Non-perturbative Lattice Studies of Exotic Multiquark Systems

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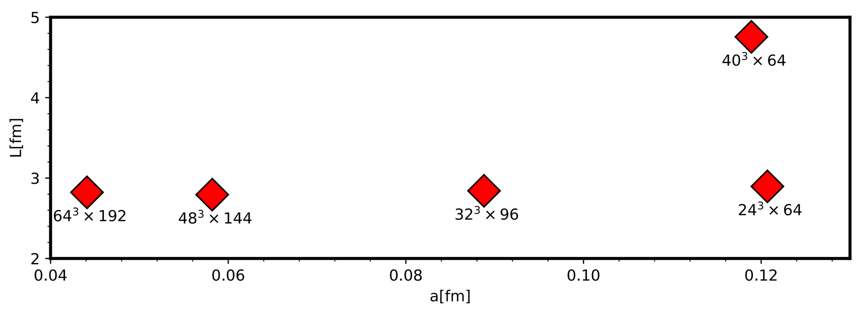
- Understanding baryon-baryon interactions from first principles is crucial in nuclear physics, as these interactions formulate the foundation of existence of atomic nuclei.
- Our focus is on studying a system of six quarks, which primarily resemble two baryons bound together and is referred to as dibaryon.
- 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 $\mathcal{O} = \epsilon_{abc} q^a_{\mu_1} q^b_{\mu_2} q^c_{\mu_3}$.
- 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 subduces to one dimensional A_1^+ irrep and dibaryon with spin 2 in continuum subduces to two dimensional E^+ and three dimensional T_2^+ irrep. Dibaryon operator with spin 0 is given as (similar 5 spin 2 operators):

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

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

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

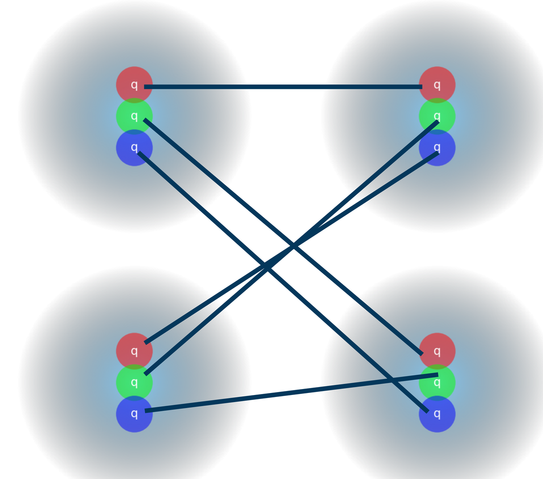
Non Relativistic [N]

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

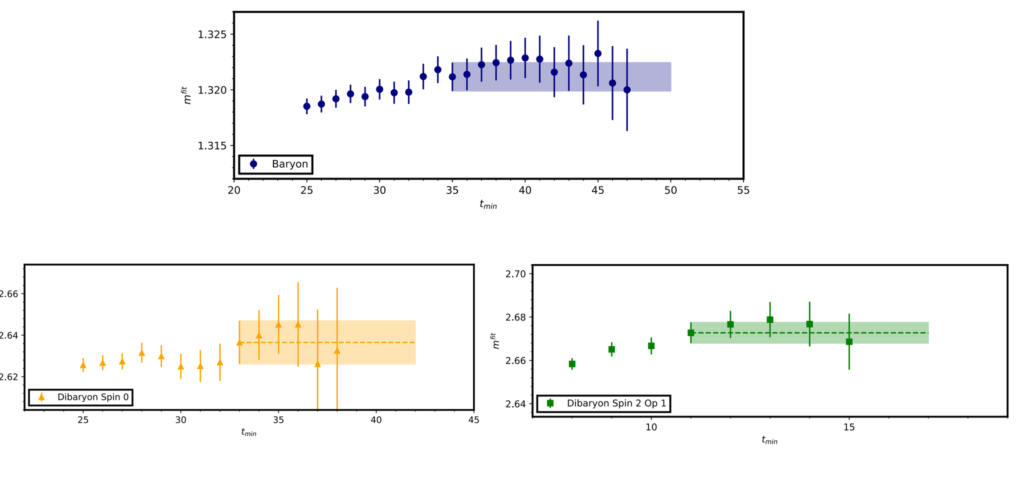
A random contraction of operators for dibaryons at source and sink time slice.



