Flavor structure of the baryon-baryon interaction from Lattice QCD

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HAL QCD Collaboration

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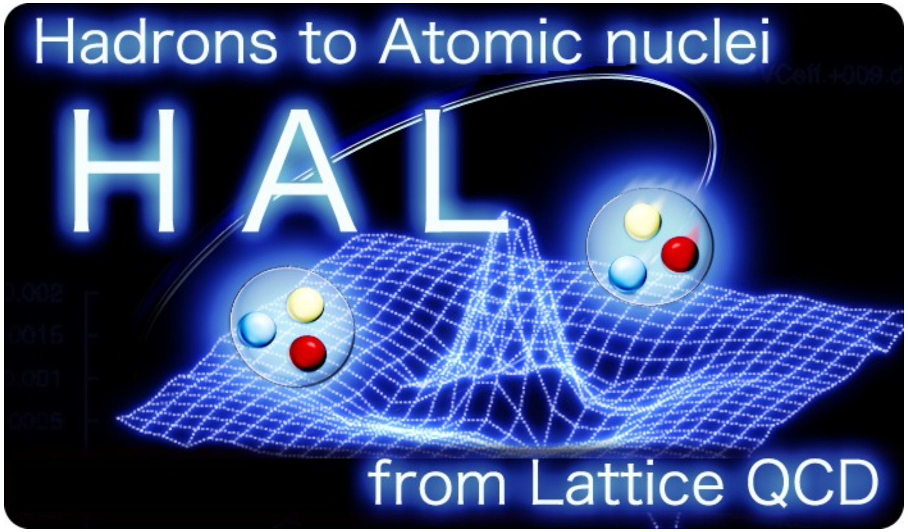
- Introduction
- SU(3) limit & Models
- Method & Setup
- Results & Discussion
- Summary & Outlook



Lattice2010, 18/06/2010, Sardinia

Introduction

- General BB interaction (inc. YN, YY) is interesting.
  - For physics of hyper-nuclei, neutron star, super nova.
  - We expect deeper understanding of nuclear force.
- But, it is not well known except for NN part.
  - Are features of nuclear force common or not?
  - What is origin of those feature?
- These questions have been attacked from 80th in effective models with flavor symmetry.
  - Quark anti-symmetrization and perturbative gluon.
    - Tamagaki, Neudachin, Smirnov (1977)
    - Oka, Yazaki (1980), Fujiwara, Nakamoto Suzuki (1994)
  - Meson exchange mechanism
    - Maessen, Rijken, de Swart (1989)

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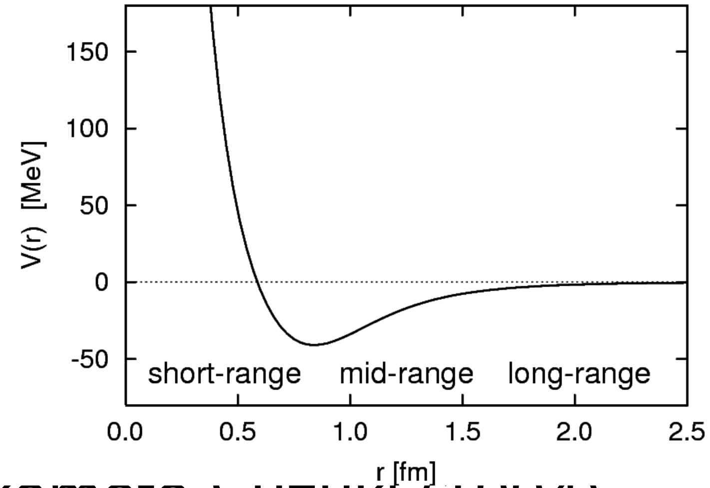

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Introduction

- Purpose and goal of this study:
  1. Draw BB interaction directly from QCD using lattice.
  2. Compare to prediction of effective models.
  3. Pin down physical origin of character of BB interaction.
  4. Get deeper understanding of BB interaction. [GOAL]
  5. Apply to various nuclear physics e.g. super-nova
- Now, we are at middle of the stage.
  Today, I show results and what we've found so far.
- Keys of this study:
  - consider flavor SU(3) symmetric limit world.
  - extract potentials of BB interaction.

Why SU(3) limit?

- In the limit, convenient basis exist, ie. flavor irreducible rep.

$$8 \times 8 = \underbrace{27 + 8s + 1}_{\text{Symmetric}} + \underbrace{10^* + 10 + 8a}_{\text{Anti-symmetric}}$$

- In S-wave, no off-diagonal interaction. All we need is

$$^1S_0 \;:\; V^{(27)}(r),\; V^{(8s)}(r),\; V^{(1)}(r)$$
$$^3S_1 \;:\; V^{(10^*)}(r),\; V^{(10)}(r),\; V^{(8a)}(r)$$

- They show essential flavor-spin structure of BB fource. In fact, all baryon base potentials (incl. transitions) can be reconstructed with them using SU(3) C.G. coefficients.
- Future, we'll extract all BB potentials at the physical point. It would be useful to see overview of it beforehand.
- Since effective models assume flavor sym., limit results are easy to compare and useful to pin down the origin.

Quark model prediction

Summary of the eigenvalues of the normalization kernel, the adiabatic potential V at $R = 0$ due to the color magnetic interaction and the effective hard core radius r_c.

