First results of baryon interactions from lattice QCD with physical masses (3)

--- Strangeness S=-2 two-baryon system ---

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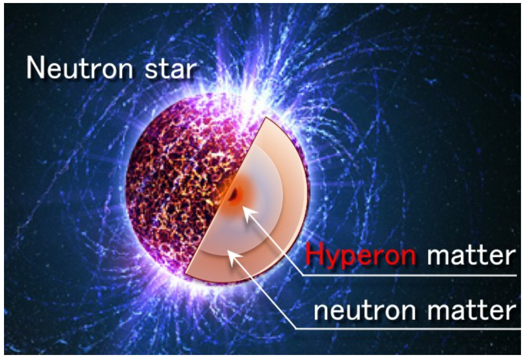
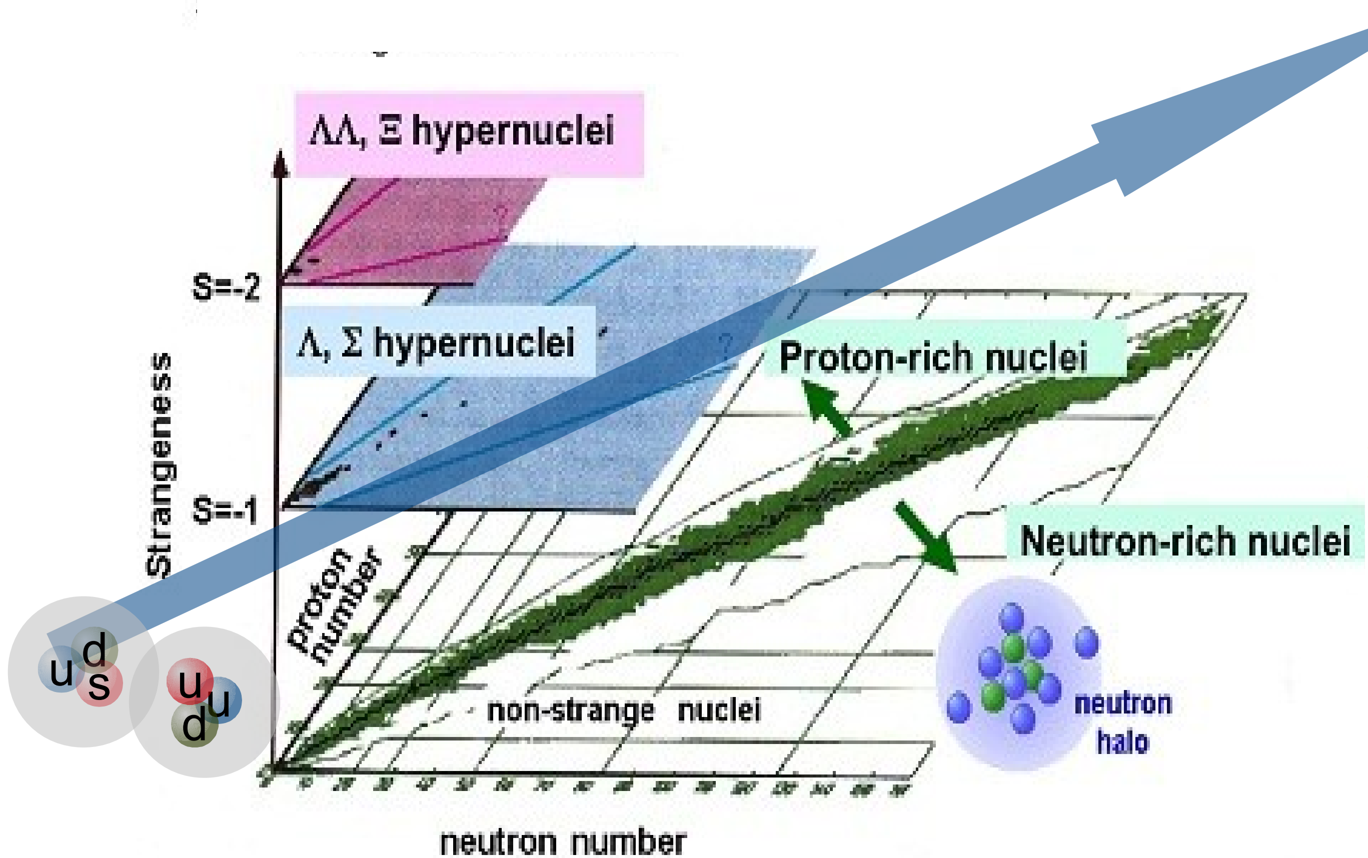
Introduction

