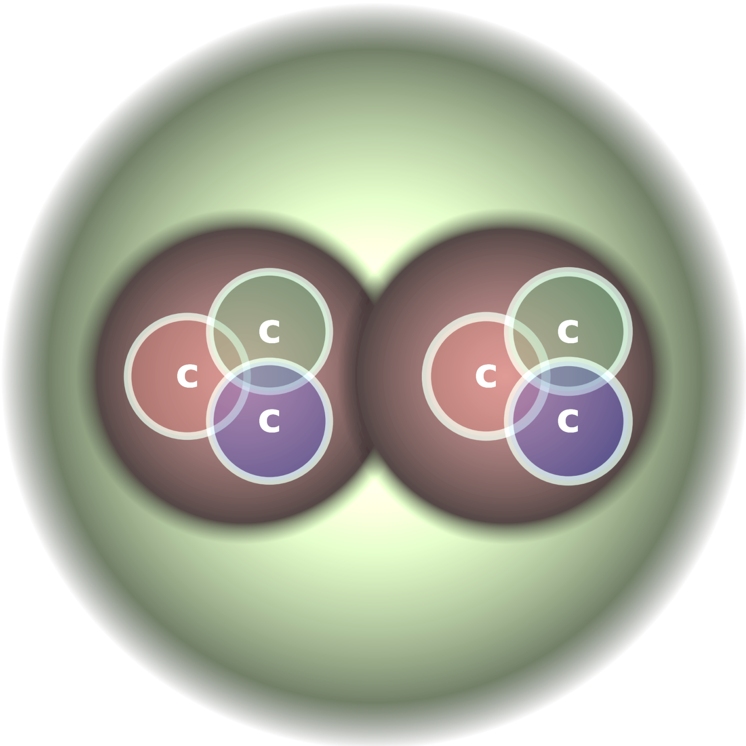

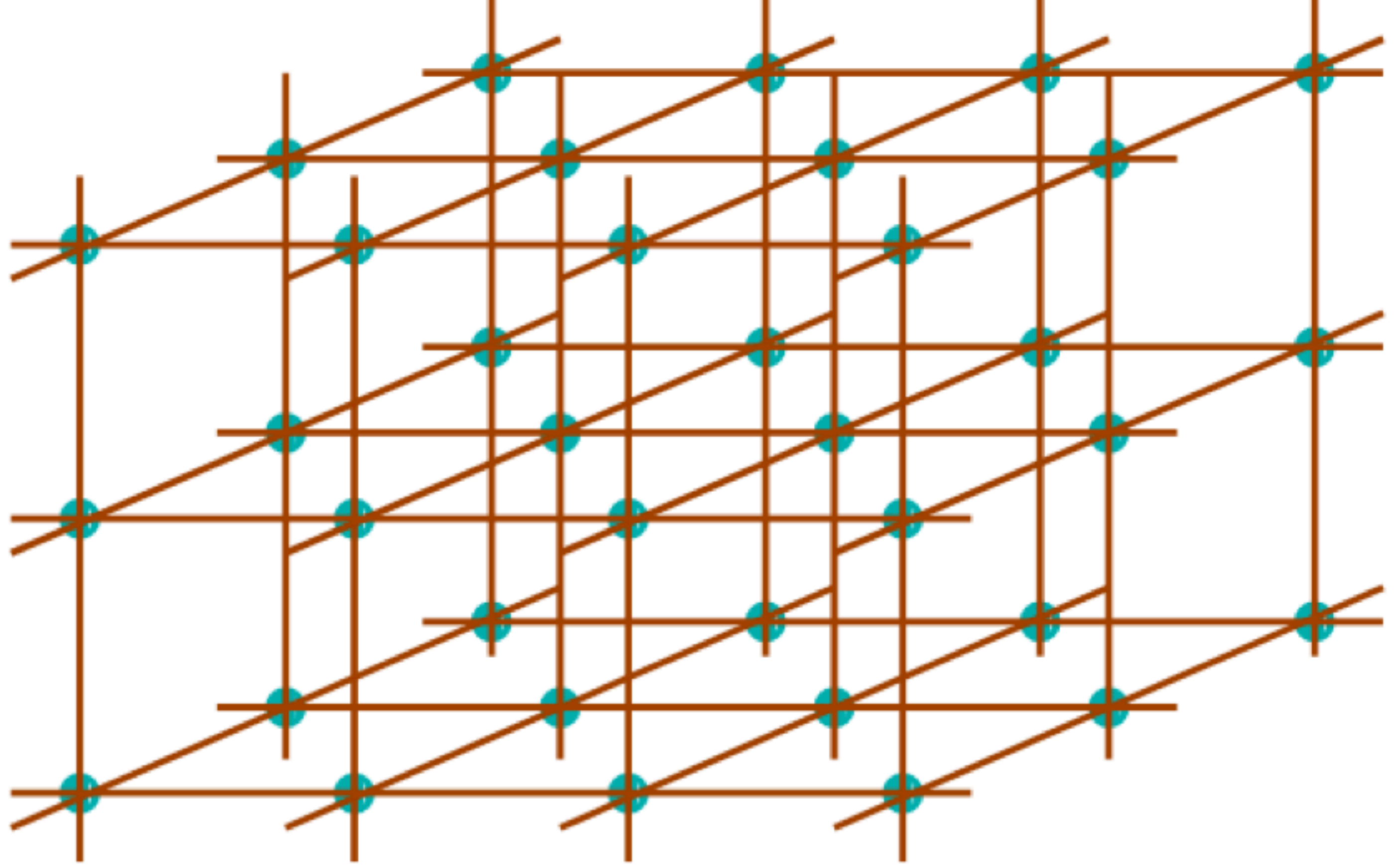

Exploring Baryon-Baryon Interactions Using Lattice QCD

Navdeep Singh Dhindsa

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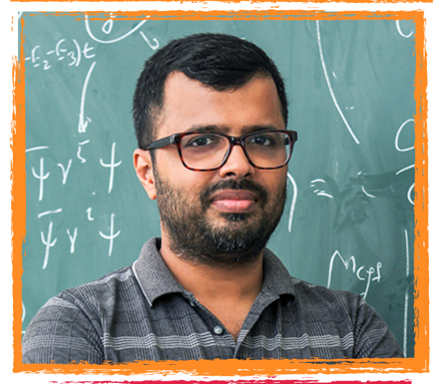
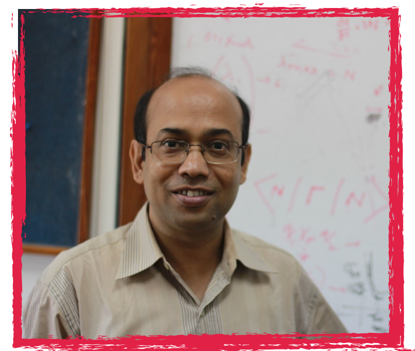
02/04/25

M Padmanath



Debsubhra Chakraborty

Archana Radhakrishnan



Nilmani Mathur

Computing Resources and Collaboration

HADRON IN NUCLEUS (HIN25)

