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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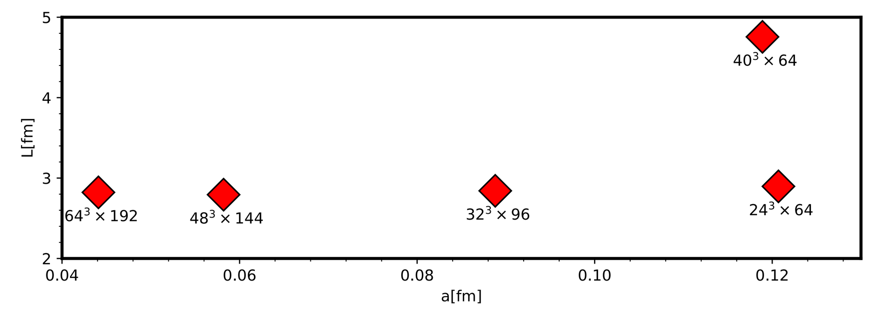
- Understanding baryon-baryon interactions from first principles is crucial in nuclear physics, as these interactions formulate the foundation of existence of atomic nuclei.
- Our focus is on studying a system of six quarks, which primarily resemble two baryons bound together and is referred to as dibaryon.
- 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 $\mathcal{O} = \epsilon_{abc} q^a_{\mu_1} q^b_{\mu_2} q^c_{\mu_3}$.
- 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 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):

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

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

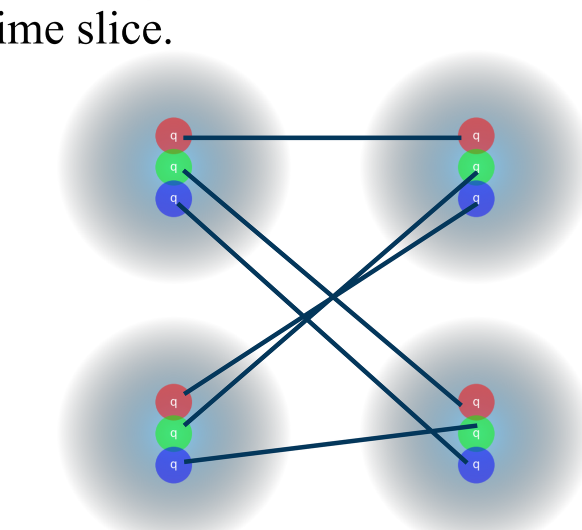
Non Relativistic [N]

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

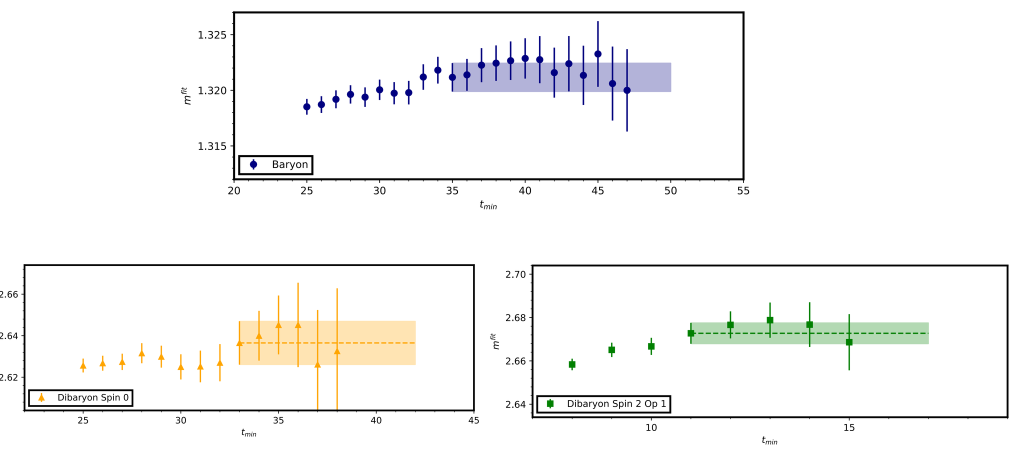
A random contraction of operators for dibaryons at source and sink time slice.



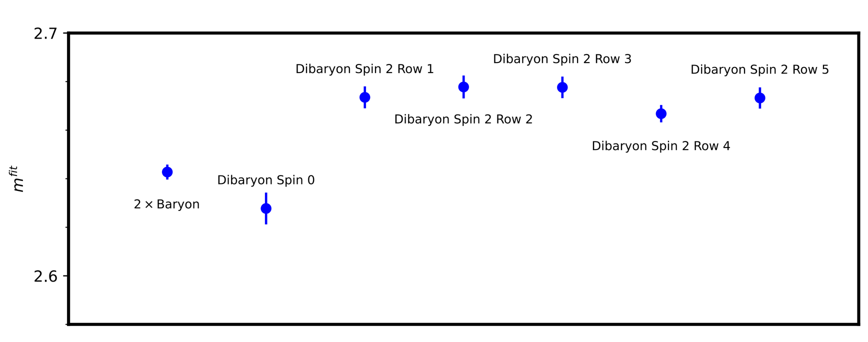
720 such contractions, but maximum four contractions are unique depending upon embedding combinations.

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 $N_s = 48$.