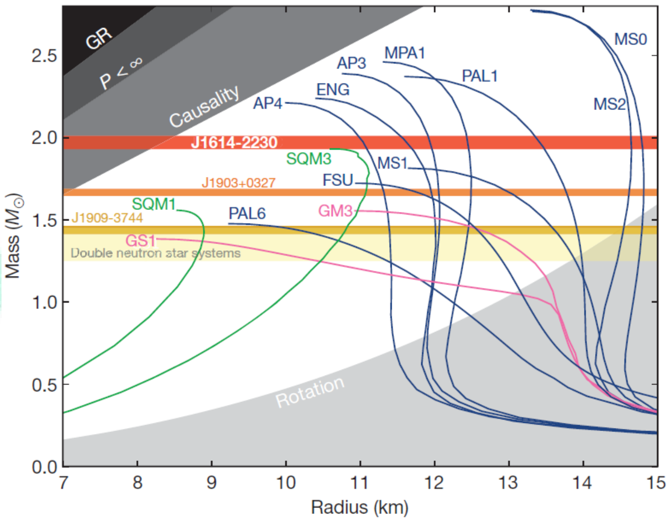
Introduction

BB interactions are inputs for nuclear structure, astrophysical phenomena

Once we obtain a “reliable” nuclear potential,
we apply them to the structure of (hyper-) nucleus
and neutron star calcration.







We derive hadronic interactions from Lattice QCD.

