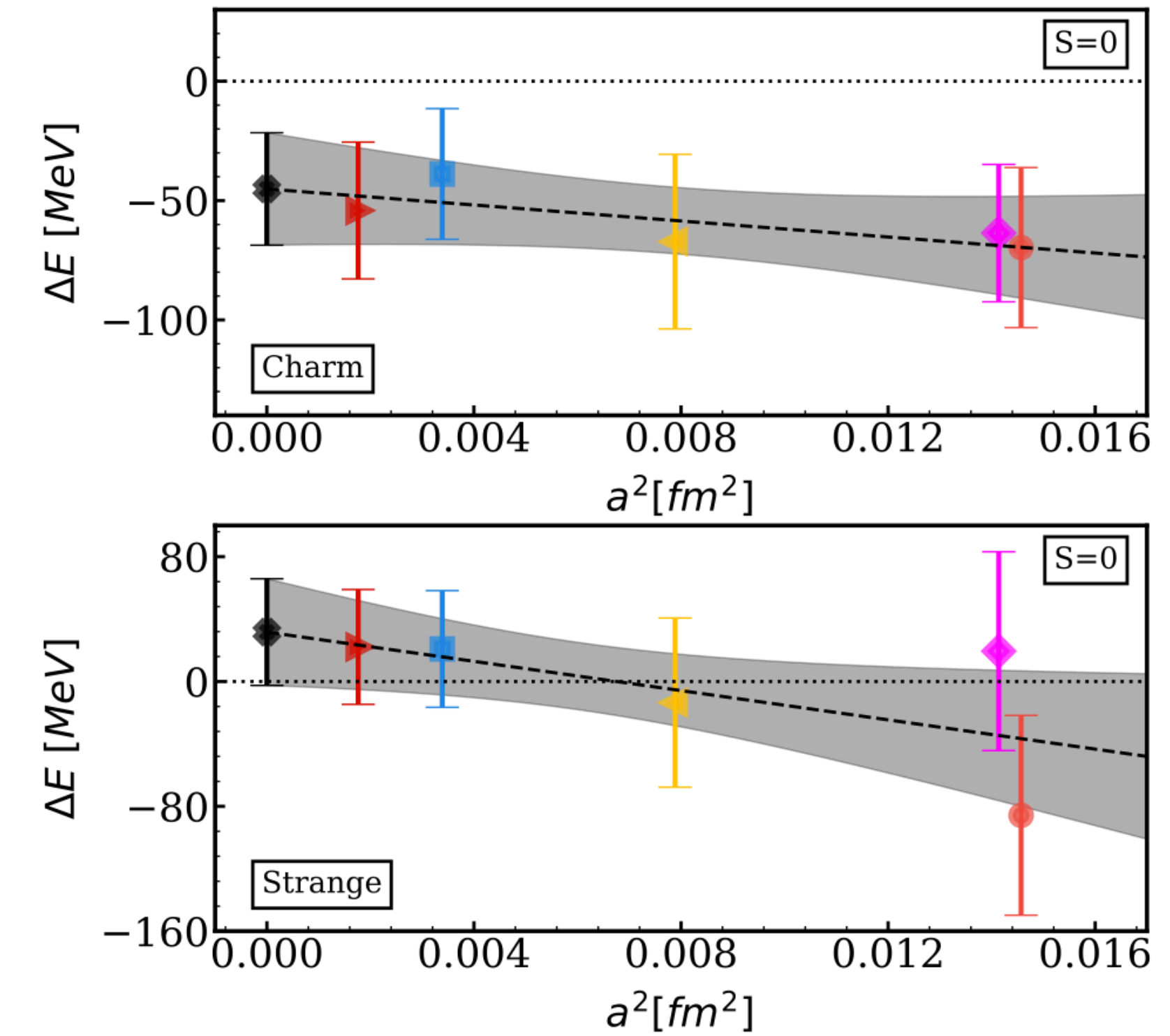
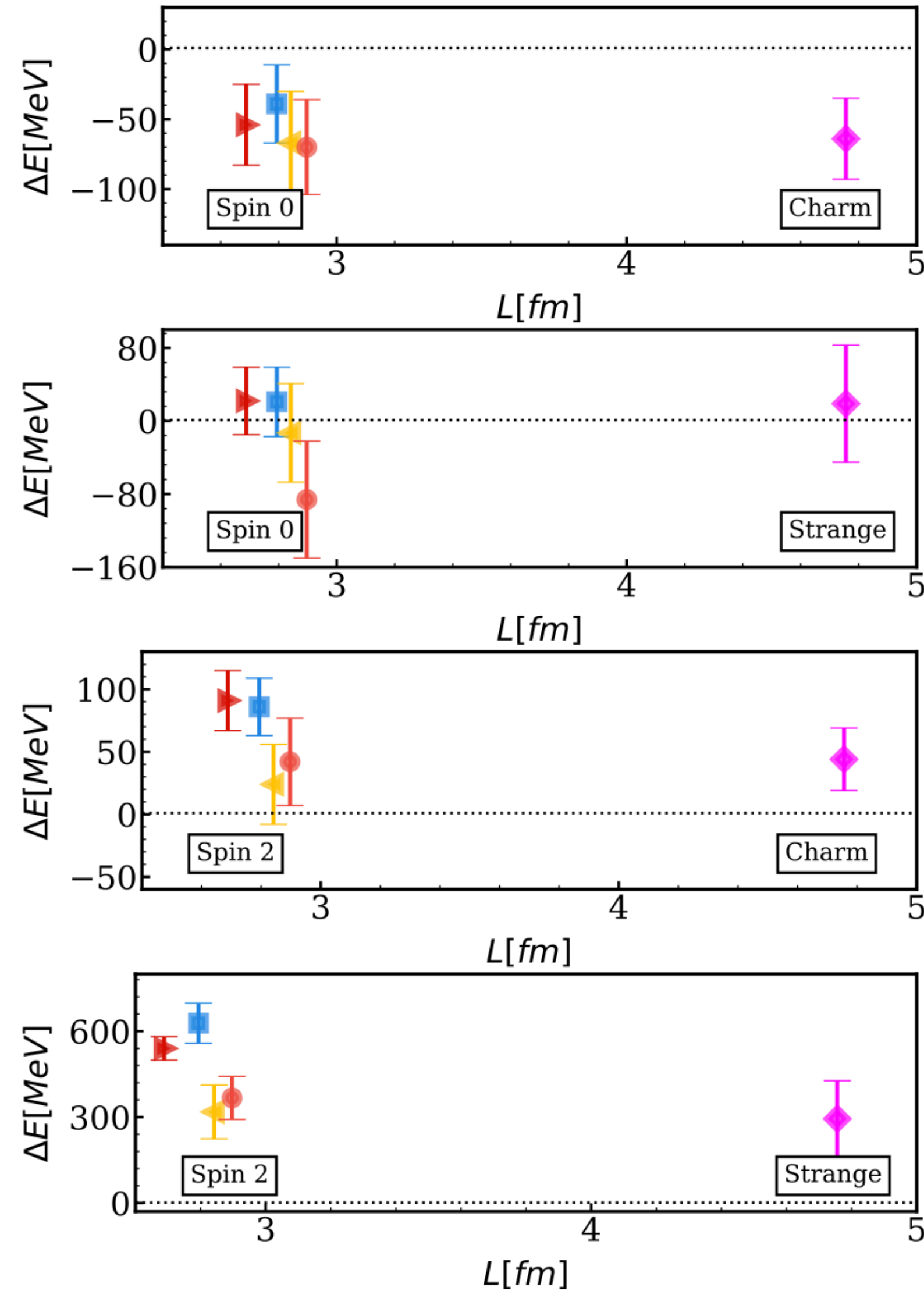
720 contractions can happen in 16 different ways depending on different embeddings