I	J	BB	P.B. Eigenvalue	O.G.E. $V(R=0)$ [MeV]	r_c [fm]
$\frac{1}{2}$	0	$N\Lambda$	1	381	0.44
		$N\Sigma$	$\frac{1}{9}$	303	0.72
$\frac{1}{2}$	1	$N\Lambda$	1	264	0.37
		$N\Sigma$	1	215	0.30
$\frac{3}{2}$	0	$N\Sigma$	$\frac{10}{9}$	391	0.40
$\frac{3}{2}$	1	$N\Sigma$	$\frac{2}{9}$	346	0.77
0	1	$N\Xi$	$\frac{8}{9}$	93	0.29
1	0	$N\Xi$	$\frac{4}{9}$	342	0.68
		$\Lambda\Sigma$	$\frac{6}{9}$	298	0.56

Oka, Shimizu, Yazaki
Nucl. Phys. A464 (1987)

8s-plet: zero-eigen = forbidden
very strong repulsion

10-plet: semi forbiden
strong repulsion

8a-plet: small Pauli and OGE
weak repulsion

- R. L. Jaffe, Phys. Rev. Lett. 38 (1977), [MIT Bag model]
  In the flavor singlet six-quark, no Pauli blocking and OGE contribute large attraction enough to support a bound state
  → H di-baryon state

True?

Method

- Potential is a useful tool in nuclear physics.
- In lattice QCD, BB potential can be defined and extracted through 4-point function

$$W^{(a)}(t-t_0,\vec{r}) = \sum_{\vec{x}} \langle 0|B_i(t,\vec{x}+\vec{r})B_j(t,\vec{x})\ \overline{BB}^{(a)}(t_0)|0\rangle$$

at $t-t_0 > t_{\mathrm{sat}}$

B.S. Amp $\phi_{P_0}(\vec{r})$

$$V^{(a)}(\vec{r}) = \frac{1}{2\mu}\frac{\nabla^2\phi^{(a)}_{P_0}(\vec{r})}{\phi^{(a)}_{P_0}(\vec{r})} + E^{(a)}(P_0)$$

constant

- Developed by Ishii, Aoki, Hatsuda for NN force (2006)

Phys. Rev. Lett. 99 022001 (2007) [arXive:nucl-th/0611096]

→ Prog. Theor. Phys. 123 89 (2010) arXiv:0909.5585[hep-lat]

- Applied to YN force by Nemura, Ishii, Aoki Hatsuda.
- Non-locality(energy dep.) is examinded by Murano etal.

Yesterday

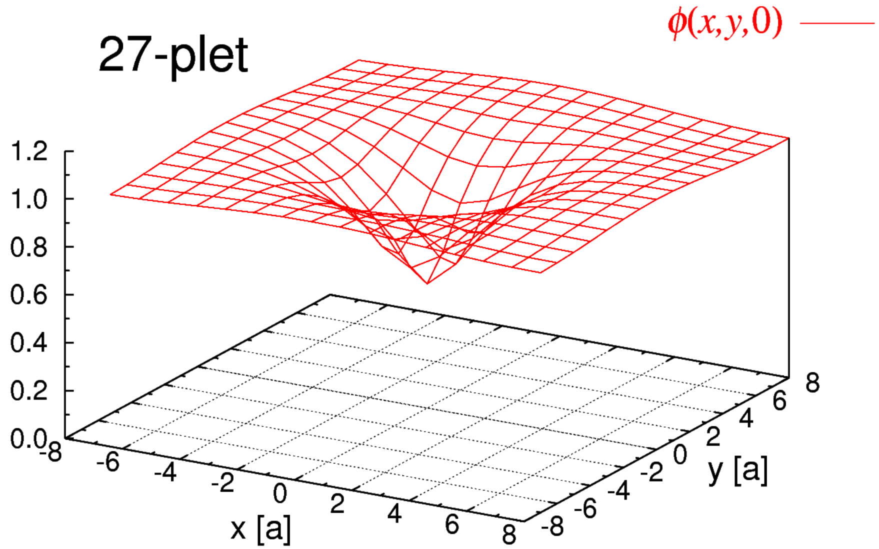
Setup

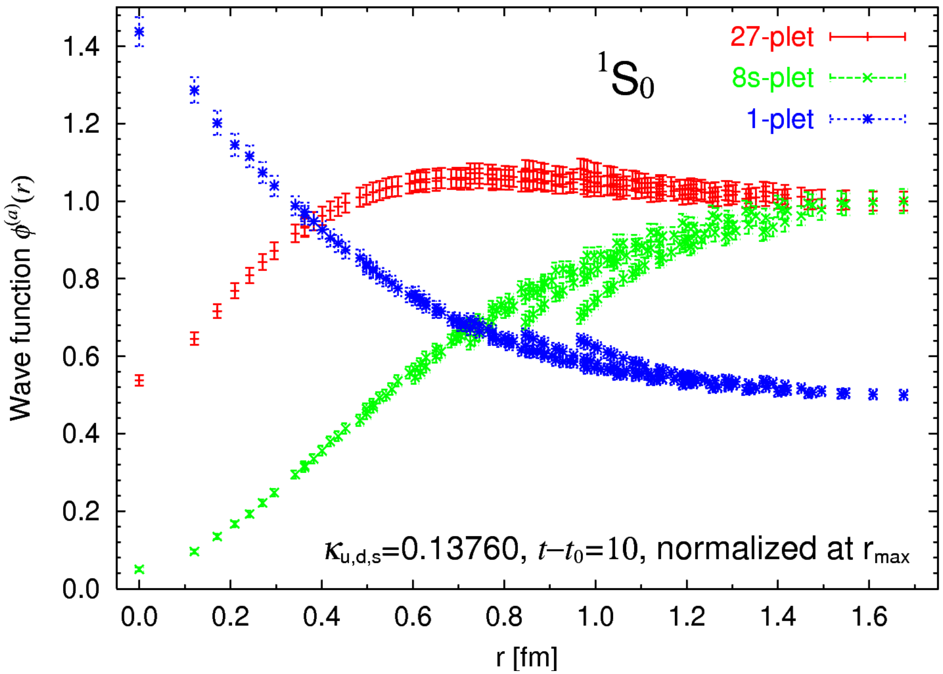
- 3-flavor Full QCD lattice simulation by using gauge conf. sets by CP-PACS/JLQCD collab.
  - RG improved gauge & O(a) improved clover quark
  - 16^3x32, a=0.1209 [fm], L=2.0 [fm].
  - Flat wall source to produce S-wave BB state.
  - 700/800 conf. x 32 sources x 2 (for/backward).
  - KEK Supercomputer system BGL and SR11000
  - Quark/Hadron masses