Introduction

Study the hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions

Lattice QCD simulation

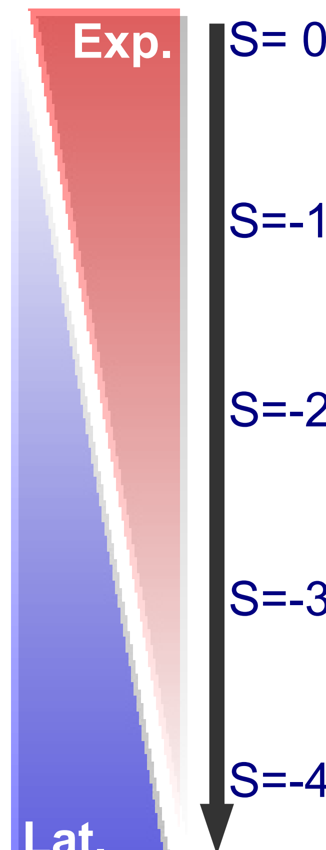
Difficult to calculate light quarks

Suffered from statistical noise

High performance for more data

Massively parallel super computer

Accessibility



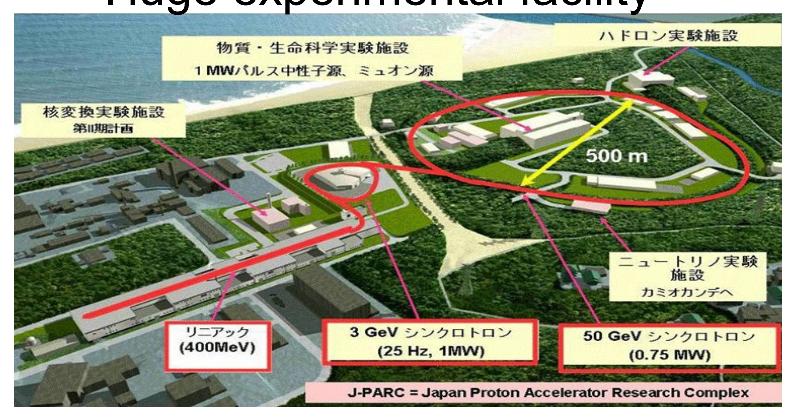
Experiment

Difficult to perform collision experiment

Collision data are scarce

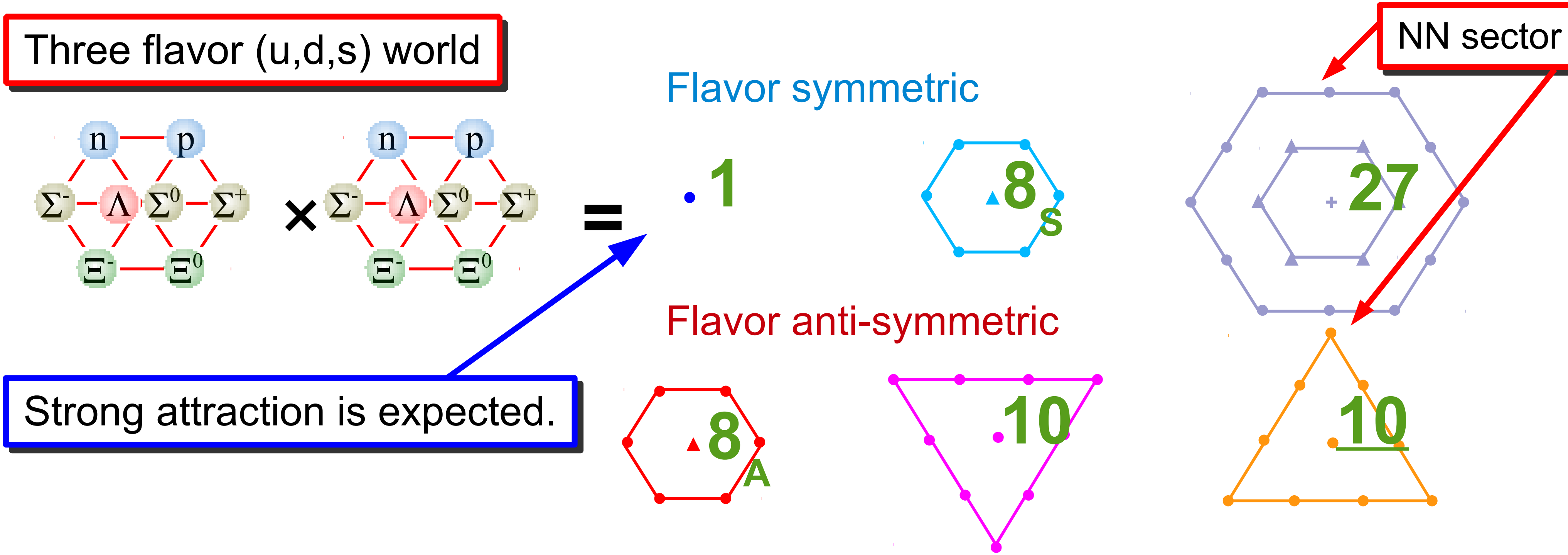
More intensity for more data

Huge experimental facility



They would be complement each other to complete knowledge of generalized BB interaction.