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

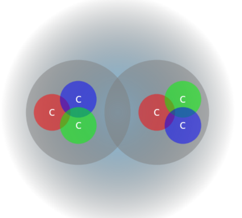
Energy Levels

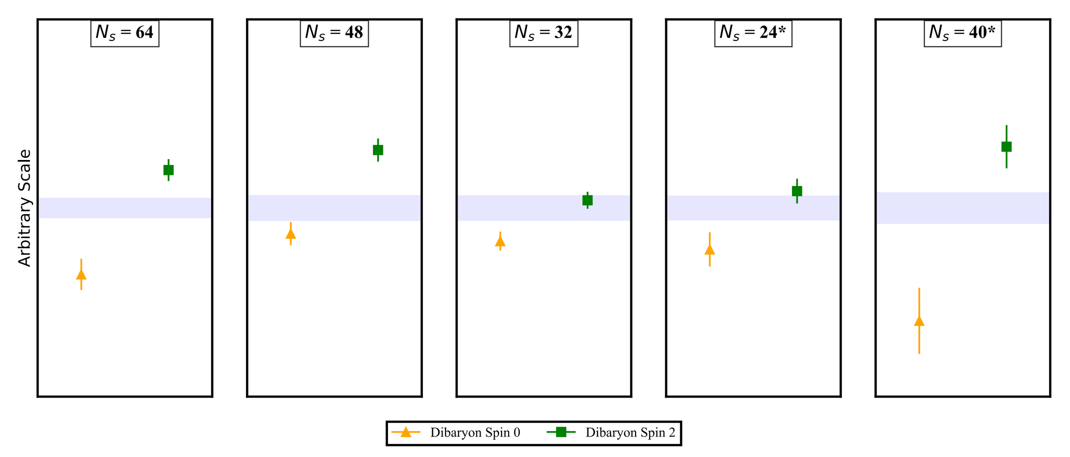
The following are the plots of t_{min} dependence for m^{fit} values of baryon, spin 0 dibaryon and one operator of spin 2 dibaryon. The results corresponds to charm system with $N_s = 48$.



$\mathcal{D}_{6c}$

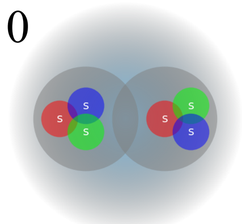
Difference of energy of dibaryon with spin 0 and spin 2 from baryonic threshold for charm dibaryon.

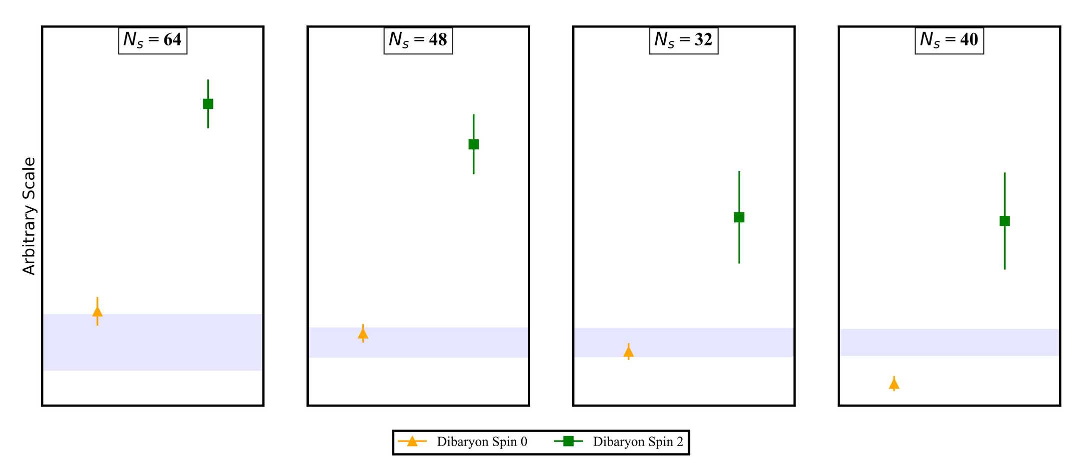




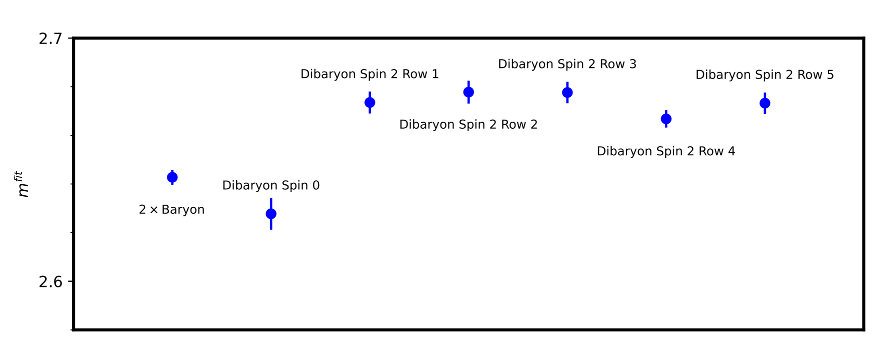
$\mathcal{D}_{6s}$

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





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.

Summary

- We observe a positive shift in the S=2 channel, indicating a repulsive interaction and inability to host any bound state for both strange and charm systems.
- In the charm sector, for spin zero, there is a slight tendency towards negative shifts, although these shifts have smaller magnitudes.
- In the strange sector, for spin zero, the results generally suggest a non-interacting scenario, with weak interactions and potentially no bound states.
- A more precise conclusion can only be drawn with larger statistics and a comprehensive finite-volume amplitude study.

References for lattice studies on strange and charm dibaryonic systems can be found in [4], [5], and [6].

[1] Mathur et al., PRL 130 (2023) 111901
[2] Bazavov et al., PRD 87 (2013) 054505
[3] Basak et al., PRD 72 (2005) 074501
[4] Buchoff et al., PRD 85 (2012) 094511
[5] Gongyo et al., PRL 120 (2018) 212001
[6] Lyu et al., PRL 127 (2021) 072003

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