κ_uds	N of conf	M_P.S. [MeV]	M_B [MeV]
0.13710	700	1014.2(1.1)	2026.2(3.4)
→ 0.13760	800	834.8(0.9)	1752.1(3.0)

Results

BS Amp.(wave function)





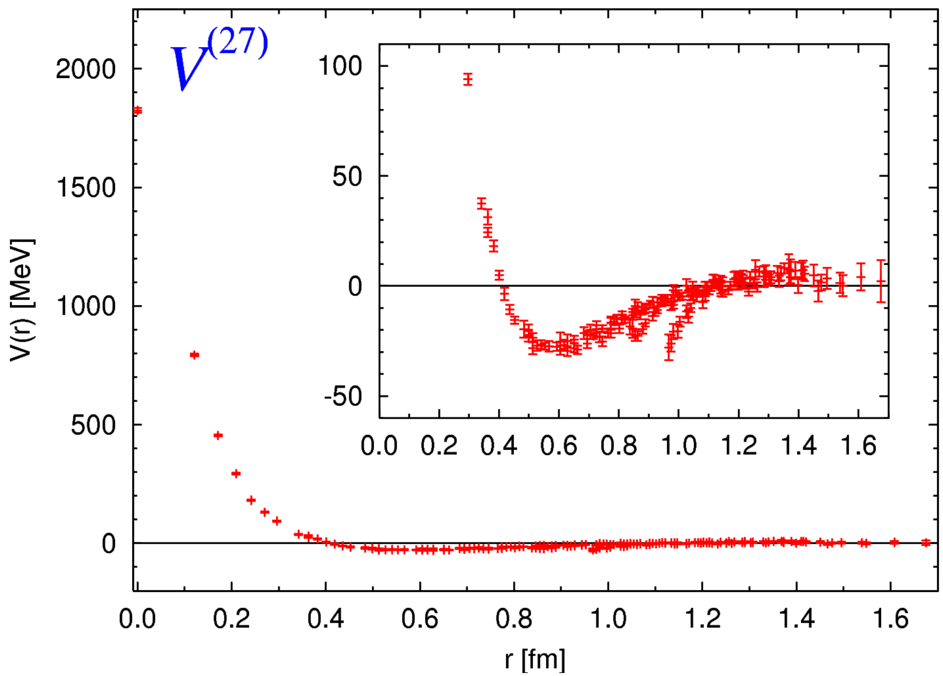
- Potentials are extracted from these amplitudes.
- I'm going to show two $V^{(a)}$ per slide in order of

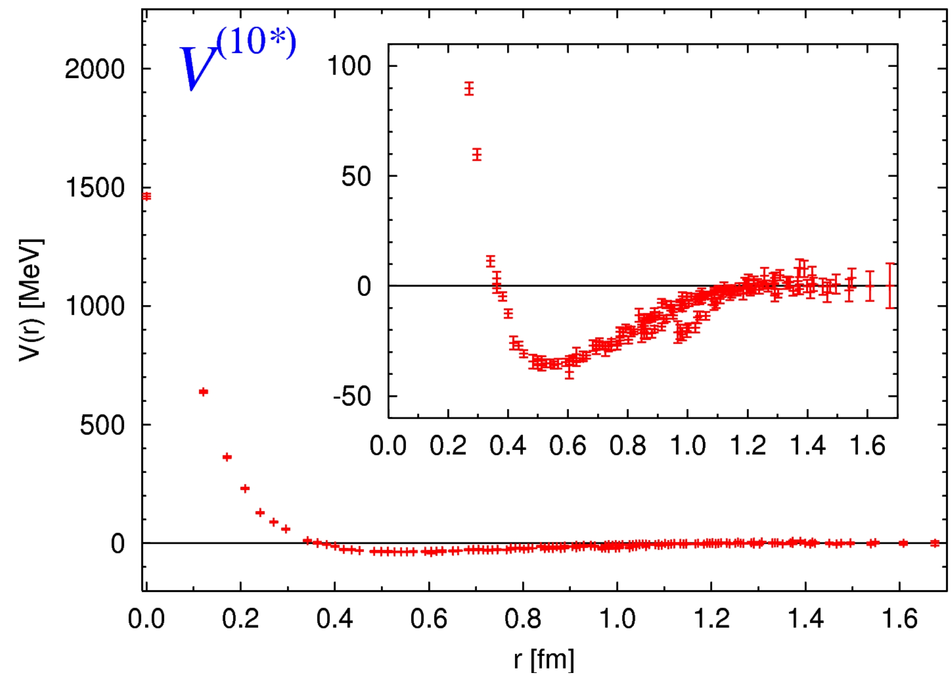
$$^1S_0 \;:\; V^{(27)}(r),\quad V^{(8s)}(r),\; V^{(1)}(r) \quad \text{3rd}$$