SU(3) feature of BB interaction

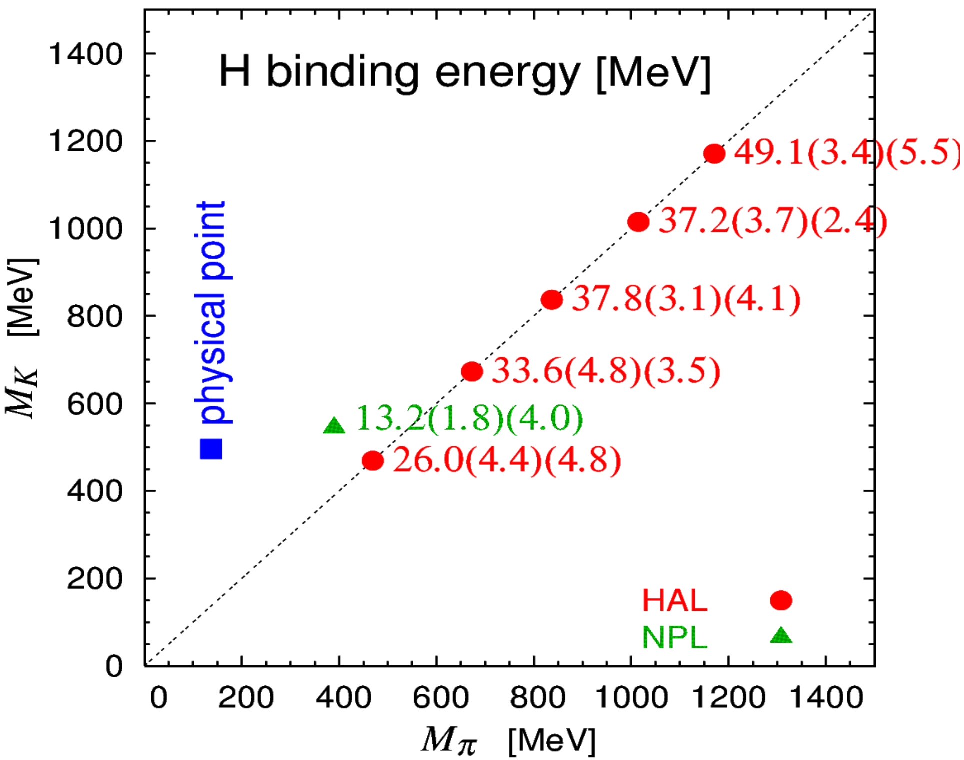


In view of quark degrees of freedom

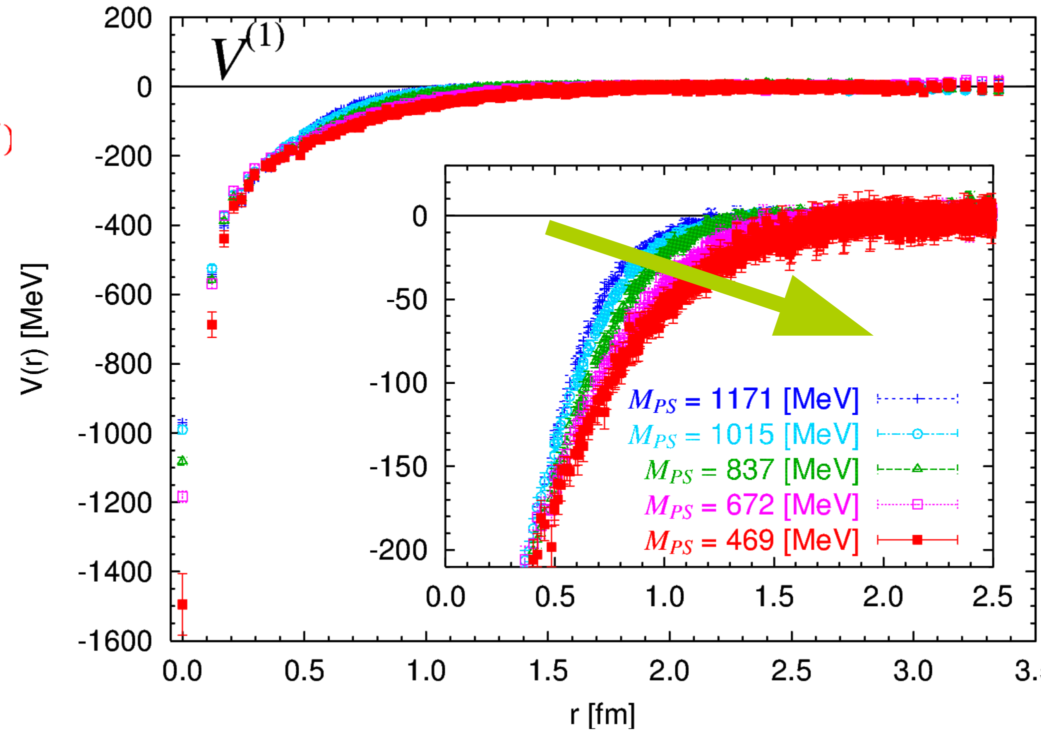
Oka, Shimizu and Yazaki NPA464 (1987)

- Short range repulsion in BB interaction could be a result of Pauli principle and color-magnetic interaction for the quarks.
- Strengths of repulsive core in YN and YY interaction are largely depend on their flavor structures.
- For the s-wave BB system, no repulsive core is predicted in flavor singlet state which is known as H-dibaryon channel.

H-dibaryon (theoretical studies)



HAL : PRL106(2011)162002
NPL : PRL106(2011)162001



- Both results shows the bound H-dibaryon state in heavy pion region.
- Potential in flavor singlet channel is getting more attractive as decreasing quark masses

Does the H-dibaryon state survive on the physical point?

Interests of S=-2 multi-baryon system

H-dibaryon

- The flavor singlet state with J=0 predicted by R.L. Jaffe.
  - Strongly attractive color magnetic interaction.
  - No quark Pauli principle for flavor singlet state.

