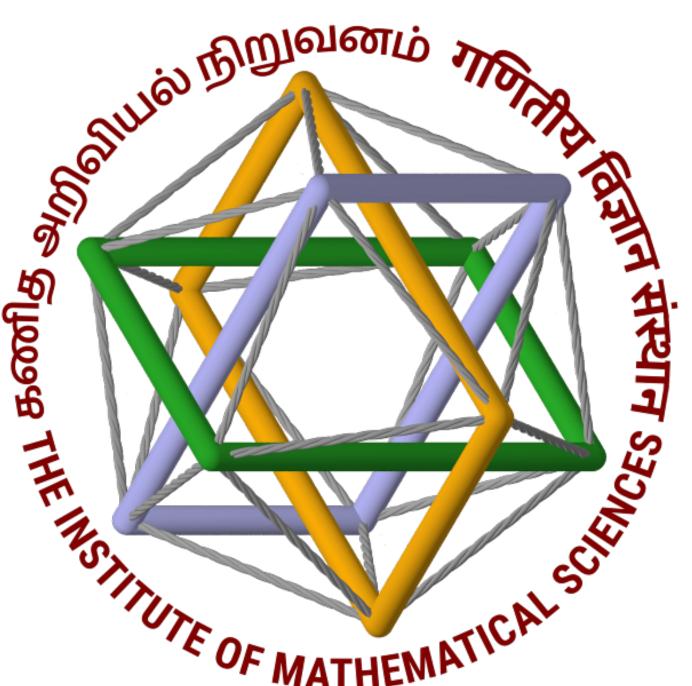
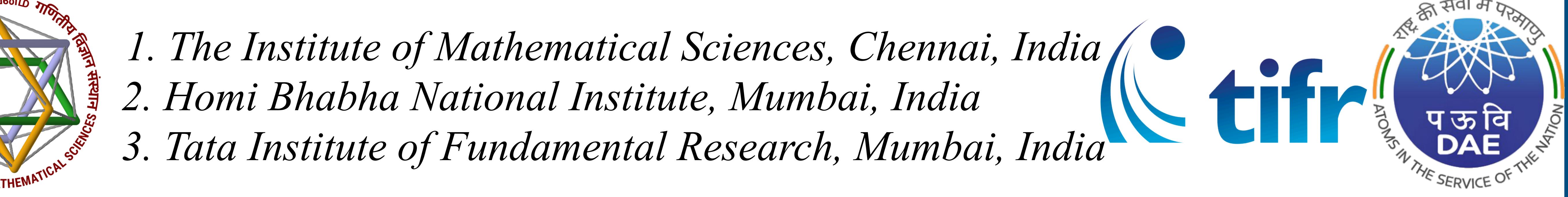
# Non-perturbative Lattice Studies of Exotic Multiquark Systems