$$^3S_1 \;:\; V^{(10^*)}(r),\quad V^{(10)}(r),\; V^{(8a)}(r) \quad \text{2nd}$$

1st

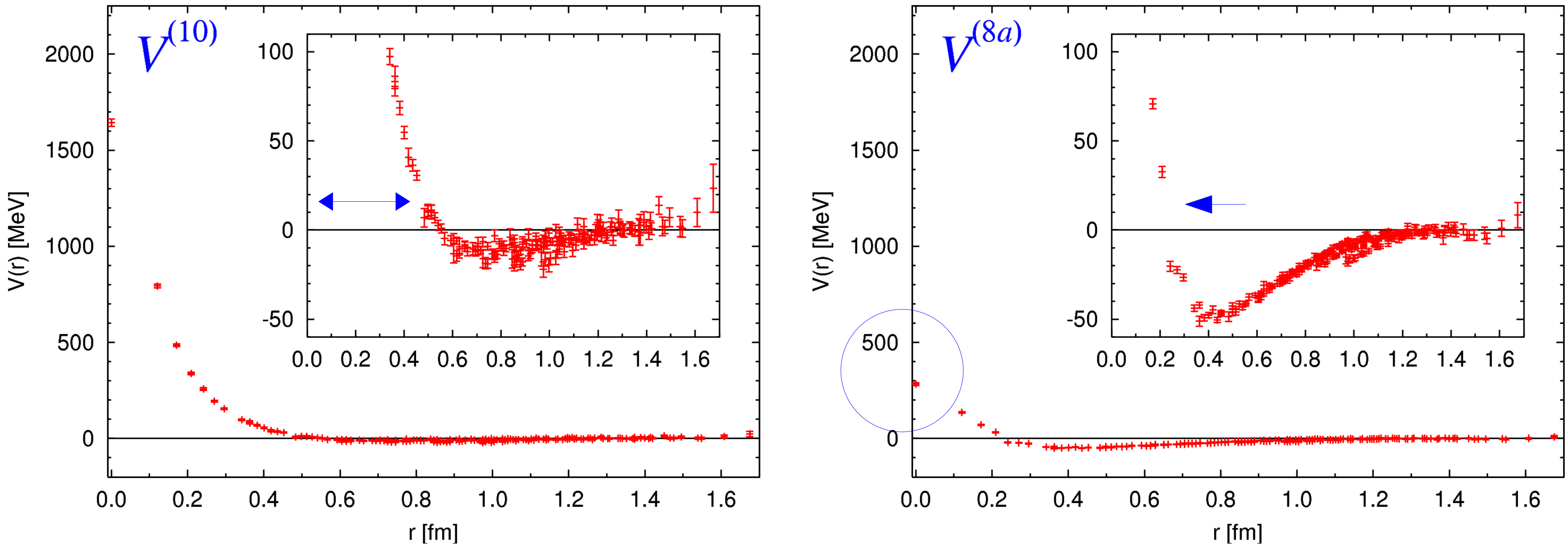
$V^{(27)}$ and $V^{(10*)}$





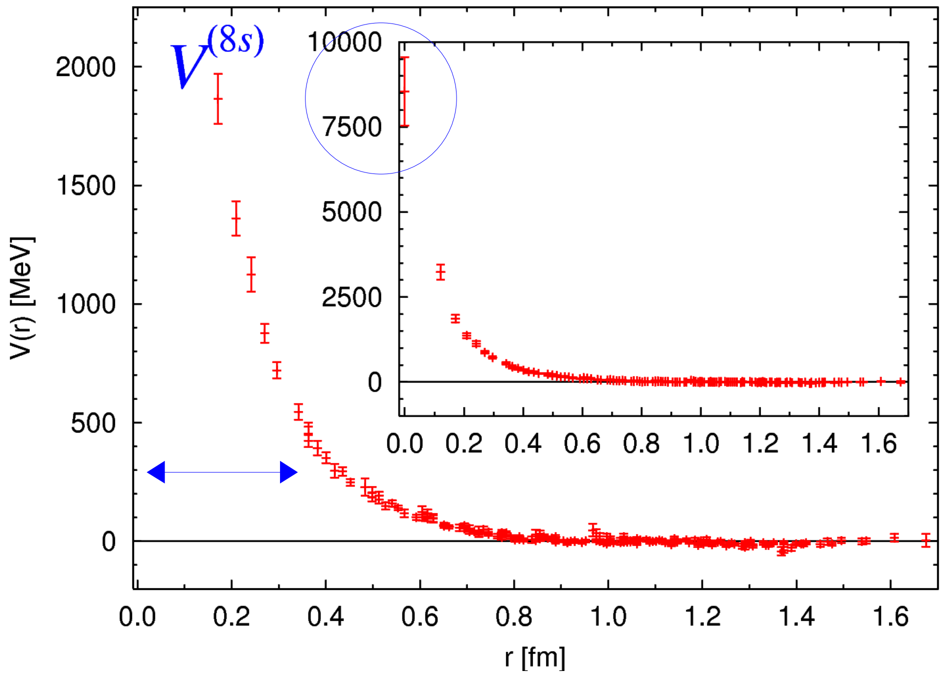
- 27- plet = SU(3) limit of NN $^1S_0$
- 10*-plet = SU(3) limit of NN $^3S_1$
- $V^{(10*)}$ is an effective central potential for $^3S_1$.
- $V^{(a)}$ include typical energy contribution so that $V(r_{max})=0$
- They are consistent to our previous study(Ishii etal).