Double-Λ hypernucleus

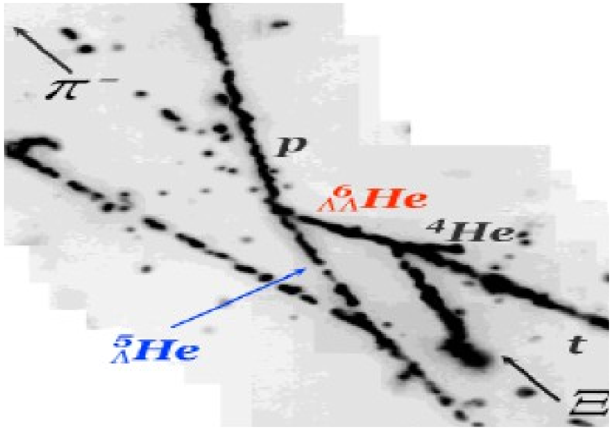
- Conclusions of the "NAGARA Event"

K.Nakazawa and KEK-E176 & E373 Collaborators

Λ–N attraction

Λ–Λ weak attraction

$m_H \geq 2m_\Lambda$ - 6.9MeV

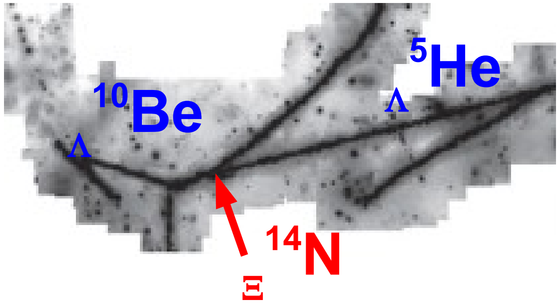


Ξ hypernucleus

- Conclusions of the "KISO Event"