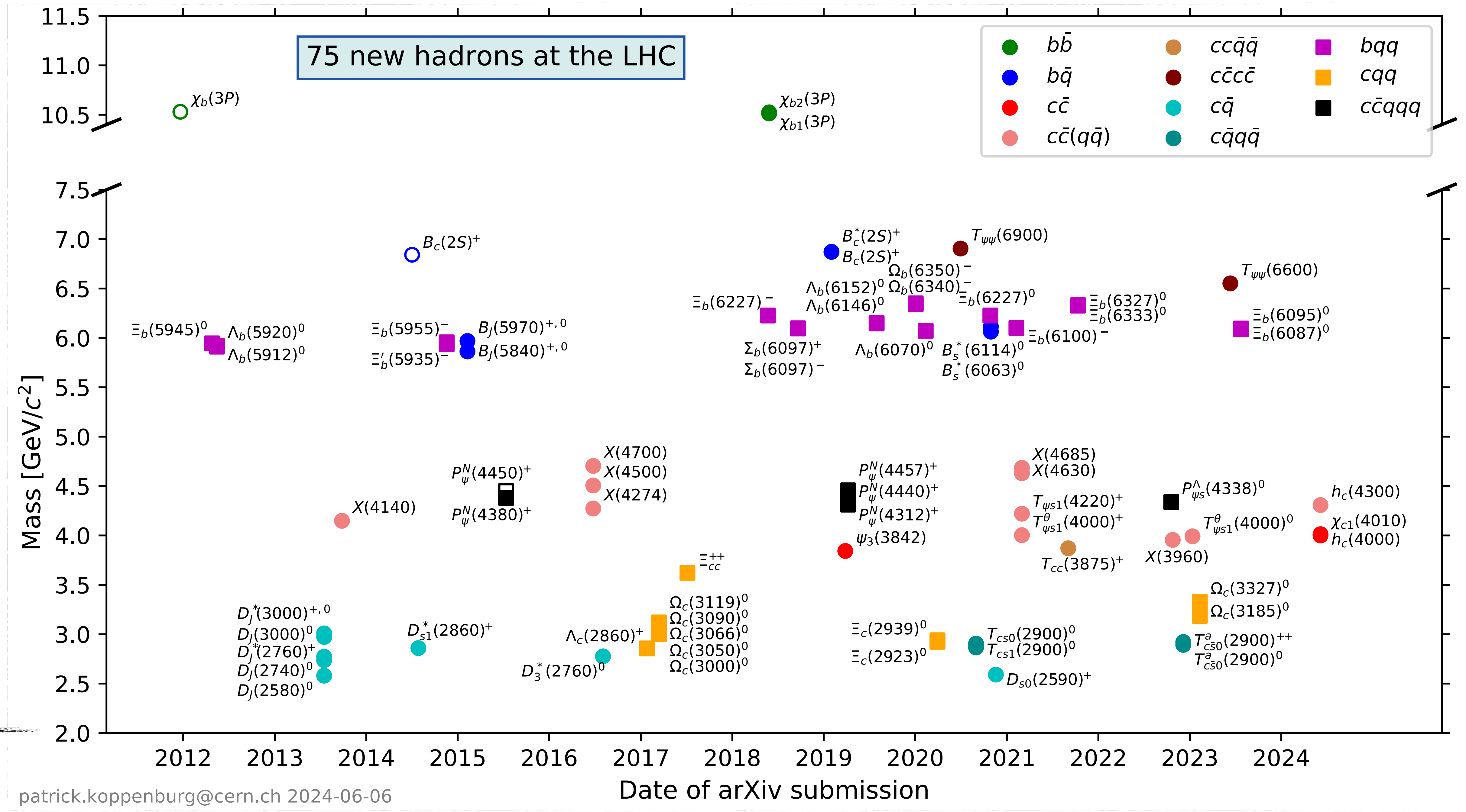
https://navdeep-dhindsa.github.io/

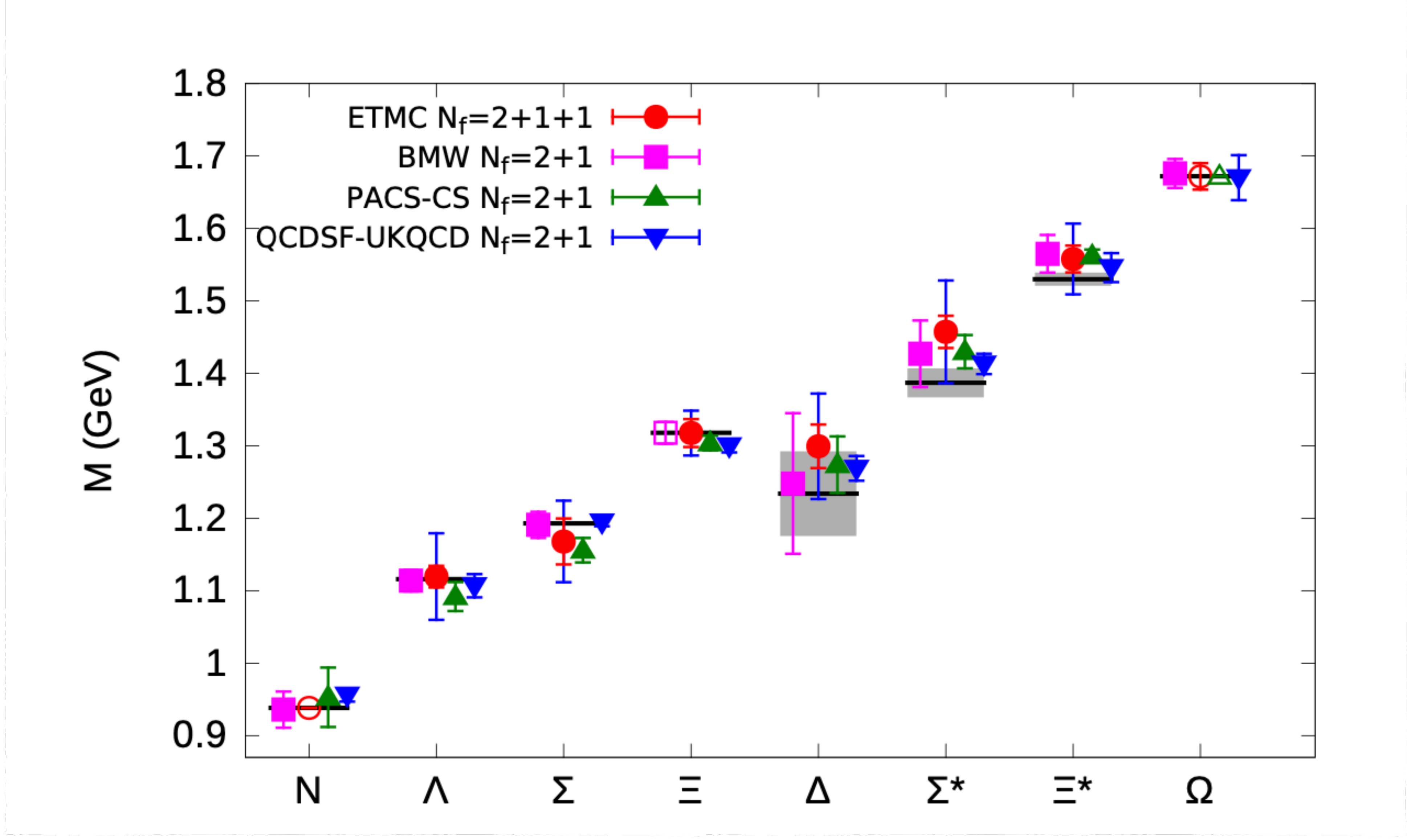
Outline

- Lattice QCD and spectroscopy
- Precise calculation of Ω_{ccc}
- Single flavoured dibaryons

Hadron Spectroscopy

- Desire to understand nature through fundamental forces and interactions.
- Recent experiments reveal missing baryon states, exotic tetraquark, and pentaquark hadrons.





- Lattice hadron spectroscopy predicted numerous bound states, including exotic hadrons. STATE OF THE ART
- More progress for bound states stable under strong decay.

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

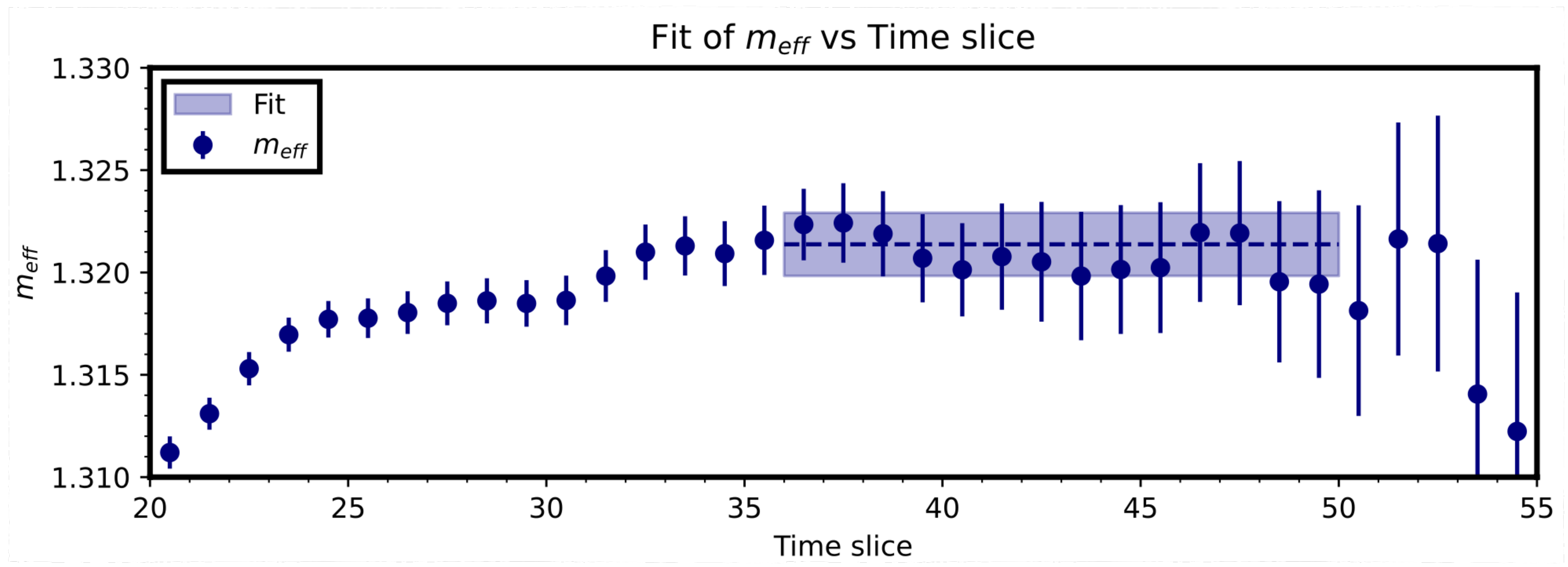
Masses from Lattice

- Euclidean two point correlator as: $C_{ji}(t_f - t_i) = \langle 0 | O_j(t_f) \bar{O}_i(t_i) | 0 \rangle = \sum_n \frac{Z_i^{n*} Z_j^n}{2m_n} e^{-m_n(t_f - t_i)}$

- $O_j(t_f)$ and $\bar{O}_i(t_i)$ are the desired interpolating operators and $Z_j^n = \langle 0 | O_j | n \rangle$