N-N-N-N	N-N-N-R	N-N-R-N	N-N-R-R
N-R-N-N	N-R-N-R	N-R-R-N	N-R-R-R
R-N-N-N	R-N-N-R	R-N-R-N	R-N-R-R
R-R-N-N	R-R-N-R	R-R-R-N	R-R-R-R

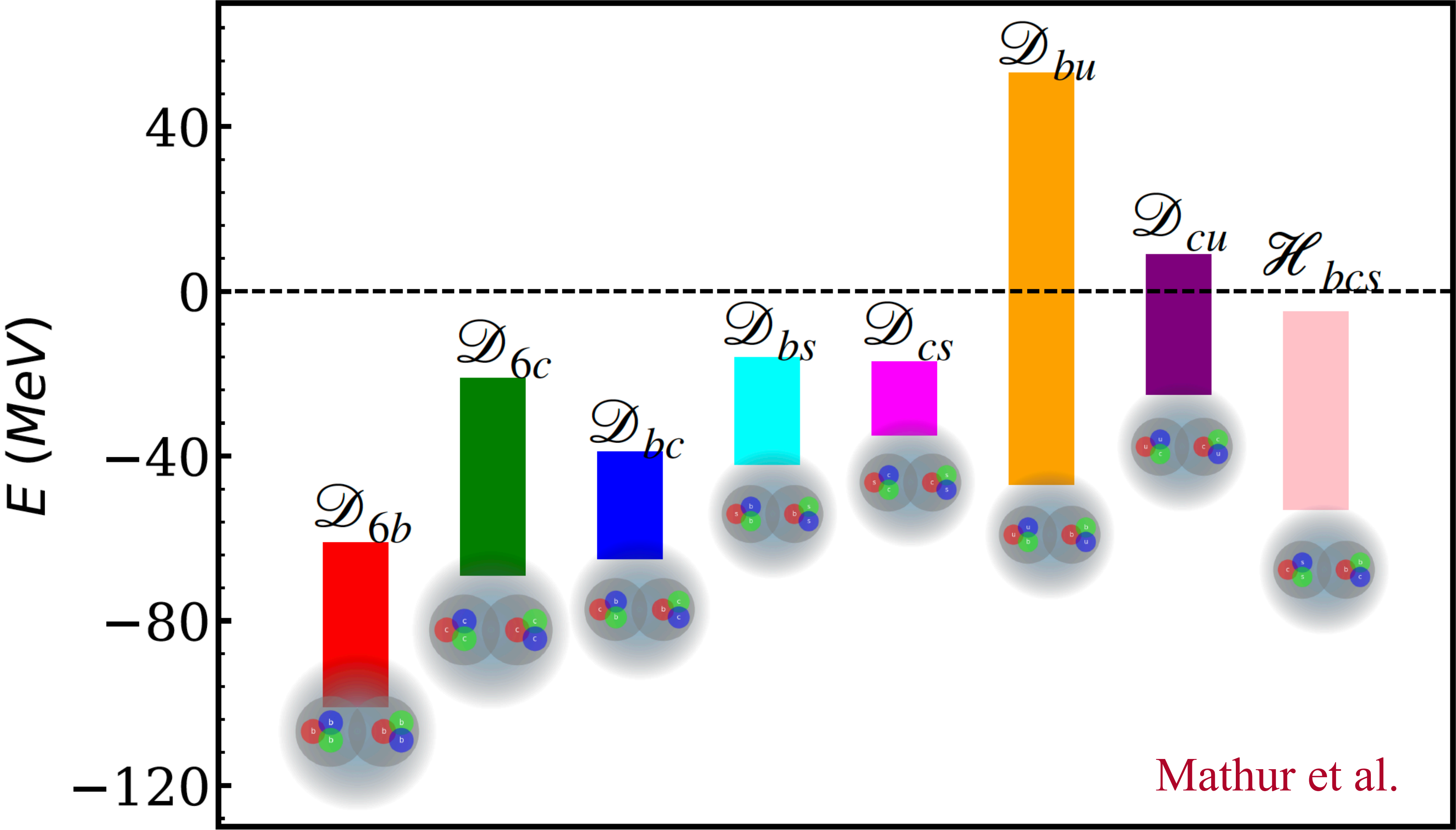
Some of these are degenerate and some of these do not contribute at all for different Spin cases

Dibaryons: Results

NSD, MATHUR, PADMANATH
PRD 112 (2025) 5, 054501



- Signal of bound state for charmed system in S=0 channel
- Near threshold behavior in S=0 strange system
- Unbound (both systems) in S=2 channel



Mathur et al.

Summary



- ☒ Lattice QCD and hadron spectroscopy
- ☒ Presented results for the Ω_{ccc} mass
- ☒ B_c family decay constants
- ☒ Fully strange and charm dibaryons
- ☐ More precise and exotic calculations underway
- ☐ Increasing focus on **algorithmic developments**, hopefully with greater computational resources

★ Any questions, comments, or expressions of interest? Feel free to reach out to any of us



THANK YOU

Navdeep Singh Dhindsa

11/08/26



tifr.link/scicomm