K.Nakazawa and KEK-E373 Collaborators

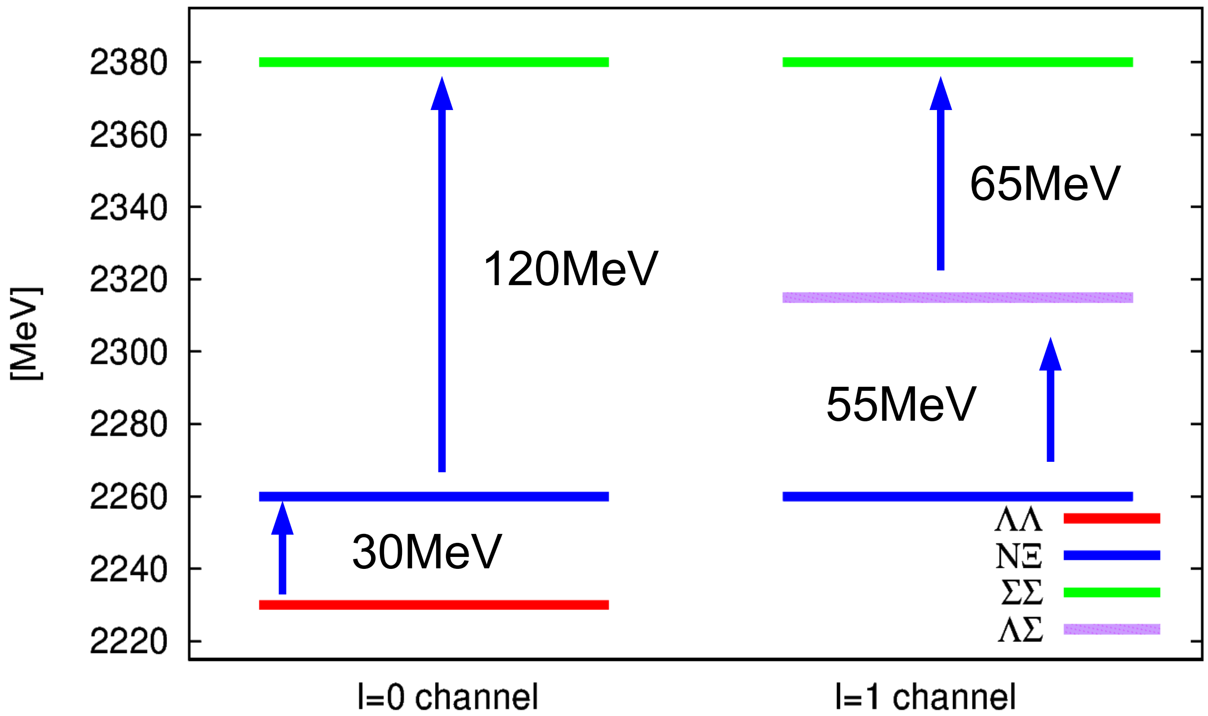
Ξ–N attraction



Numerical setup

- 2+1 flavor gauge configurations.
  - Iwasaki gauge action & O(a) improved Wilson quark action
  - a = 0.086 [*fm*], a^{-1} = 2.300 GeV.
  - *96^3x96 lattice, L* = 8 [*fm*].
  - 200 confs x 12 sources x 4 rotations.
- Flat wall source is considered to produce S-wave B-B state.

Exp.	Mass [MeV]
π	140
K	495
m_π/m_K	0.28
N	940
Λ	1115
Σ	1190
Ξ	1320



Numerical results

Lists of channels

I=0 states

Spin	BB channels			SU(3) representation		
$^1S_0$	$\Lambda\Lambda$	$N\Xi$	$\Sigma\Sigma$	1	8s	27
$^3S_1$	--	$N\Xi$	--	8a	--	--

I=1 states

Spin	BB channels			SU(3) representation		
$^1S_0$	$N\Xi$	--	$\Lambda\Sigma$	--	8s	27
$^3S_1$	$N\Xi$	$\Sigma\Sigma$	$\Lambda\Sigma$	8a	10	10*

I=2 states

Spin	BB channels			SU(3) representation		
$^1S_0$	$\Sigma\Sigma$			--	--	27
~~$^3S_1$~~						

Strong attraction (H-dibaryon)