- Effective mass = $\log \left[\frac{C(t)}{C(t+1)} \right]$

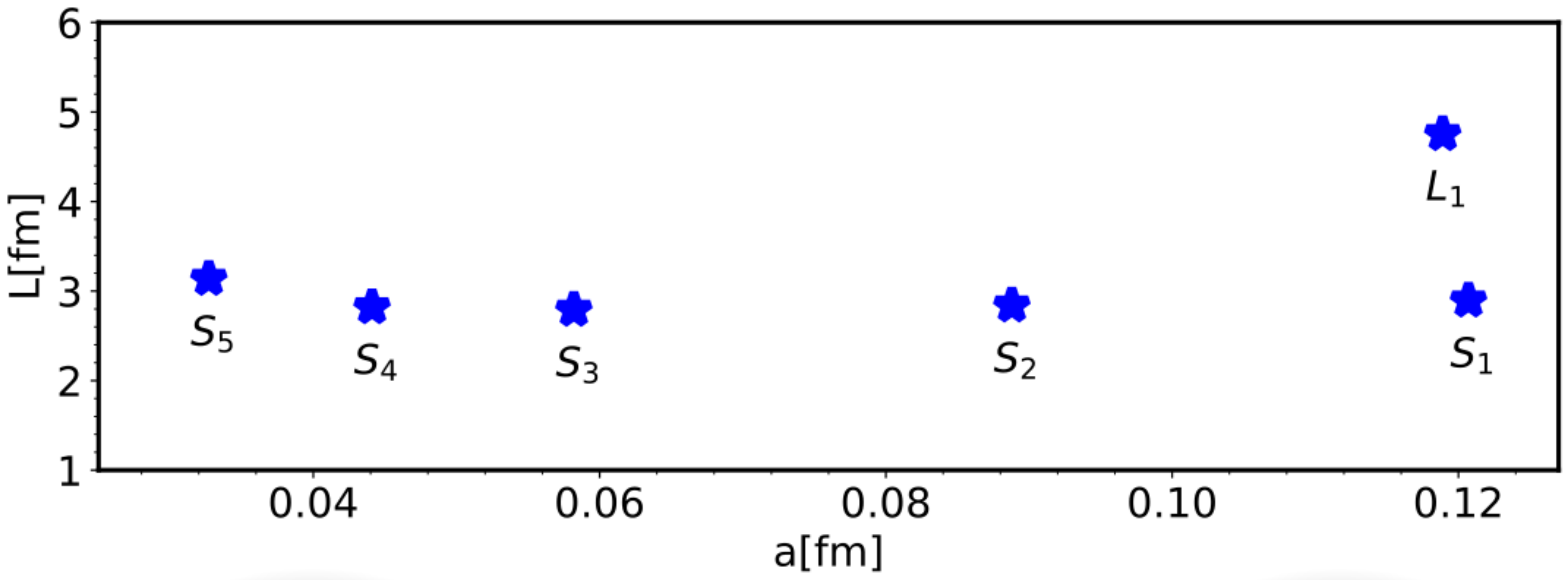
- Using GEVP



Ω_{ccc}

Heavier single flavor baryons offer simplistic system for studying quark-quark interactions and quark confinement without the complexities of valence light quark dynamics.

- Precise prediction can guide the experiments in discovering Ω_{ccc} in near future.
- 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.



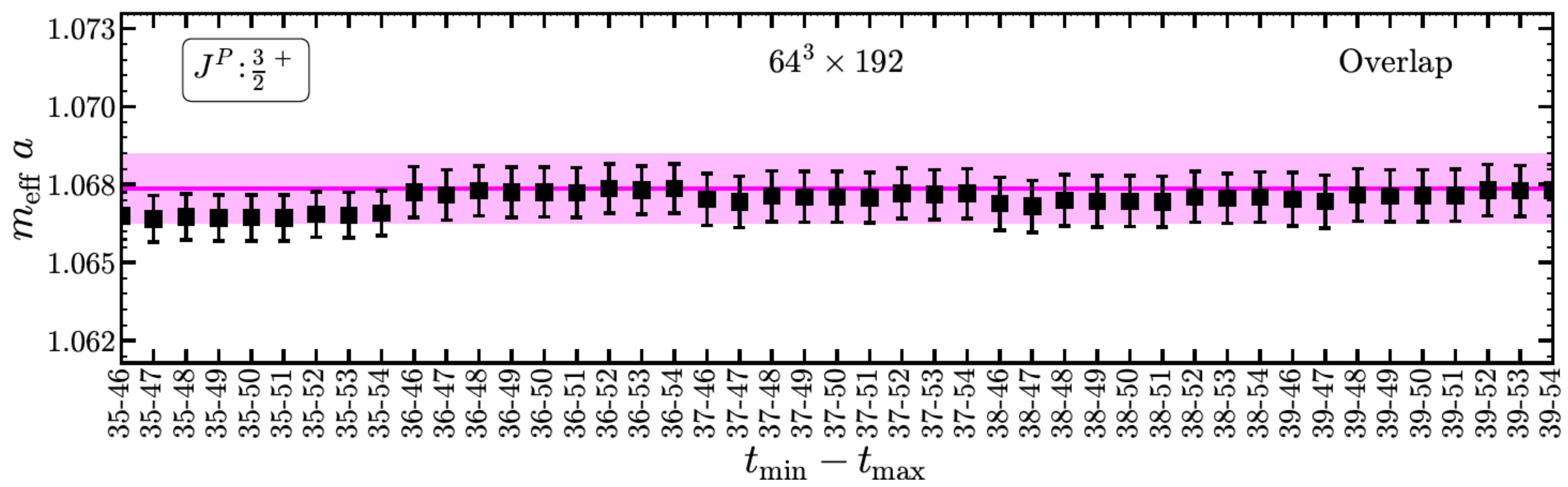
arXiv:2411.12729 NSD, Chakraborty, Radhakrishnan, Mathur, Padmanath

Ω_{ccc}

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

$$xyz_S = xyz + yzx + zxy$$

Systematics improved by varying fit ranges



Extended operator basis in Overlap calculation

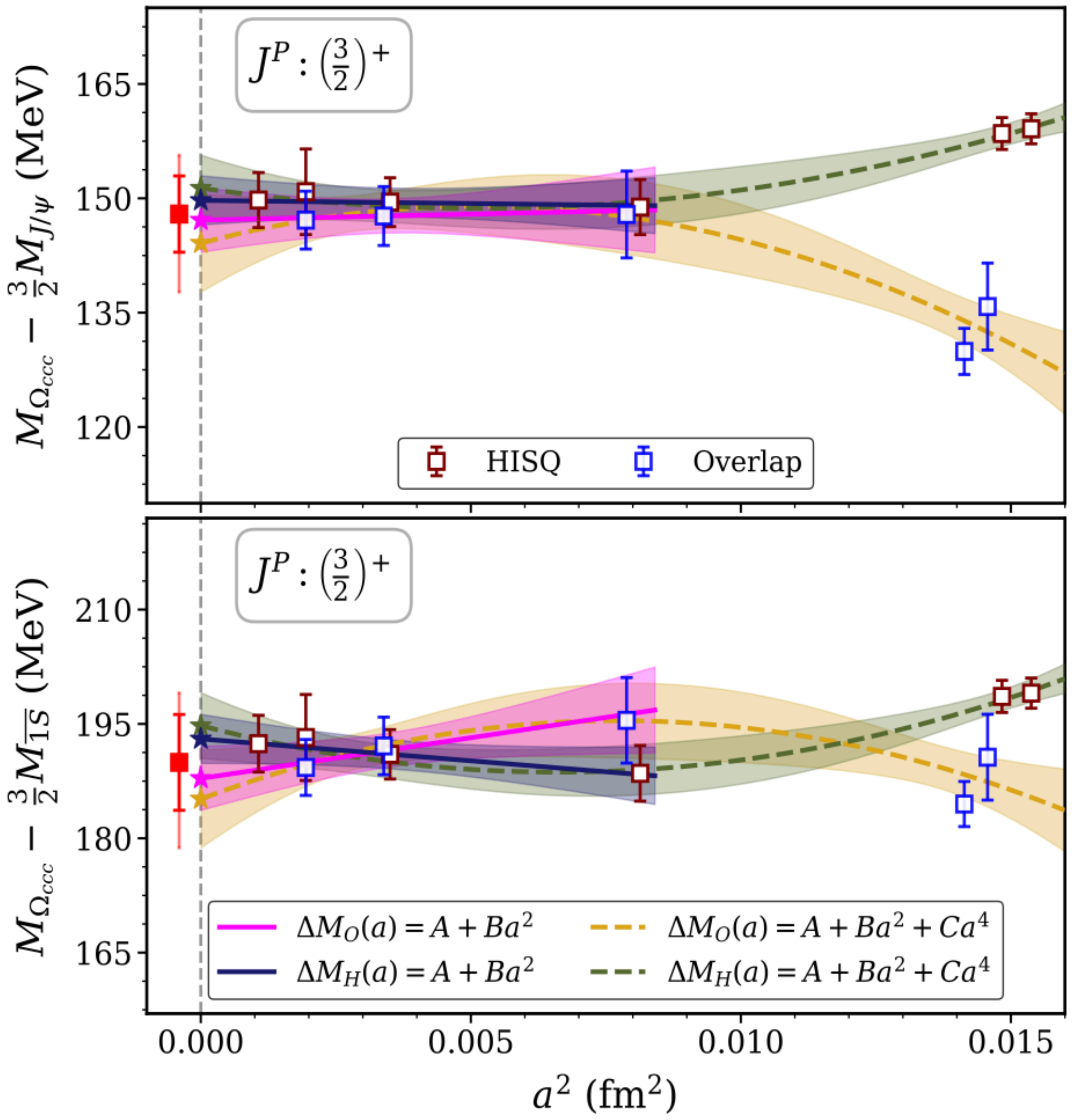
$$C_b(t) = \begin{bmatrix} \mathcal{O}^N_{b,H}\mathcal{O}^N_{b,H} & \mathcal{O}^N_{b,H}\mathcal{O}^R_{b,H} \\ \mathcal{O}^R_{b,H}\mathcal{O}^N_{b,H} & \mathcal{O}^R_{b,H}\mathcal{O}^R_{b,H} \end{bmatrix}$$