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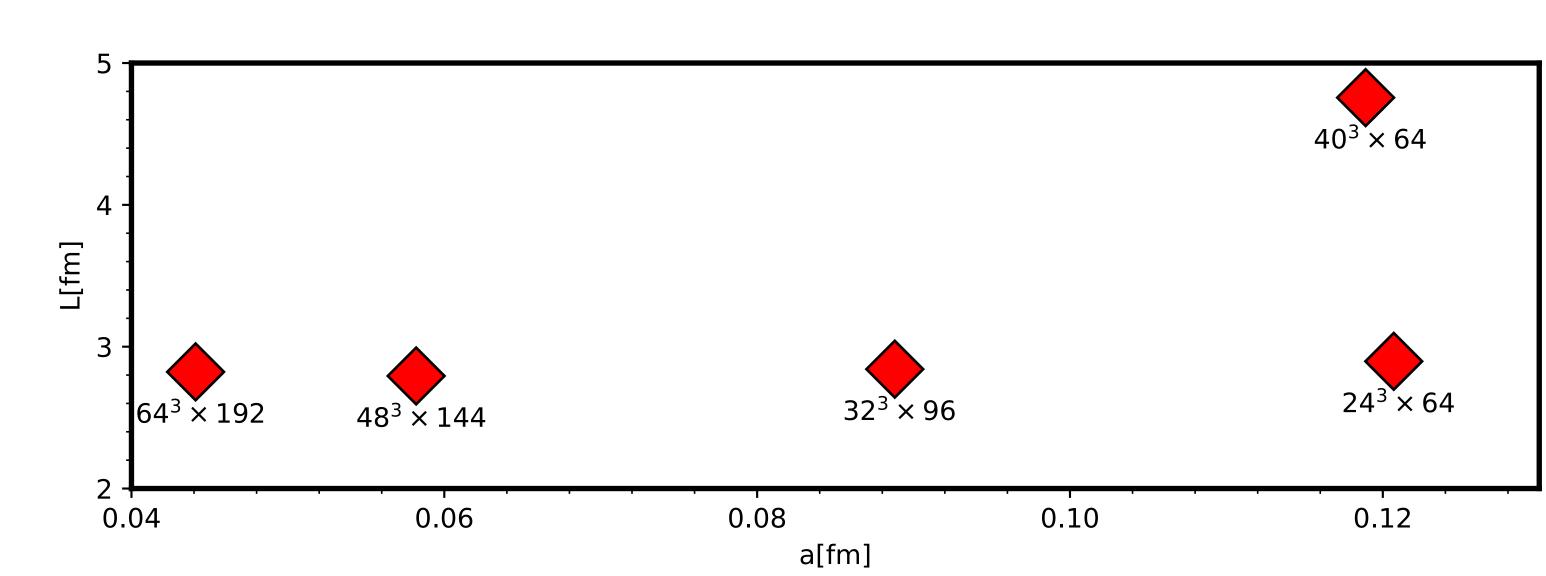
#### CONTINUUM FOUNDATIONS OF LATTICE GAUGE THEORIES, 22-26 July 2024, CERN, GENEVA

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- Understanding baryon-baryon interactions from first principles is crucial in nuclear physics, as these interactions formulate the foundation of existence of atomic nuclei.
- Our focus is on studying a system of six quarks, which primarily resemble two baryons bound together and is referred to as dibaryon.
- Despite extensive experimental efforts, Deuteron remains the only confirmed dibaryon bound state, with recent experimental evidence suggesting an unstable light dibaryon, d\*(2380).
- Recent experimental observations of exotic multi quark systems by Belle and LHCb experiments have increased interest in the lattice hadron spectroscopy of exotic systems beyond the conventional hadrons.
- We primarily concentrate on heavy dibaryons, as the large separation of scales between heavy quark masses and confinement facilitates spectroscopy analysis with cleaner signals.
- In this work, we focus on single-flavored dibaryons composed of either strange or charm quarks, building on recent lattice studies of dibaryons composed solely of bottom quarks [1].

## Lattice Setup

We utilize five set of lattice ensembles with  $N_f = 2 + 1 + 1$  dynamical HISQ fields generated by MILC collaboration [2]. For valence charm and strange quark propagators we use the overlap action. The details about the lattice ensembles is shown in the below figure.



#### Masses from Lattice

The effective masses from the lattice are calculated using the Euclidean two point correlator function as:

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

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

effective mass can be calculated as:  $m_{eff} = \log \left[ \frac{C(t)}{C(t+1)} \right]$ .

## Dibaryon Operators

- We assume only s-wave interactions in two baryon systems. As baryons are color singlets and we work with single flavor systems, hence spin must be anti-symmetric which corresponds to even spin.
- The dibaryon operator constructed from the linear combinations of the single baryon operators with the help of CG coefficients as  $\mathcal{O}_d = \mathcal{O}_1$ . CG.  $\mathcal{O}_2$ where baryon operator is given as  $\mathcal{O} = \epsilon_{abc} q_{\mu_1}^a q_{\mu_2}^b q_{\mu_3}^c$ .
- Subduction coefficients are used to project the continuum based operators onto their suitable octahedral group on lattice. Baryon with spin 3/2 is represented by  $H^+$  irrep. Dibaryon with spin 0 in continuum subdues to one dimensional  $A_1^+$  irrep and dibaryon with spin 2 in continuum subdues to two dimensional  $E^+$  and three dimensional  $T_2^+$  irrep. Dibaryon operator with spin 0 is given as (similar 5 spin 2 operators):

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

a and b corresponds to relativistic or non-relativistic embedding as given below [3].