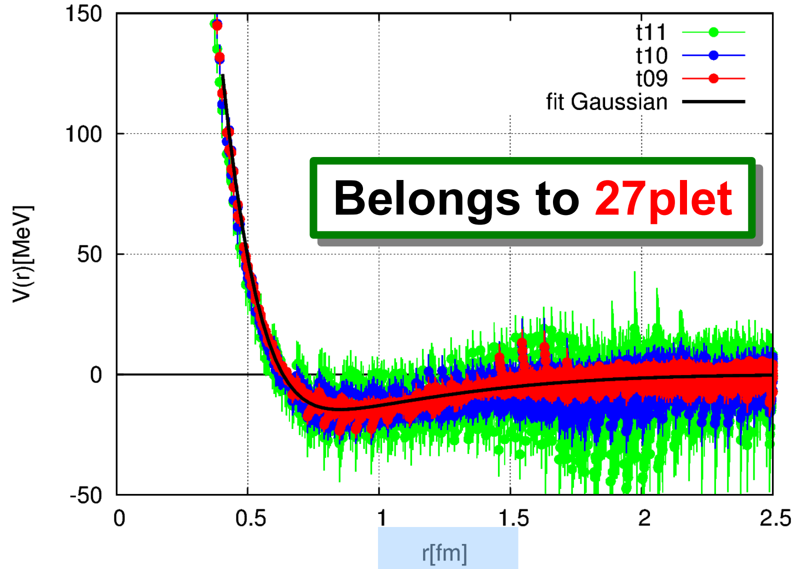
Attraction

Strong repulsion

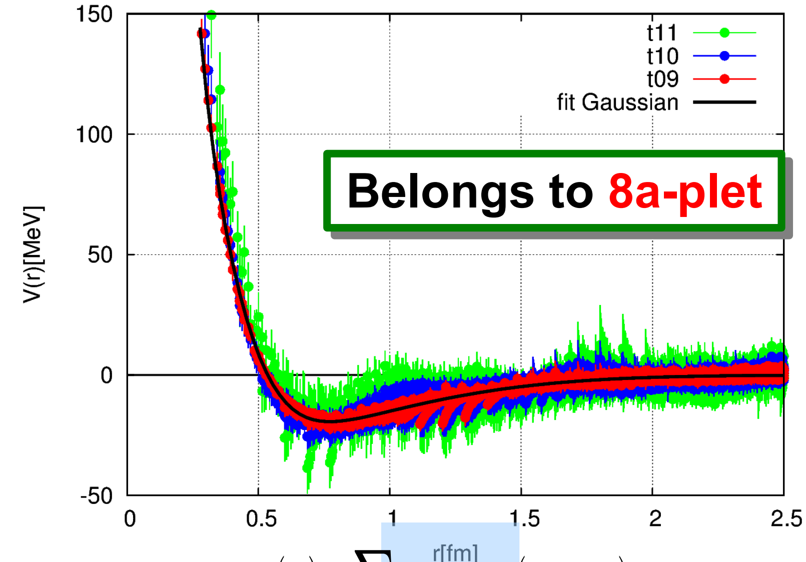
Similar to The NN potential

Repulsion

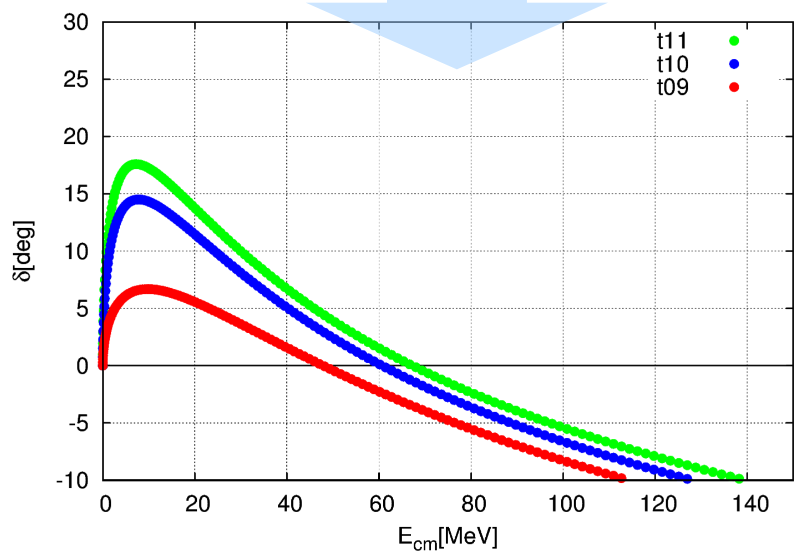
ΣΣ (I=2) $^1S_0$ channel

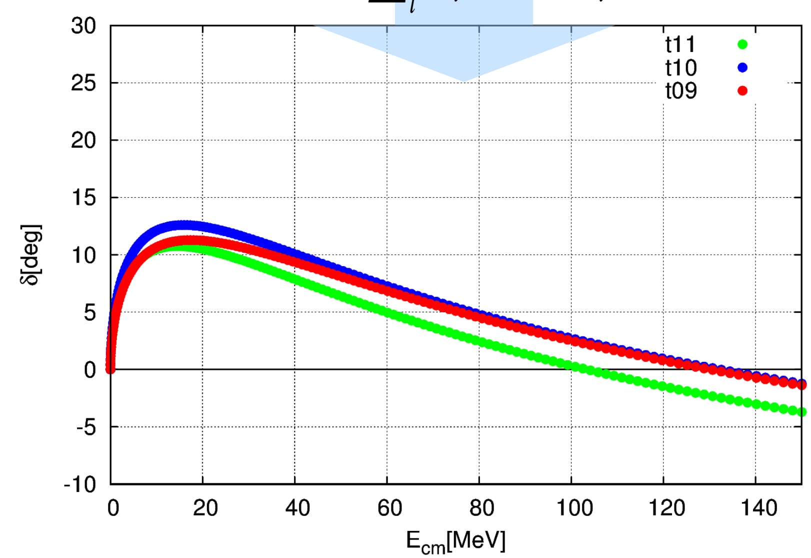


NΞ (I=0) $^3S_1$ channel