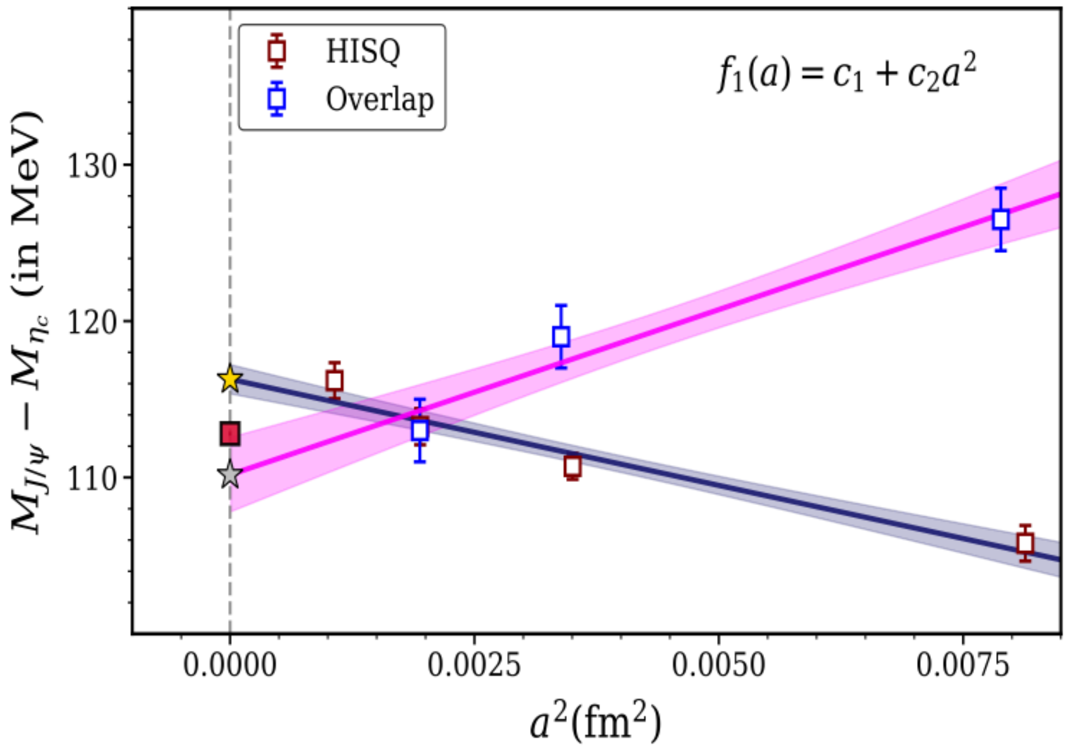
- Charmed system - much cleaner signals
- Extended basis helps with strange system as well: Not reported yet

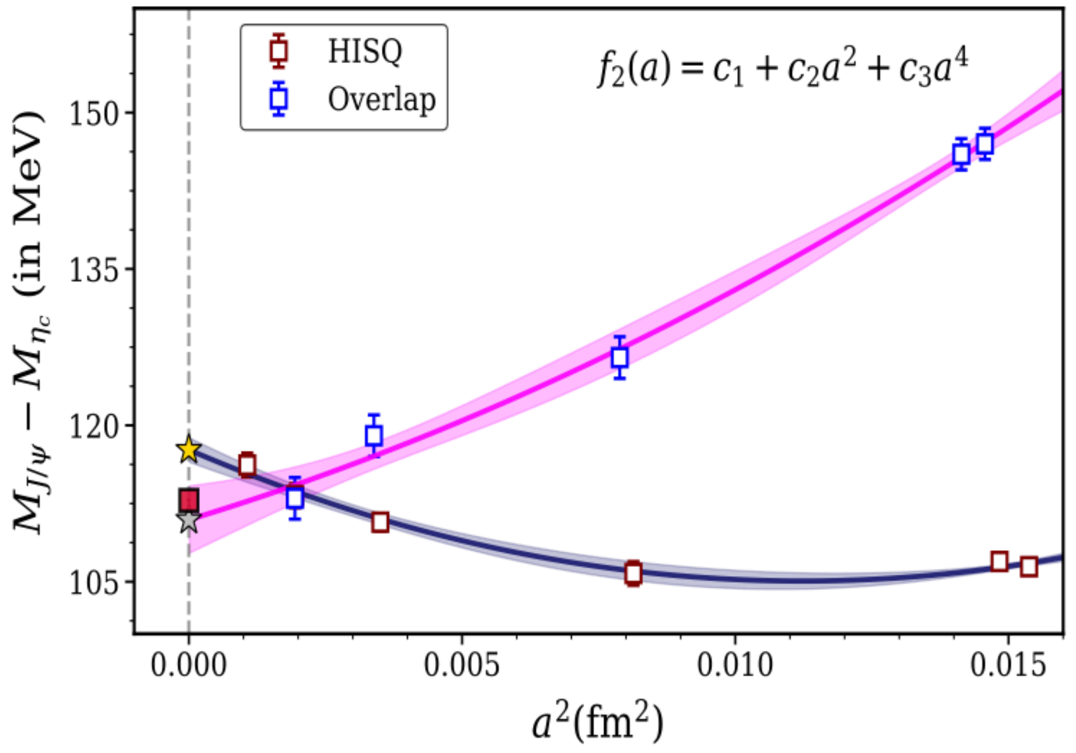
arXiv:2411.12729 NSD, Chakraborty, Radhakrishnan, Mathur, Padmanath

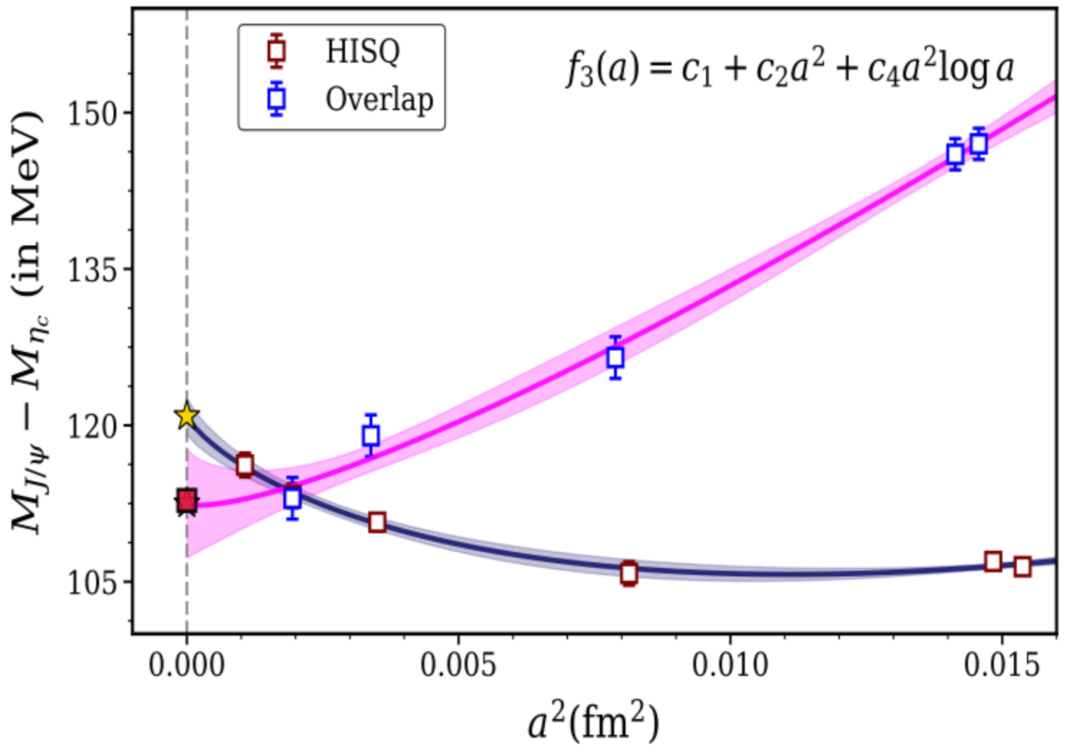
Ω_{ccc}

- $\Omega_{ccc}\left(\frac{3}{2}\right)^{+}$ estimate from its mass splitting with J/ψ.
- Utilized various fitting ansatz for continuum limit on top of two valence actions.
- Our estimate for $\Omega_{ccc}\left(\frac{3}{2}\right)^{+}$ is 4793(5)(7) MeV