$S_z$	Operator	State
$\overline{3/2}$	$  ^{1}H_{3/2}  $	111
1/2	$  {}^{1}H_{1/2}  $	$112 \!+\! 121 \!+\! 211$
-1/2	$\mid {}^{1}H_{-1/2}^{'} \mid$	$122 \!+\! 212 \!+\! 221$
-3/2	$\mid {}^{1}H_{-3/2} \mid$	222
<b>7</b> T	1 . • •	, • FN TT

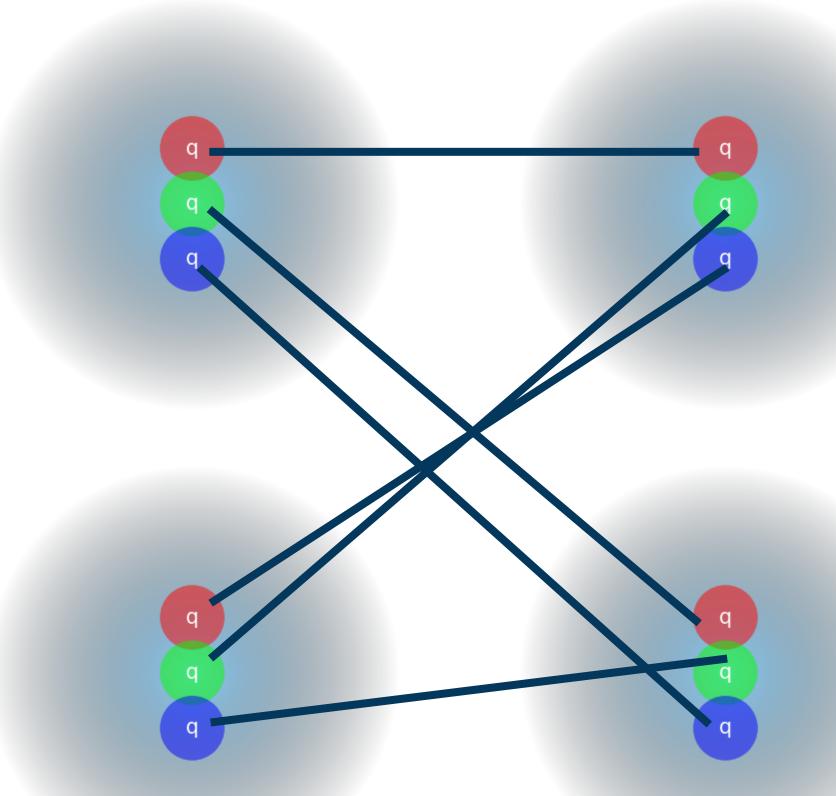
Non Relativistic [N]

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

Relativistic [R]