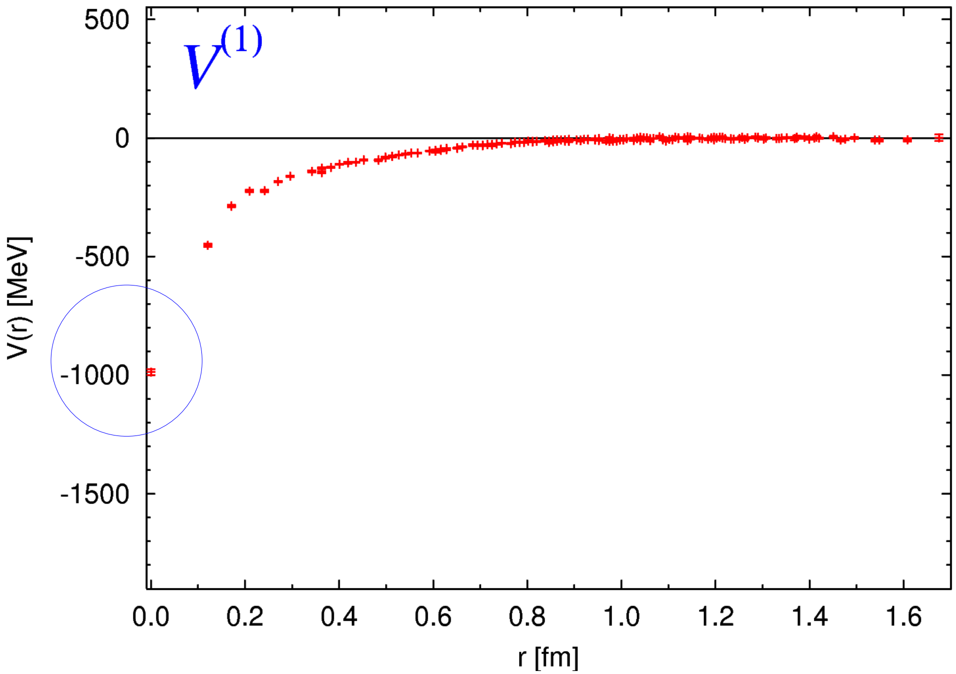
$V^{(10)}$ and $V^{(8a)}$



- Both are effective central potential for $^3S_1$ state.
- 10-plet = SU(3) limit of NΣ (I=3/2, J=1) .
  Stronger repulsive core. Shallow attractive pocket.
- 8a-plet = SU(3) limit of NΞ (I=0, J=1).
  Weaker repulsive core. Vivid attractive pocket.
- The reviewed quark model predictions are correct !!

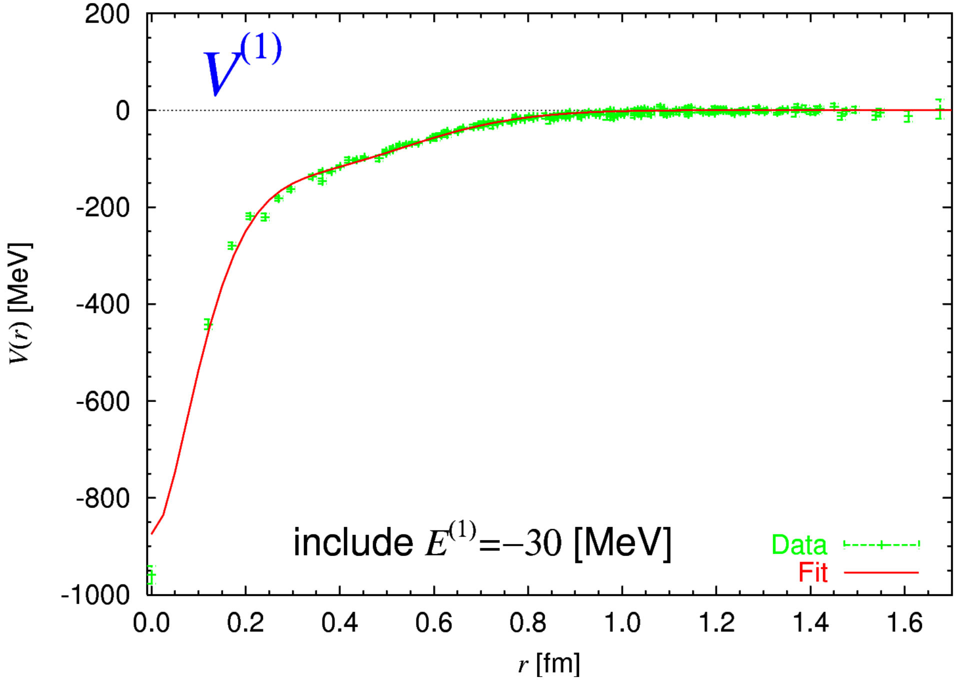
$V^{(8s)}$ and $V^{(1)}$





- Both are $^1S_0$ potential.
- 8s-plet has a very strong repulsive core. Strongest.
- 1-let has no repulsive core. Attractive core!!
- Again, the quark model predictions are correct !!
- How about the predicted bound state?
  With single volume, it is Impossible to see directly from lattice data.

Prediction via $V^{(1)}$

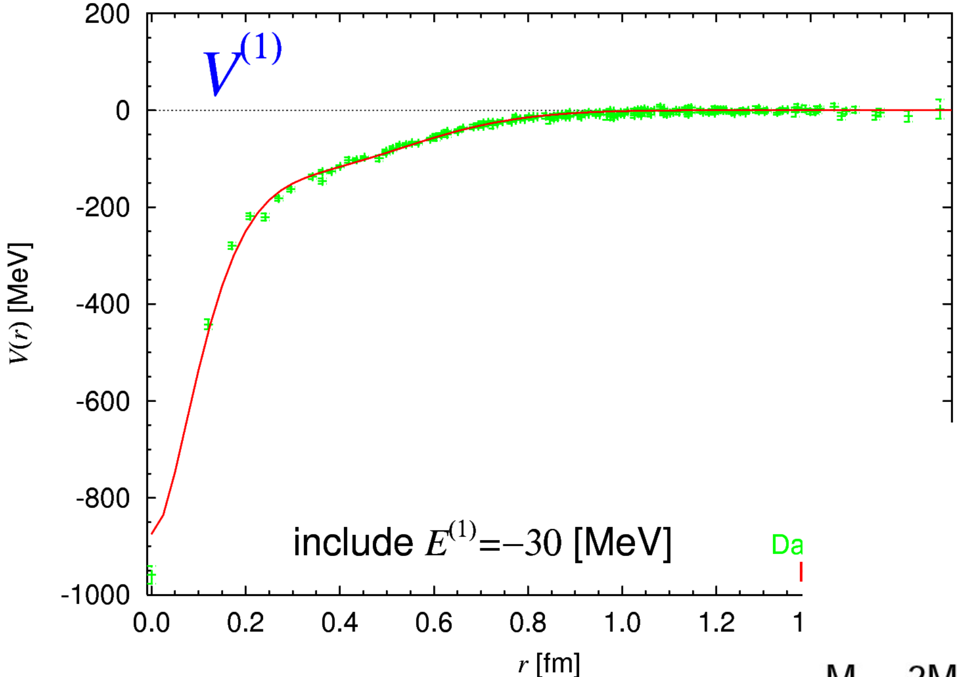


$E^{(1)}$ [MeV]	E bound [MeV]	$\sqrt{\langle r^2 \rangle}$ [fm]
−30	−0.018	24.7
−35	−0.72	4.1
−40	−2.49	2.3