MIXED ACTION

HISQ

DISCRETIZATION

arXiv:2411.12729 **NSD, Chakraborty, Radhakrishnan, Mathur, Padmanath**

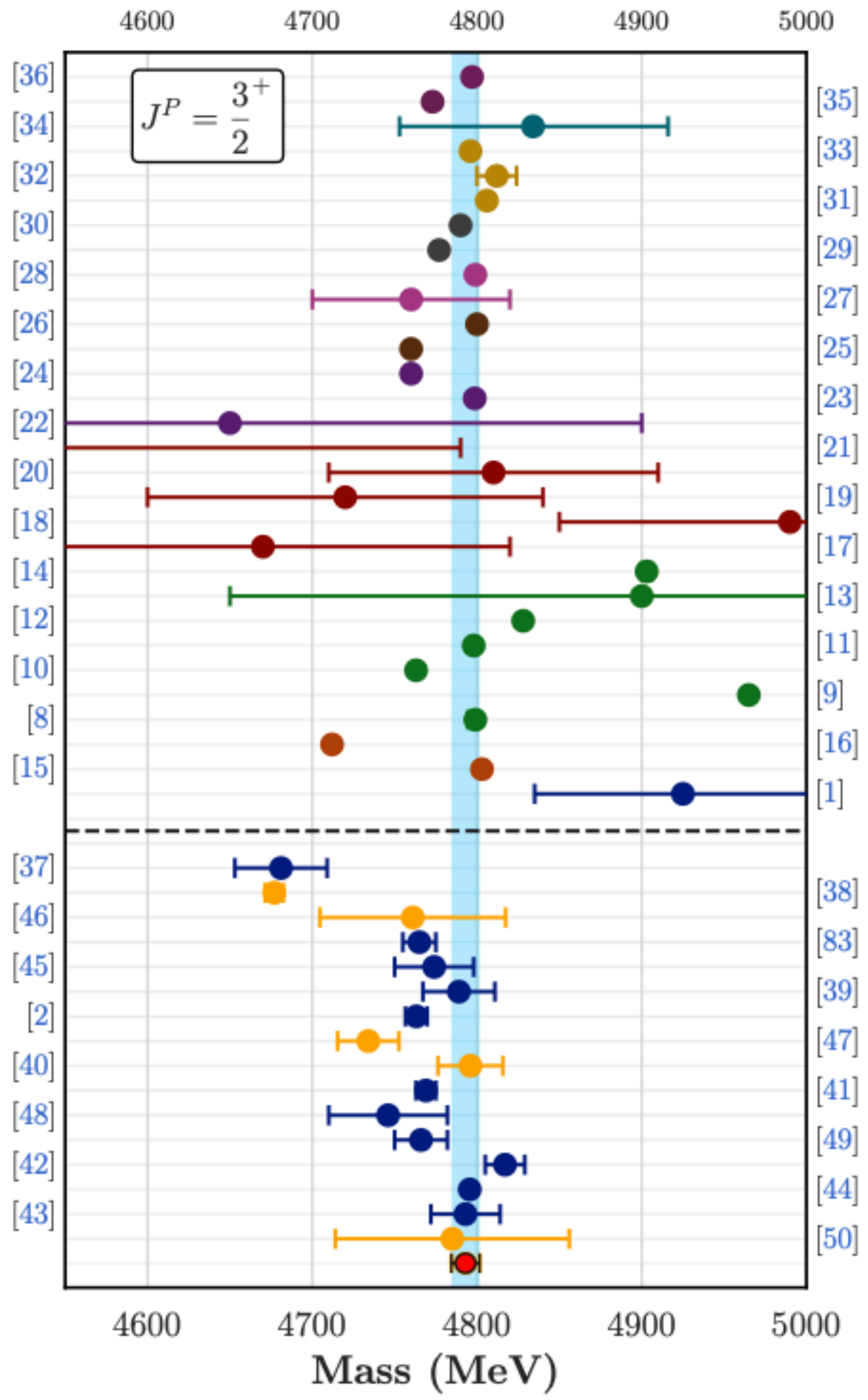
Ω_{ccc}

- Most precise results for ground state mass of triply charmed spin-3/2 baryon using lattice.

- We also give estimate to mass of $\Omega_{ccc}\left(\frac{3}{2}\right)^{-}$ to be 5094(12)(13) MeV.

- First calculation with continuum limit for a set of ensembles with lattice spacings.

- We take into account all possible sources of systematic errors that can affect our calculation.



arXiv:2411.12729 NSD, Chakraborty, Radhakrishnan, Mathur, Padmanath

Dibaryons

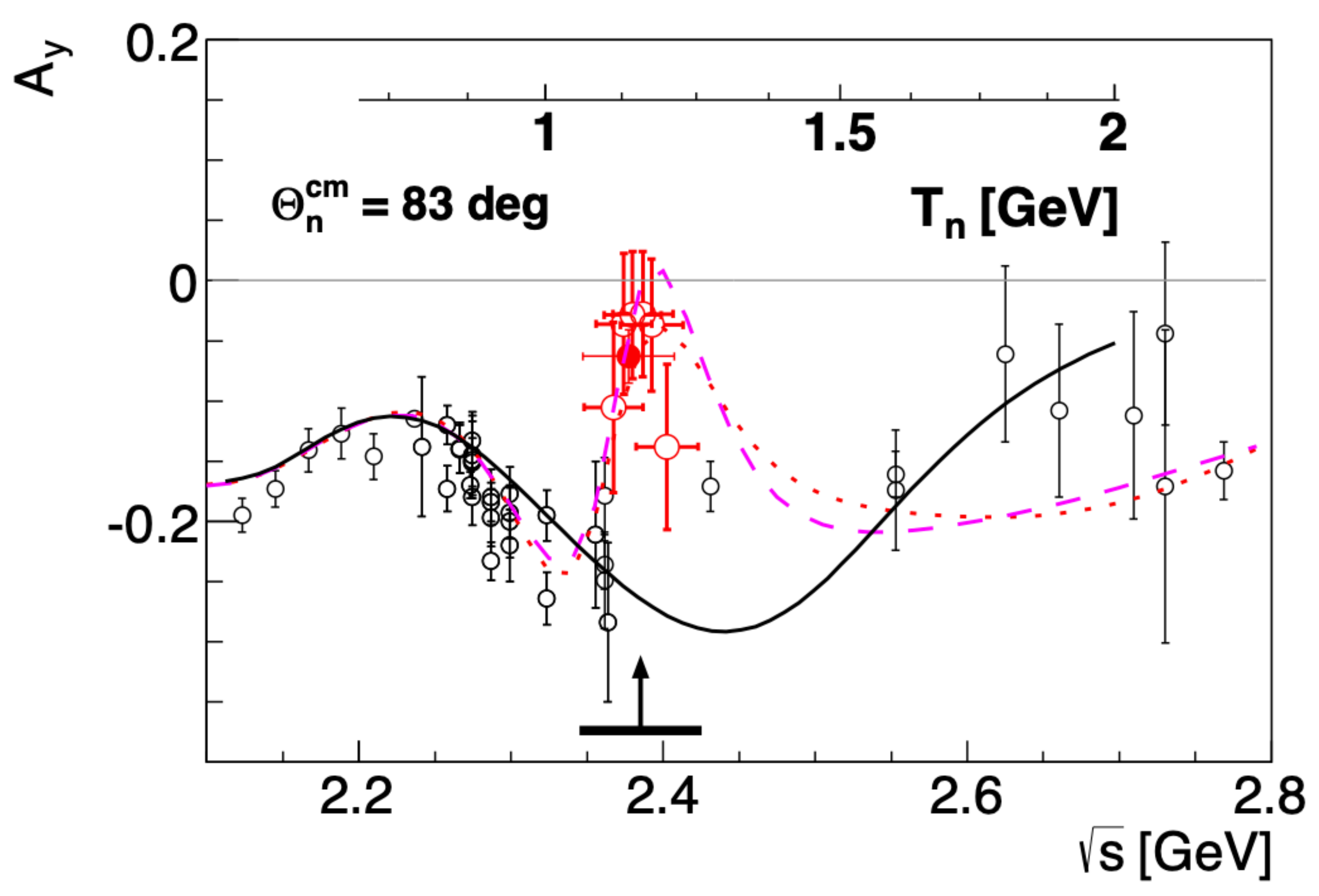
- Deuteron only dibaryon confirmed (signal of d*).
- Lesser prospect of discovery for heavy dibaryons but good test bed for baryon-baryon interactions, lesser light quark effects.
- Lighter dibaryons investigated with very high unphysical pion mass due to signal-to-noise ratio. Contrasting results on the lattice.

Tetraquarks, Pentaquarks, Hexaquarks?

- **QCD** - theory of strong interactions; can't rule out more dibaryons in nature

Dibaryons

WASA @ COSY PRL **112** (2014) 202301



Dyson and Xuong PRL **13** (1964) 815

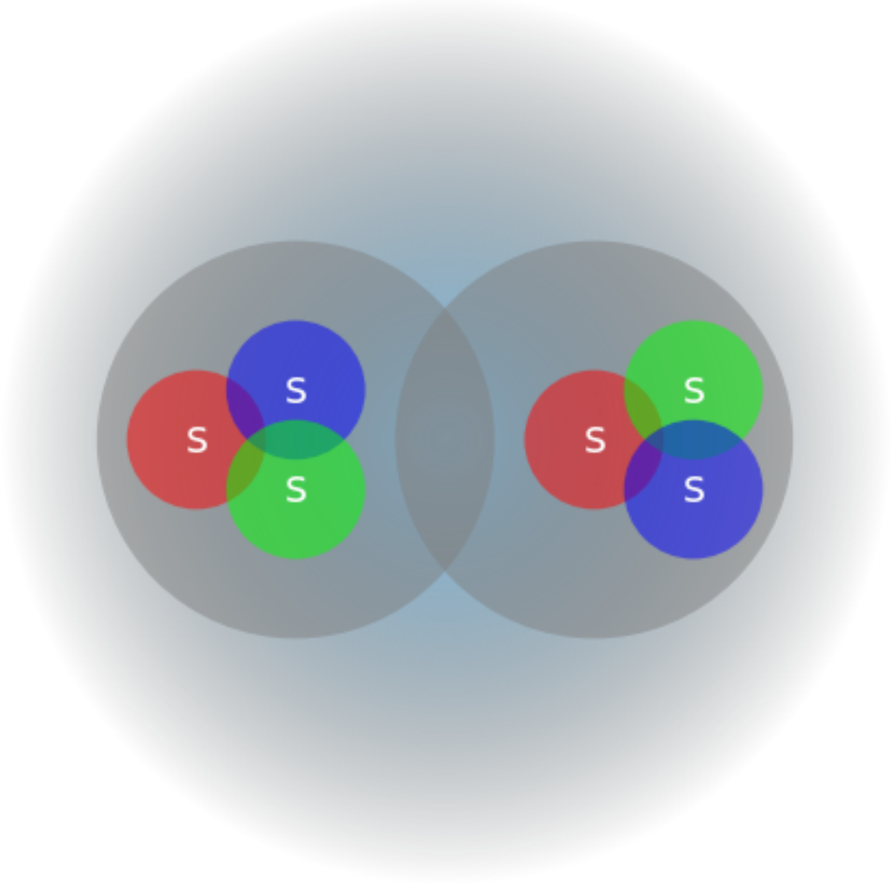
1964 - Prediction of possible bound states