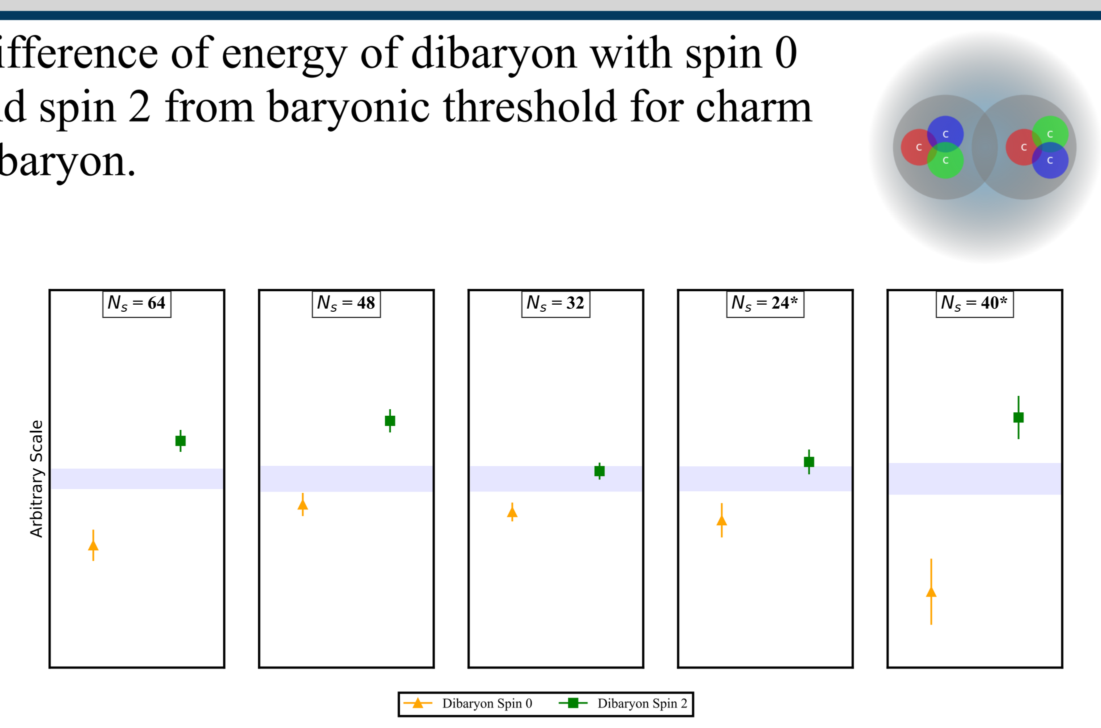
Ground state energy for $N_s = 48$ lattice for all five dibaryon spin 2 operators, spin 0 operator and comparison with twice of baryon ground state.



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

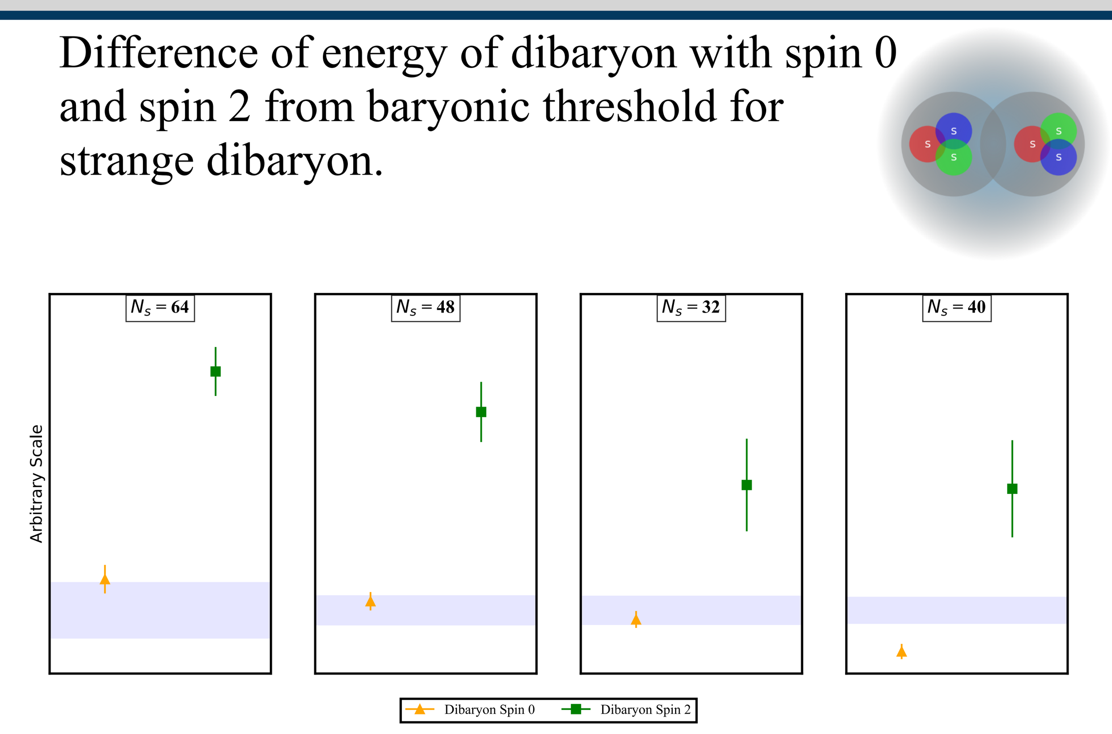
$\mathcal{D}_{6c}$

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.



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 $\mathcal{D}_{6s}$, 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 $\mathcal{D}_{6c}$, 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.

[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

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