$$V(r) = a(1)\, e^{-a(2)\, r^2} + a(3)\, (1 - e^{-a(4)\, r^2})^2 \left(\frac{e^{-a(5)\, r}}{r} \right)^2$$

- One loosely bound state is found with $V^{(1)}(r)$ including energy contribution $E^{(1)}$ larger than −30 MeV.
- It is a stable H-dibaryon in this SU(3) limit world.
- In contrast to [Wetzorke and Karsch, hep-lat0208029]

Prediction via $V^{(1)}$



$$V(r) = a(1)\, e^{-a(2)\, r^2} + a$$

$\frac{M_H - 2M_\Lambda}{2M_\Lambda}$

$E^{(1)}$ [MeV]	E bound [MeV]	$\sqrt{\langle r^2 \rangle}$ [fm]
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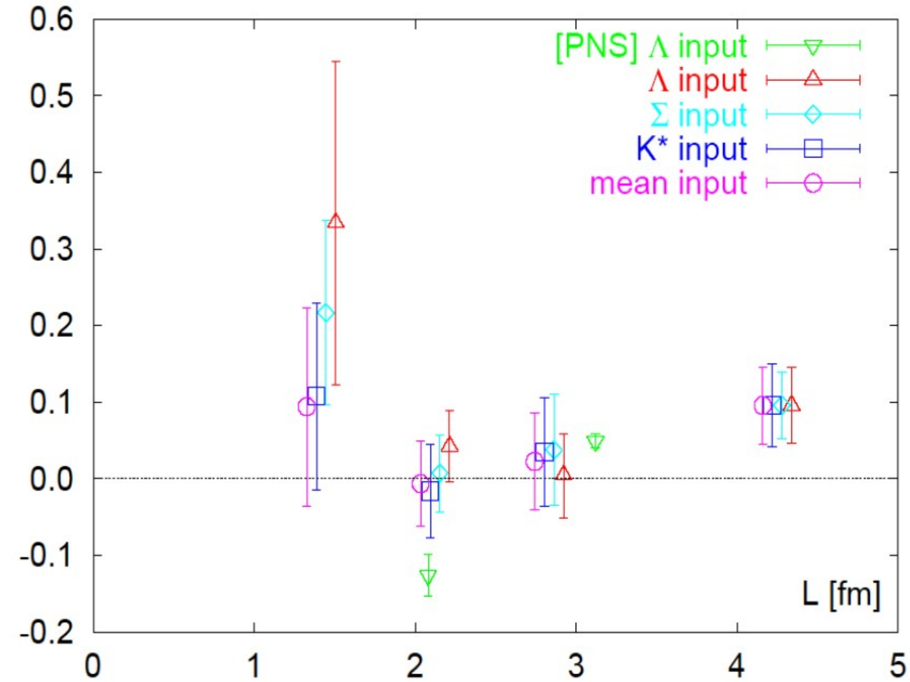