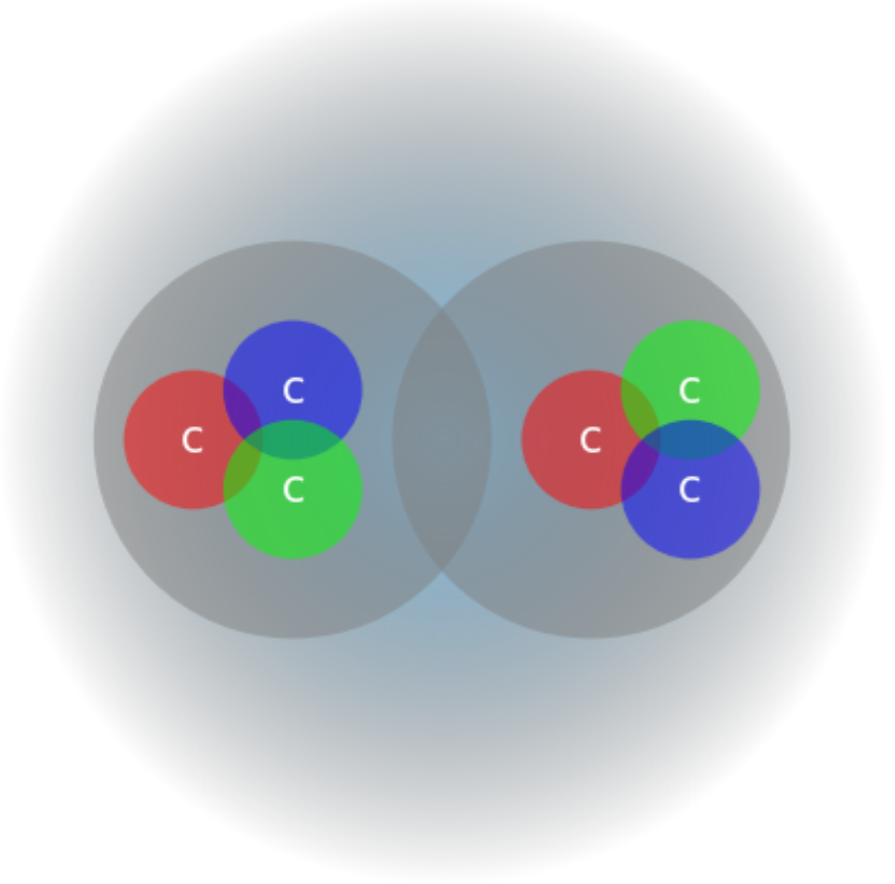
They predicted mass of D_{03} (close to d* which was found later)

On Lattice: Signal to Noise ratio exponentially degrades for $m_q \to 0$

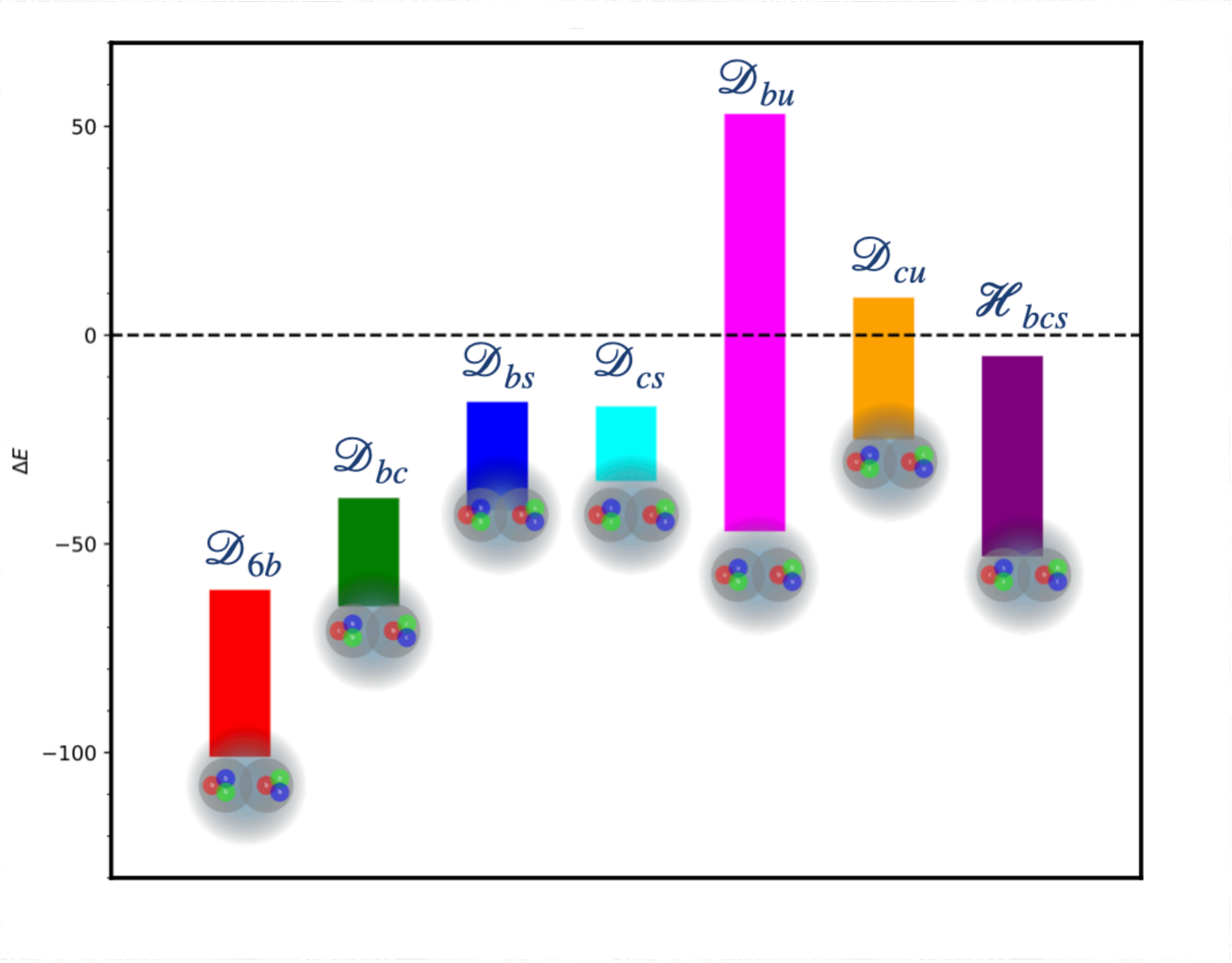
Lepage, TASI (1989)

Our this work we focus on:





Dibaryons



$\mathcal{D}_{6b}, \quad S = 0$

Mathur, Padmanath, Chakraborty PRL, 130, 111901 (2023)

$\mathcal{D}_{bc}, \ \mathcal{D}_{bs}, \ \mathcal{D}_{cs}, \ \mathcal{D}_{bu}, \ \mathcal{D}_{cu}, S = 1$

Junnarkar, Mathur PRL, 123, 162003 (2019)

$\mathcal{H}_{bcs}, \quad S = 0$

Junnarkar, Mathur PRD, 106, 054511 (2022)

Where does $\mathcal{D}_{6c}, \mathcal{D}_{6s}$ stand ??

Dibaryons

$$\mathcal{O}_d = \mathcal{O}_1 \,.\, CG \,.\, \mathcal{O}_2$$

- 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.

$$^{[S]}\mathcal{O}^{a,b}_{d,\Lambda,\lambda} = \sum_{S_j} \mathcal{S}^{S,S_j}_{\Lambda,\lambda}\, \mathcal{O}^{[S,S_j]a,b}_{d}$$

PoS(LATTICE2024)082, arXiv:25xx.yyyyy NSD, Mathur, Padmanath

Dibaryons

$$\mathcal{O}_d = \mathcal{O}_1 \,.\, CG \,.\, \mathcal{O}_2$$

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

- $S = 0$ continuum spin subduces to one dimensional A_1^+ irrep.
- $S = 2$ continuum spin subduces to two dimensional E^+ and three dimensional T_2^+ irrep.