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-N R-R-R

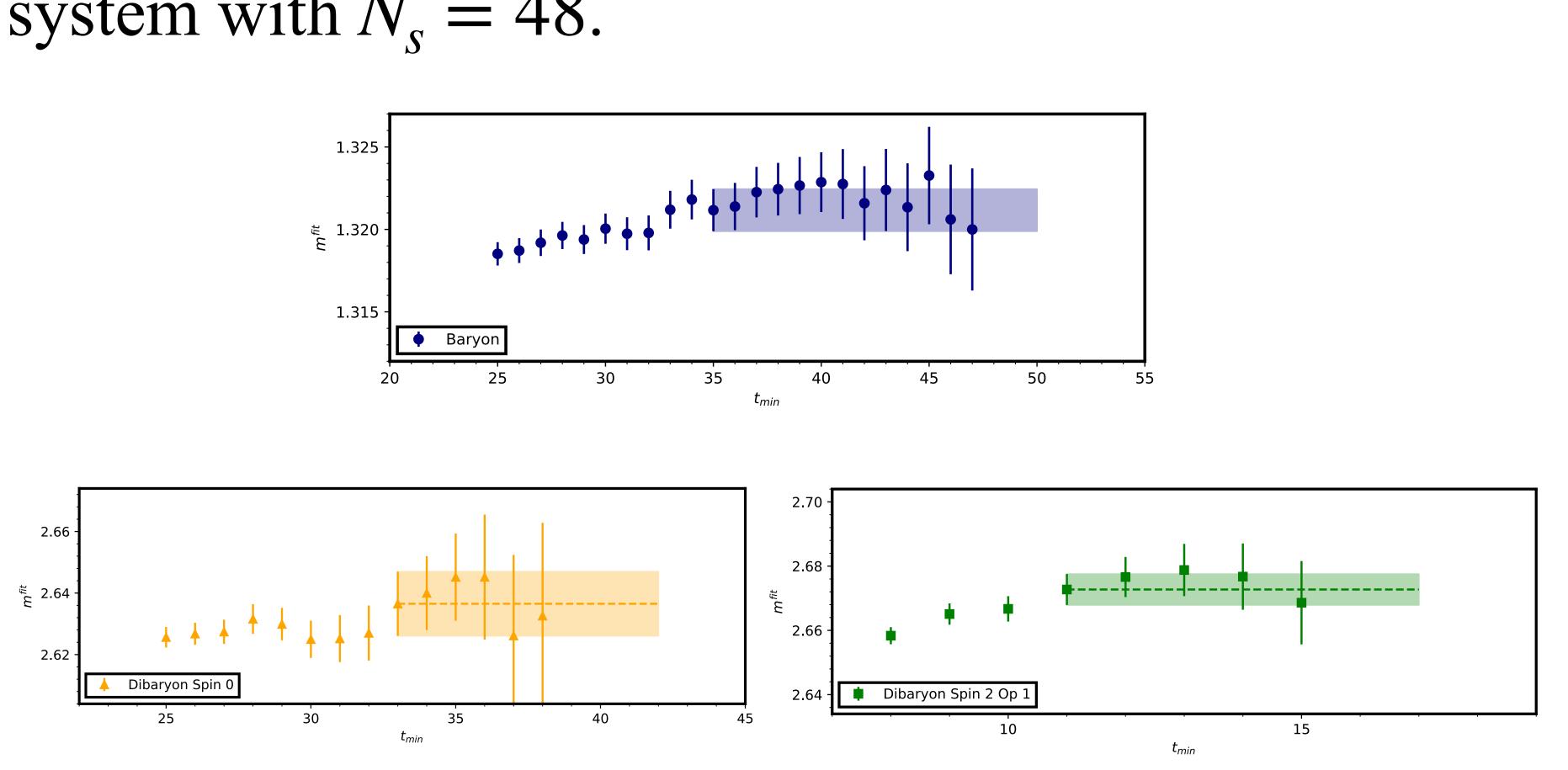
A random contraction of operators for dibaryons at source and sink time slice.