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energy contribution |
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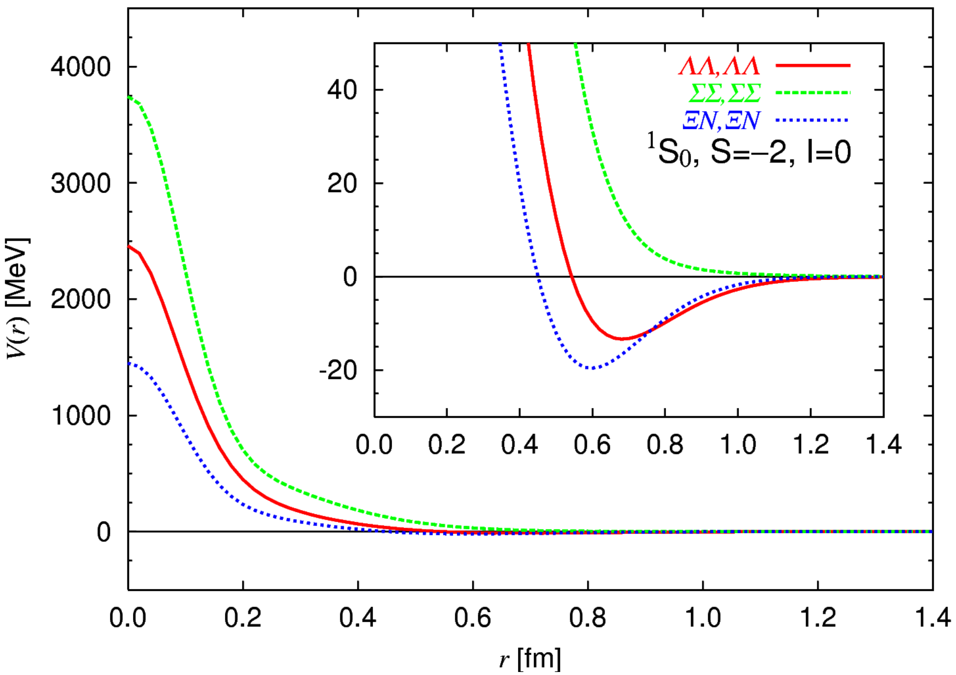
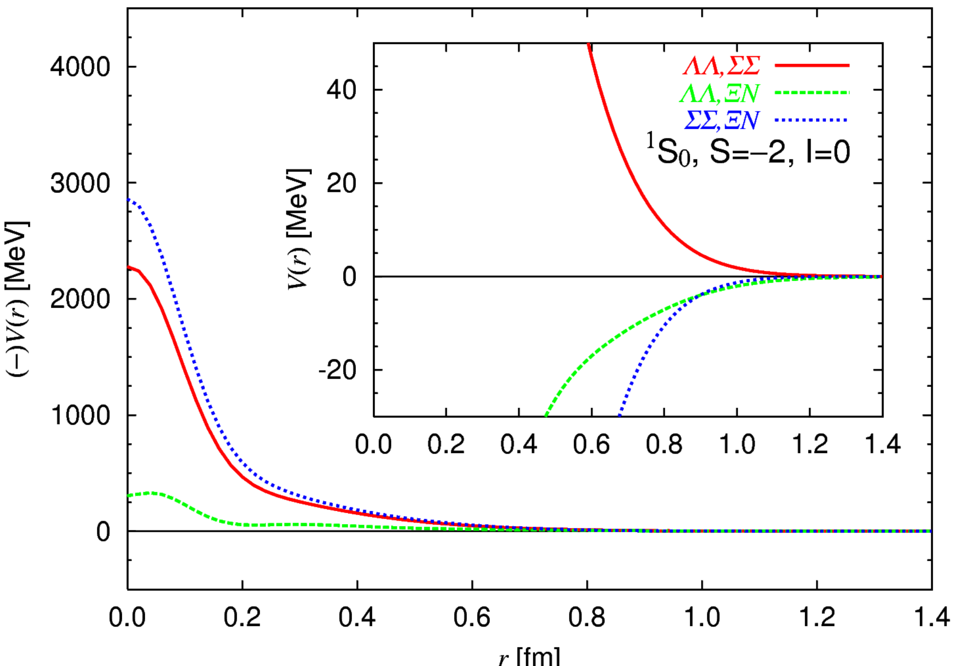
Baryon base potential (S=−2, I=0)

$$\begin{pmatrix} \Lambda\Lambda \\ \Sigma\Sigma \\ \Xi N \end{pmatrix} = U \begin{pmatrix} |27\rangle \\ |8\rangle \\ |1\rangle \end{pmatrix}, \quad U \begin{pmatrix} V^{(27)} & & \\ & V^{(8)} & \\ & & V^{(1)} \end{pmatrix} U^t \rightarrow \begin{pmatrix} V^{\Lambda\Lambda} & V^{\Lambda\Lambda}_{\Sigma\Sigma} & V^{\Lambda\Lambda}_{\Xi N} \\ & V^{\Sigma\Sigma} & V^{\Sigma\Sigma}_{\Xi N} \\ & & V^{\Xi N} \end{pmatrix}$$

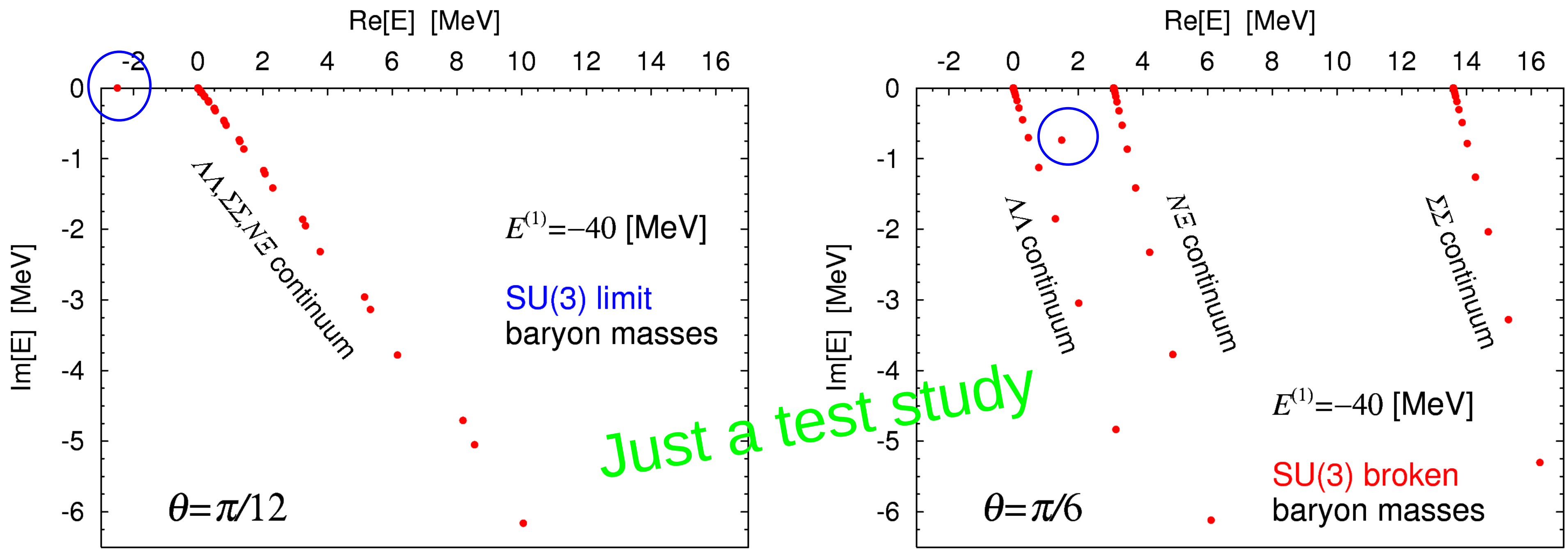




- Such coupled channel potential $V_{ij}(r)$, instead of $V^{(a)}(r)$, are used in SU(3) broken world e.g. the physical one.