a,b - different embeddings

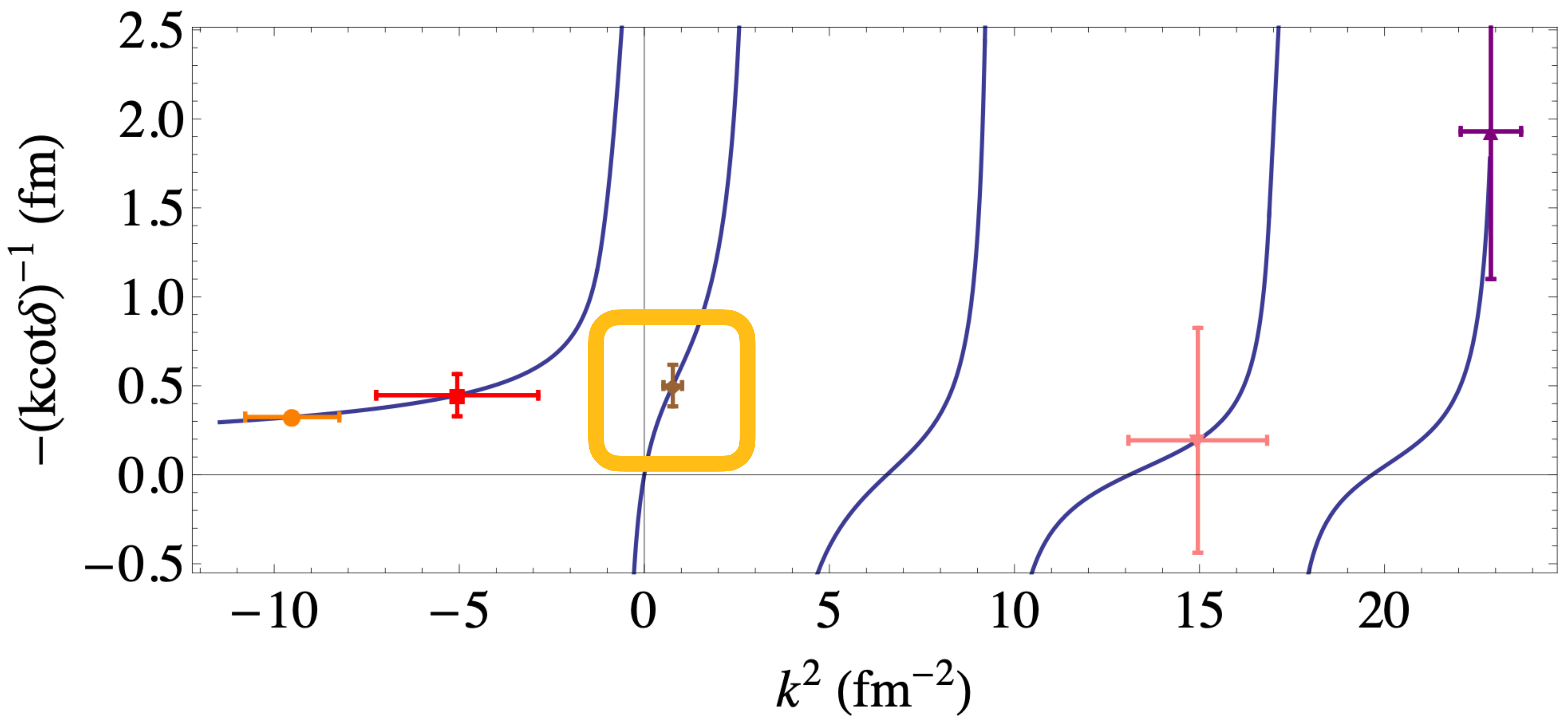
$$\mathcal{O}^{[0]}_{d,A_1,1} = \frac{1}{2}\left({}^aH_{3/2}\ {}^bH_{-3/2} - {}^aH_{1/2}\ {}^bH_{-1/2} + {}^aH_{-1/2}\ {}^bH_{1/2} - {}^aH_{-3/2}\ {}^bH_{3/2}\right)$$

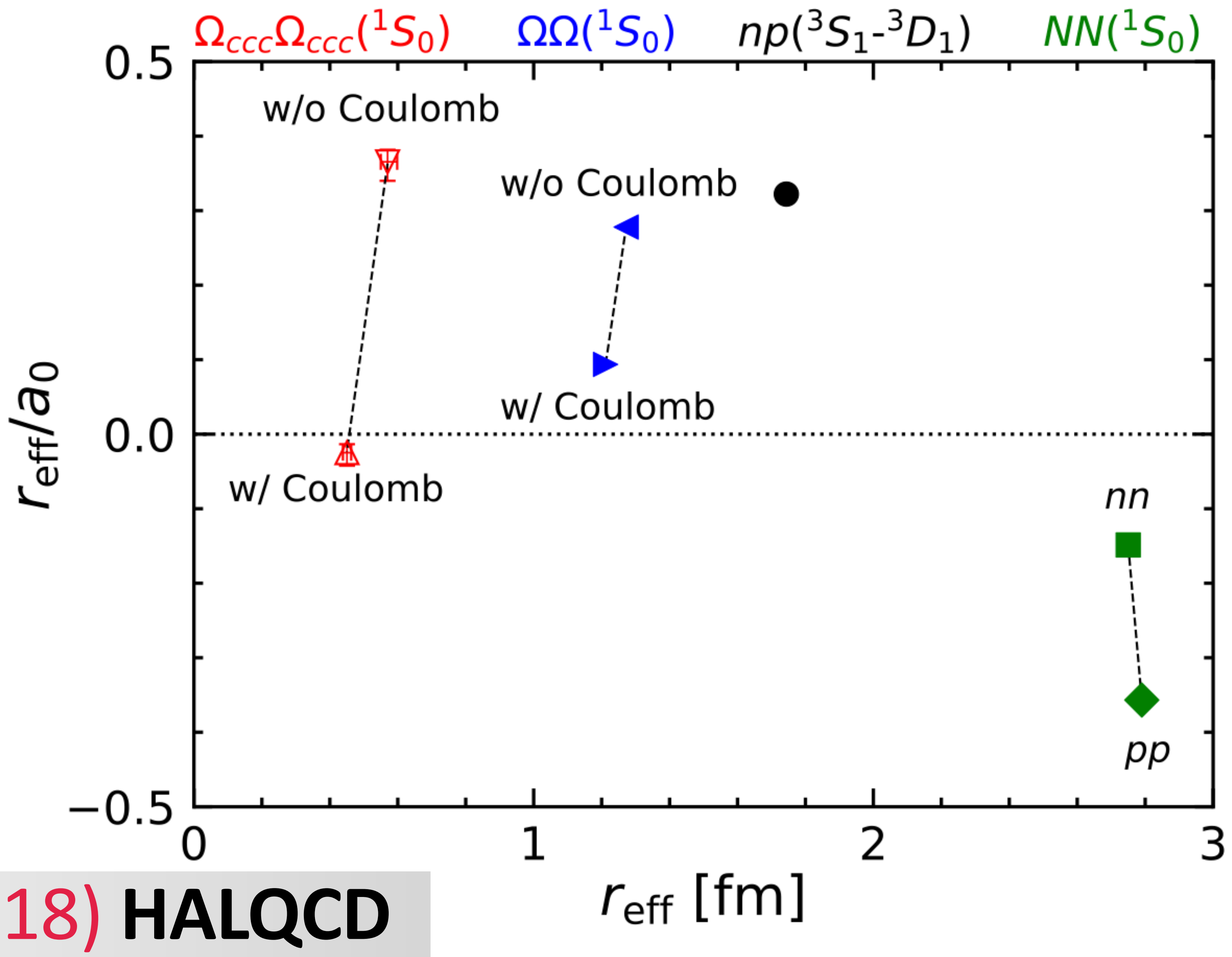
PoS(LATTICE2024)082, arXiv:25xx.yyyyy NSD, Mathur, Padmanath

Dibaryons

Model calculations for both fully strange and charmed systems remains conflicting

- Only single lattice calculation for $\mathscr{D}_{6c}$ and two* for $\mathscr{D}_{6s}$





PRL **120**, 212001 (2018) **HALQCD**

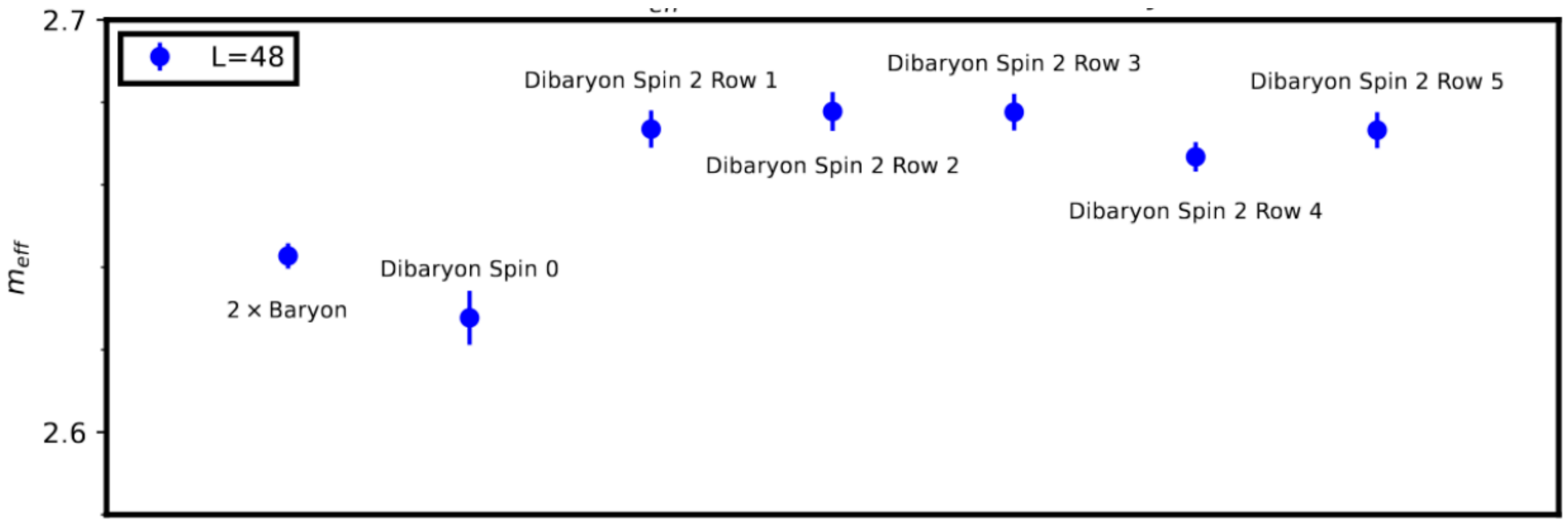
- Weakly repulsive in Spin 0 H^+H^+ irrep, No bound state

PRD **85**, 094511 (2012) **Buchoff, Luu, Wasem**

- $\mathscr{D}_{6s}$ Weakly attractive in Spin 0, hence bound state
- $\mathscr{D}_{6c}$ Dibaryon existence without Coulomb interaction, near unitary region with Coulomb interaction.