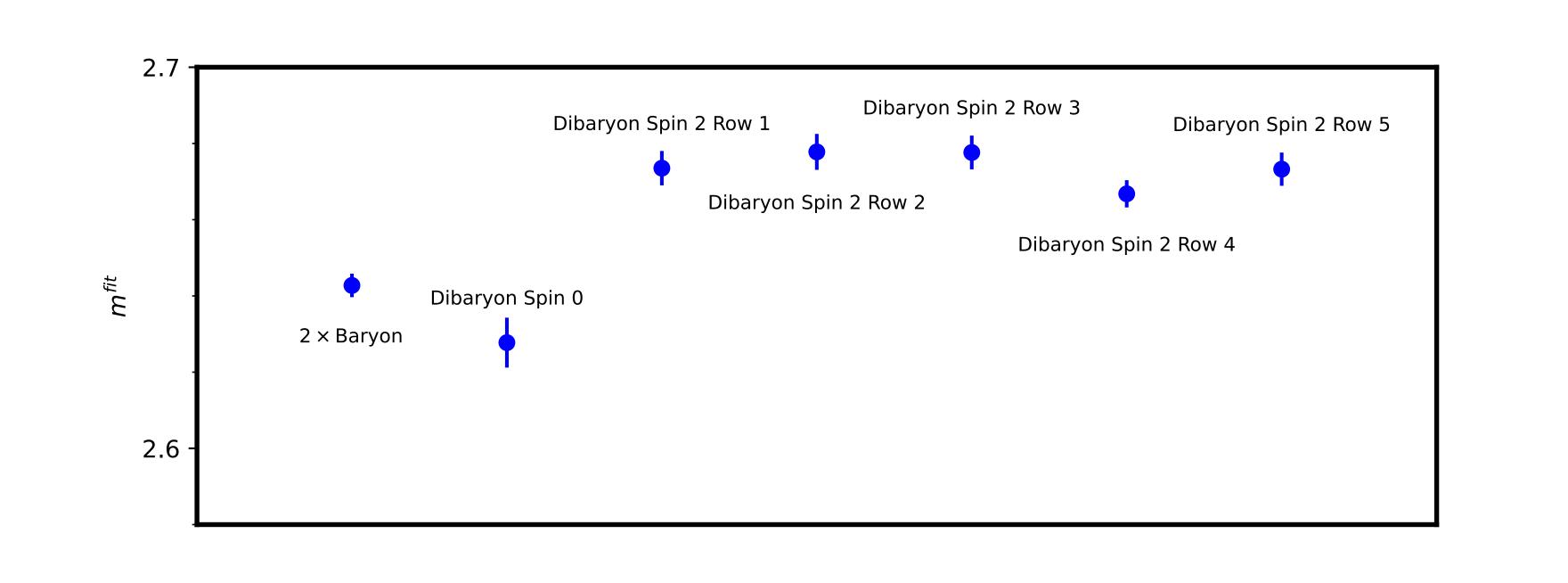
720 such contractions, but maximum four contractions are unique depending upon embedding combinations.