Unstable H-dibaryon

Complex Scaling Method

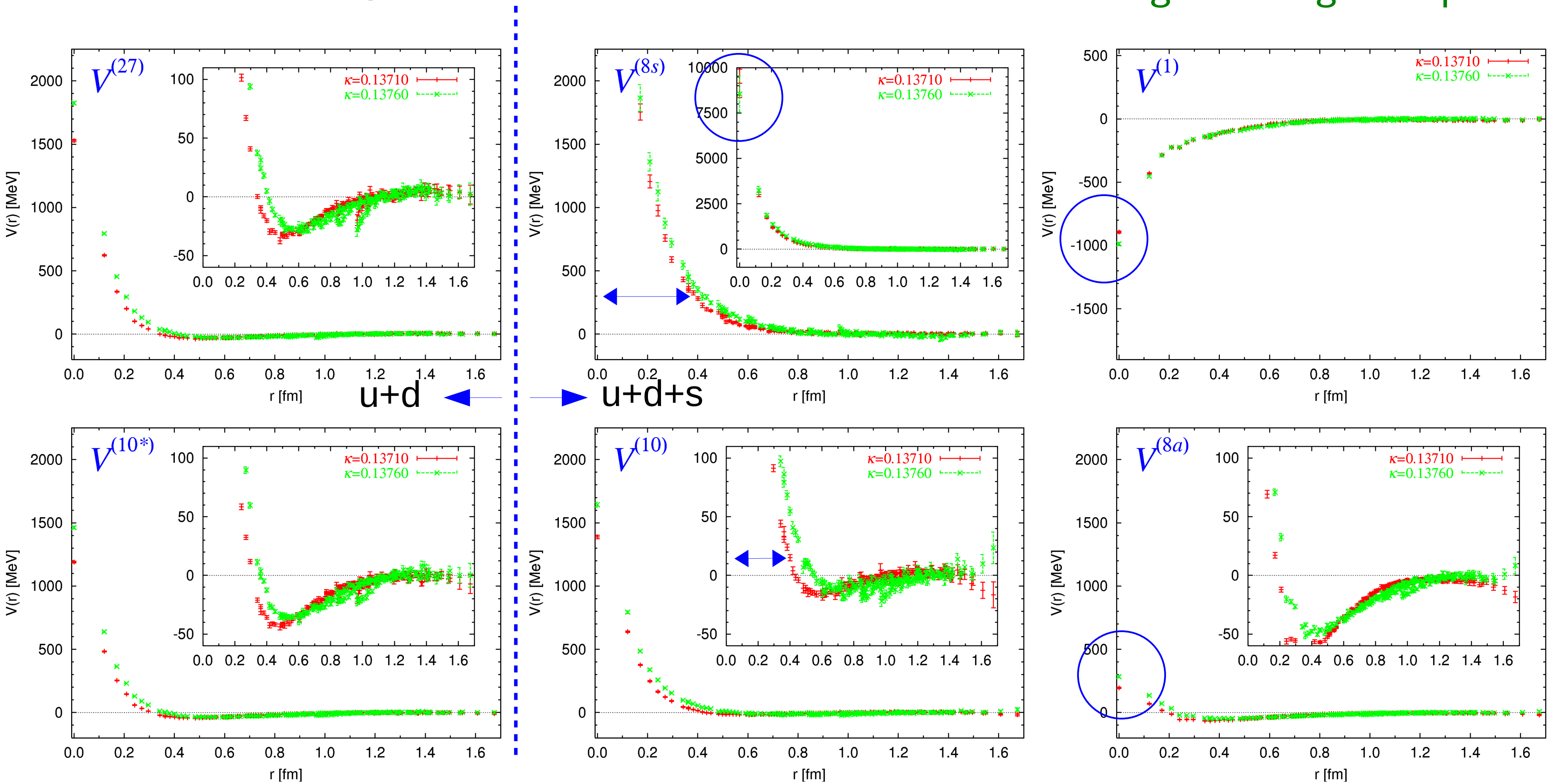


Kud=0.13760, Ks=0.13710

- Energy spectrum of S=−2,I=0 with $V_{ij}(r)$ in the CSM.
- [Left] The stable H-dibaryon in the SU(3) limit world.
- [Right] With some small SU(3) breaking in baryon mass, the state appear at energy between ΛΛ and NΞ thresh. It is an unstable H-dibaryon in this theoretical world. Such state is not excluded by experiment yet.

Summary of $V^{(a)}$

red : heavier quark
green : lighter quark



- Strong flavor-spin dependence in the flavor rep. base.
- Variety of BB interaction in the 3-flavor world.
- Quark mass dependence of BB interaction are evident.

Summary

- We've introduced our motivation, purpose, goal.
  - draw BB interaction directly from QCD using lattice
  - to obtain deeper understanding e.g. physical origin.
- We've explained key points of this study.
  - use flavor SU(3) limit to capture essential part
  - extract potentials as a convenient tool/concept.
- We've shown
  - strong flavor-spin dependence of S-wave interaction
  - variety of BB interaction in the 3-flavor world.
  - quark model predictions are surprisingly correct.
    It is very indicative to physical origin of BB int. at short r.
  - $V^{(1)}$ = attractive core + attraction
    H-dibaryon may exists in QCD and the real. (hope)

Outlook

- On-going
  - Flavor SU(3) point simulation in larger volume.
    - H-dibaryon search in lattice QCD.
    - the first 2-hadron bound state in lattice QCD ?
  - Precise determination of BB energy in lattice.
  - Include SU(3) breaking toward to the physical point.

Next talk

- Future
  - Extract all BB potential at the physical point.
    - conclude about H-dibaryon in the real world.
  - Compare to models and experimental information.
    - finally, we'll understand BB interaction completely.