PRL **127**, 072003 (2021) **HALQCD**

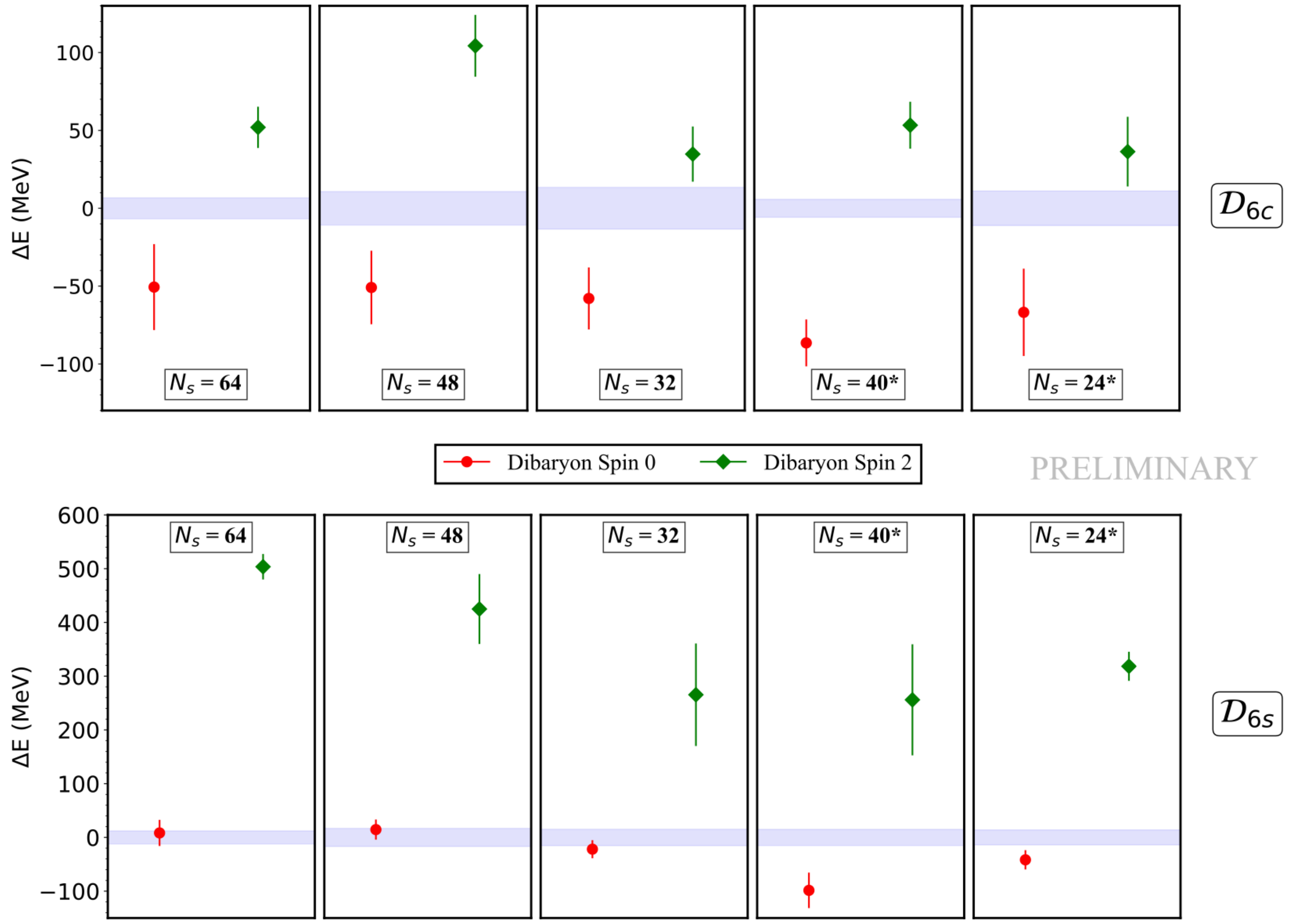
Dibaryons



- Plot for charmed system for $48^3 \times 144$ lattice.
- For all the ensembles observed repulsive behaviour for Spin 2 sector (also for strange system).
- Similar behaviour for all operators in S = 2.
- $\mathscr{D}_{6c}$ shows a signal of attractive interaction.

PoS(LATTICE2024)082, arXiv:25xx.yyyyy NSD, Mathur, Padmanath

Dibaryons

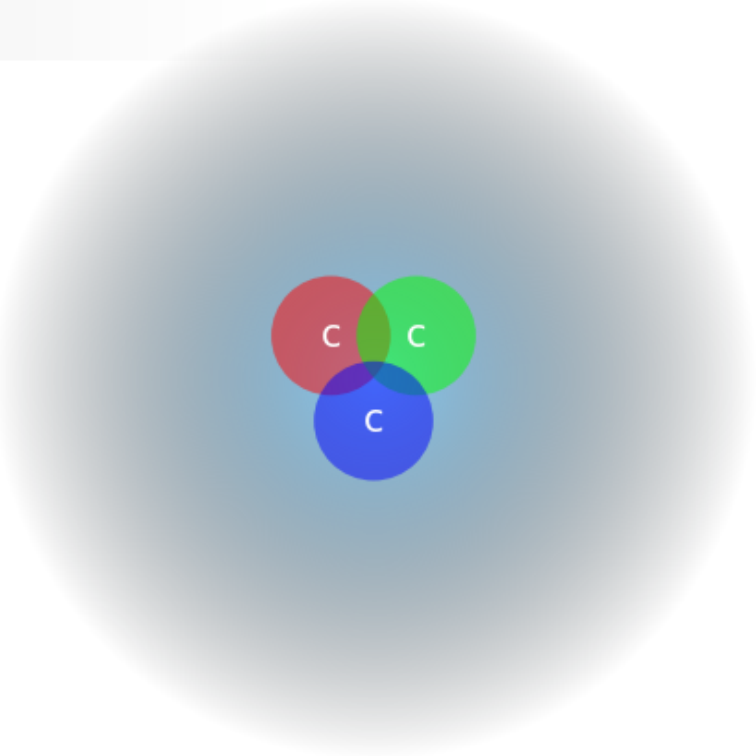


- Five different ensembles generated by MILC collaboration.
- Presence of bound state by looking at the energy difference of dibaryon with corresponding baryons.
- $\mathscr{D}_{6c}$ shows a bound state for S = 0, whereas $\mathscr{D}_{6s}$ does not show such signature.

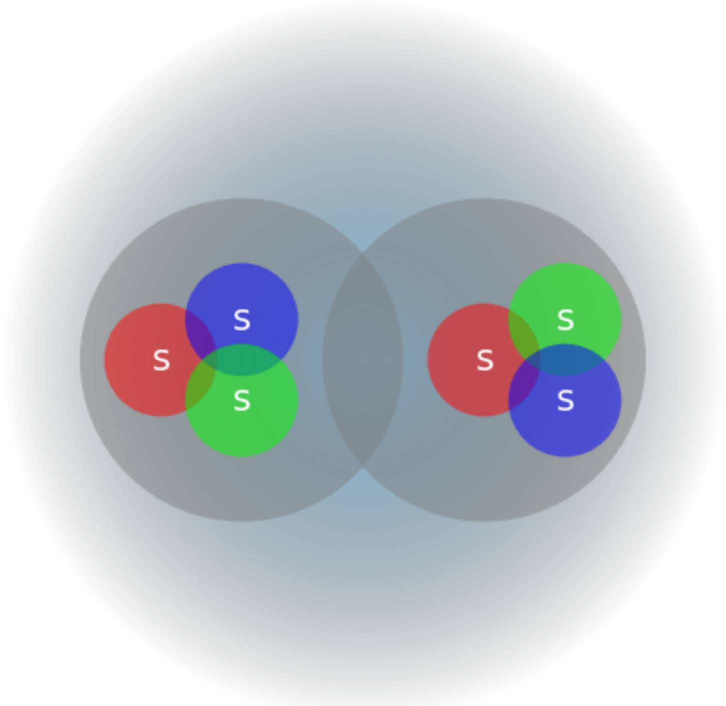
PoS(LATTICE2024)082, arXiv:25xx.yyyyy **NSD, Mathur, Padmanath**

Remarks

Ω_{ccc}

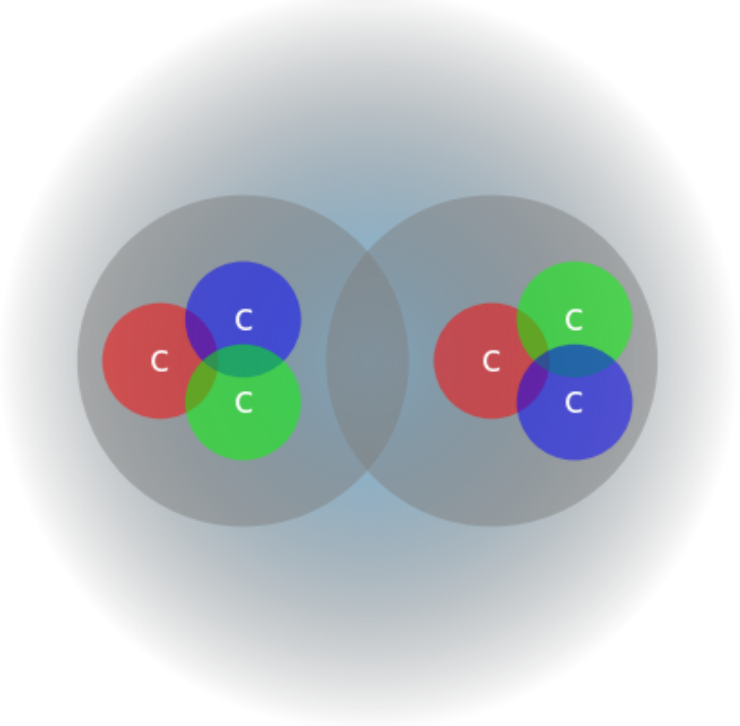


Precise calculation of Ω_{ccc}



Dibaryons

Dibaryonic interactions



Work in progress

- Better understanding of interactions - Luscher's formalism
- Lattice investigations of lighter hadrons
- Exotics at exotic conditions.

More work around hadrons using Lattice @IMSc:
https://www.imsc.res.in/~padmanath/index.html#/publications

Thank you for your attention

Thanks to ANRF, IMSc and YITP

Questions?