#### Energy Levels

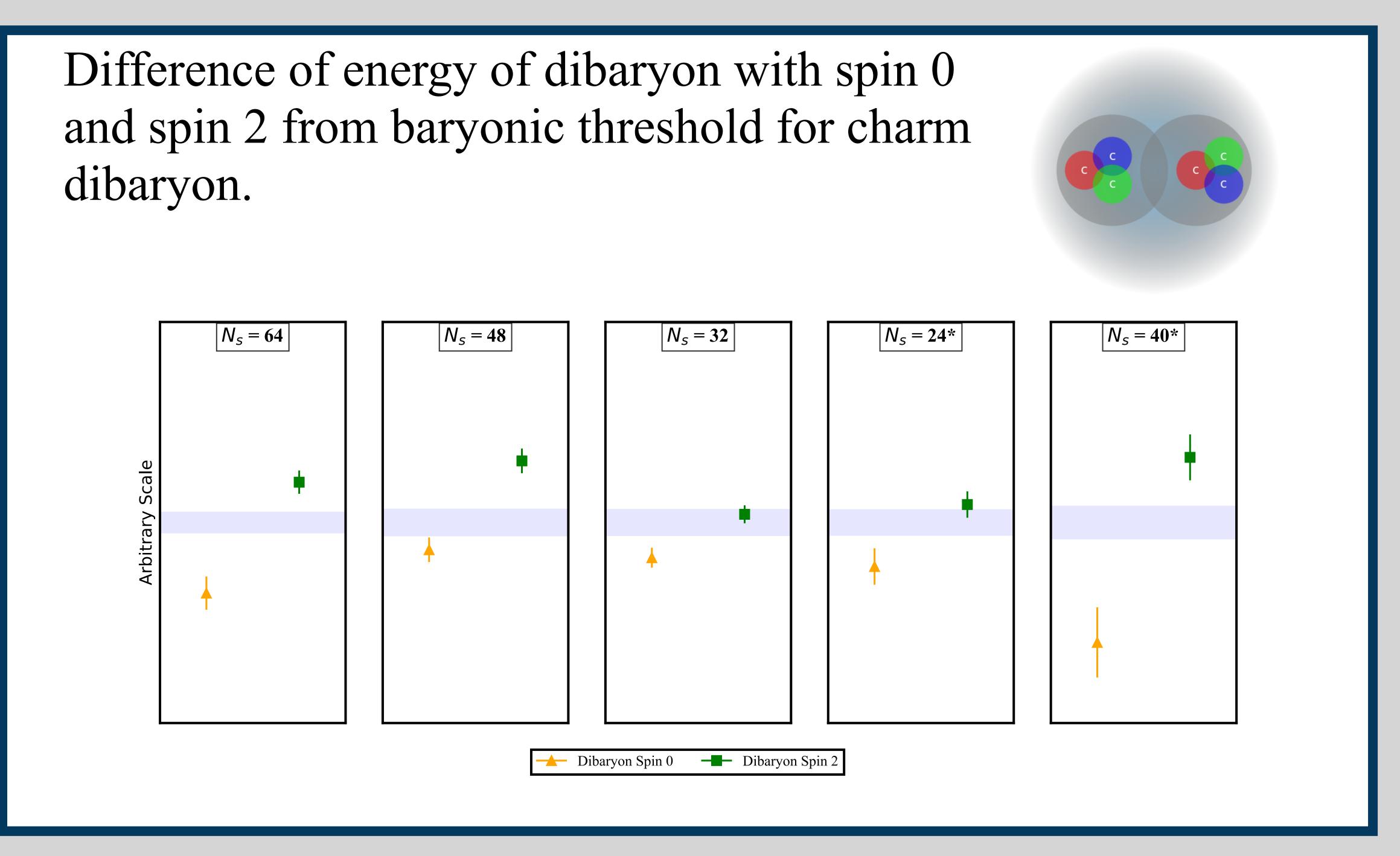
The following are the plots of  $t_{min}$  dependence for  $m^{fit}$ values of baryon, spin 0 dibaryon and one operator of spin 2 dibaryon. The results corresponds to charm system with  $N_s = 48$ .



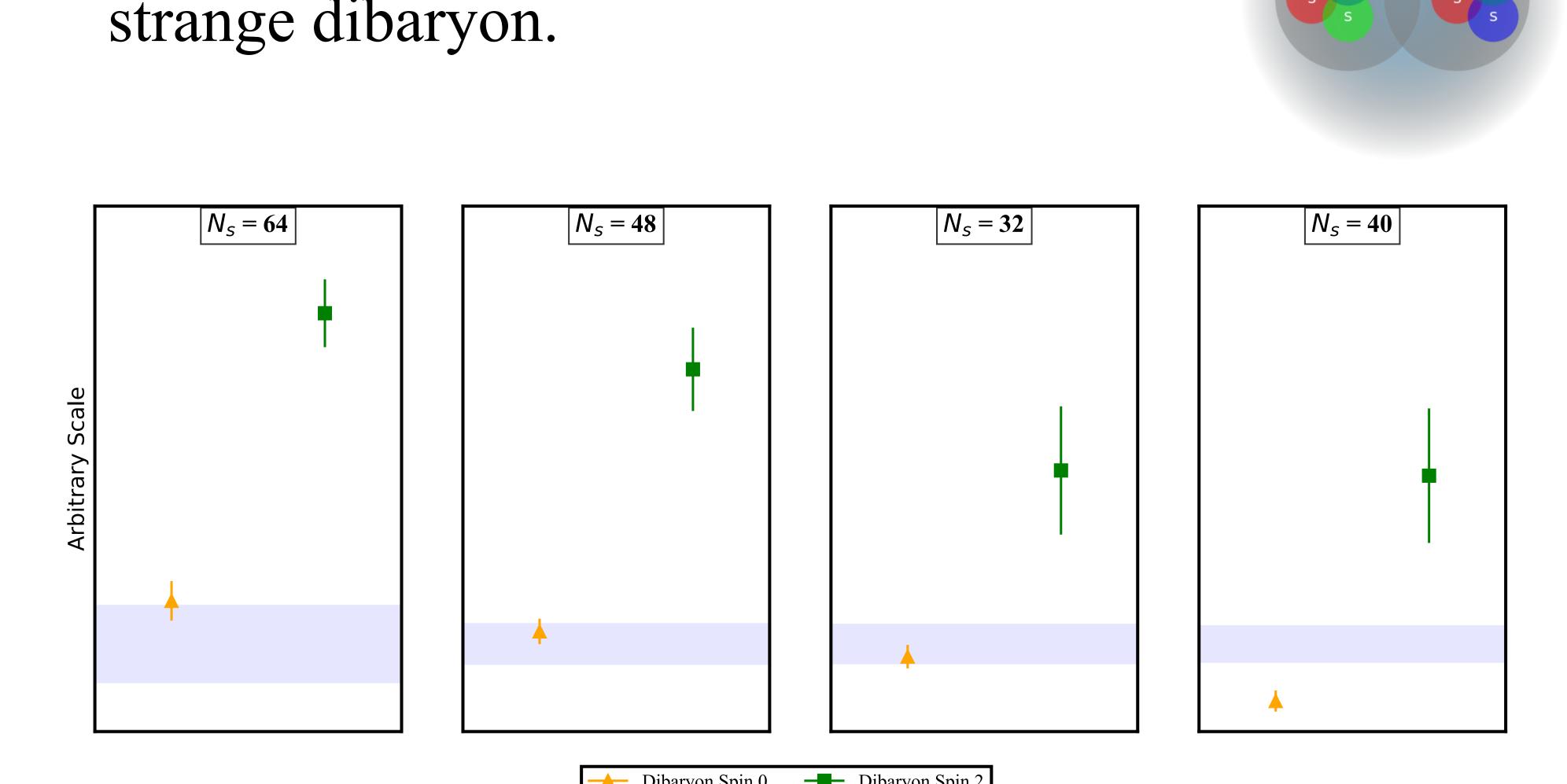
Ground state energy for  $N_s = 48$  lattice for all five dibaryon spin 2 operators, spin 0 operator and comparison with twice of baryon ground state.



The comparison is for charm dibaryon. All the five operators for spin 2 shows similar behaviour. Similar analysis is observed for strange dibaryon.



Difference of energy of dibaryon with spin 0 and spin 2 from baryonic threshold for strange dibaryon.



### Summary

- The energy splitting analysis between interacting and non-interacting systems suggest absence of bound state in strange system and no conclusive remarks can be made about charm system. If there is a bound state for charm dibaryon that is shallow.
- For  $\mathscr{D}_{6s}$ , the observation seems consistent with results of [4] which predicted no bound state but there has been studies which predicted bound state for this system [5].
- For  $\mathscr{D}_{6c}$ , a recent study [6] by HAL QCD predicted absence of bound state with Coulomb interactions in their approach of investigating systems hadron-hadron interactions by solving QM potentials from Nambu-Bethe-Salpeter wave function.
- We will make use of finite volume scattering analysis to robust our understanding of these systems.

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[1] PRL 130 (2023) 111901 [2] PRD 87 (2013) 054505 [3] PRD 72 (2005) 074501 [4] PRD 85 (2012) 094511 [5] PRL 120 (2018) 212001 [6] PRL 127 (2021) 072003