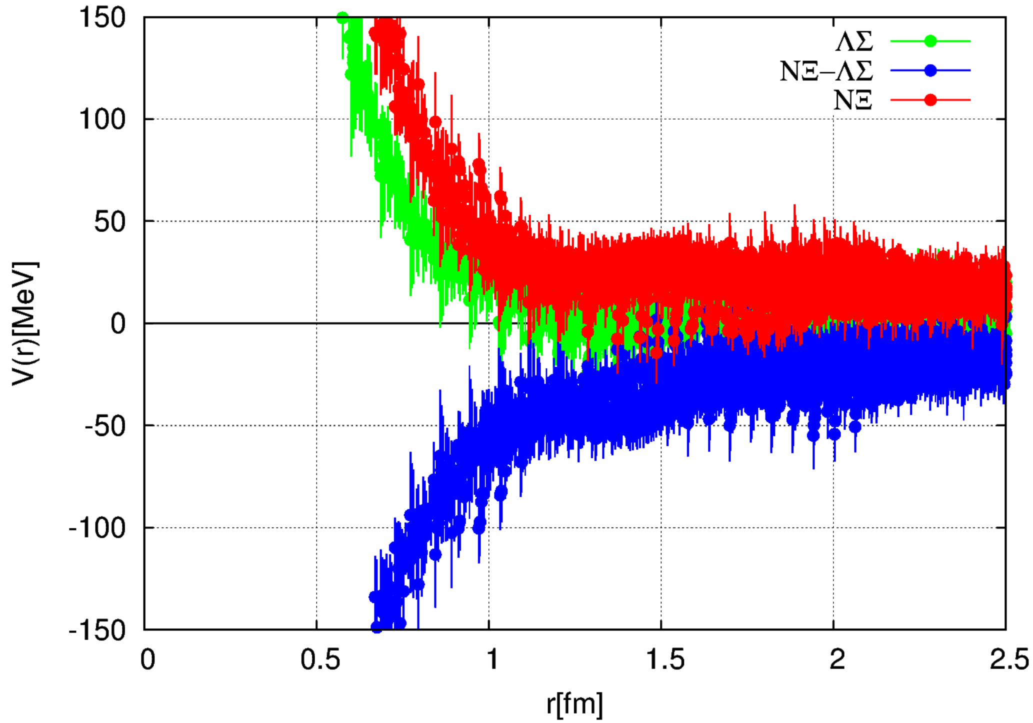
Potential is fitted by three-ranged Gaussian function. $f(r)=\sum_i A_i \exp(-B_i r)$





Potential looks almost saturated at t=10.

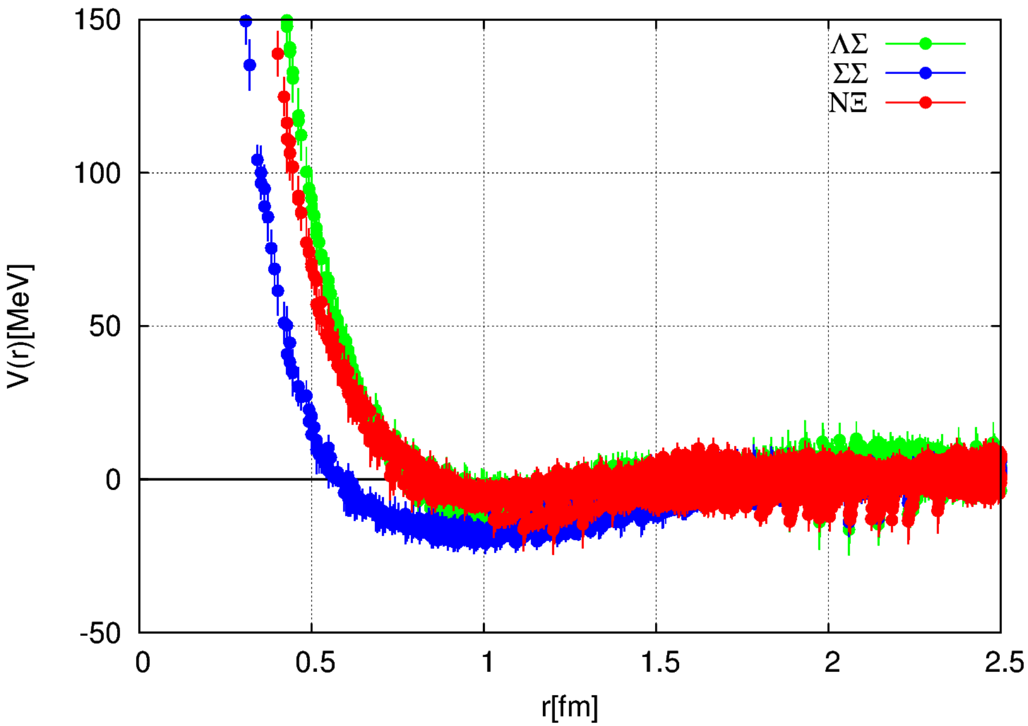
$N\Xi$, $\Lambda\Sigma$ (I=1) $^1S_0$ channel



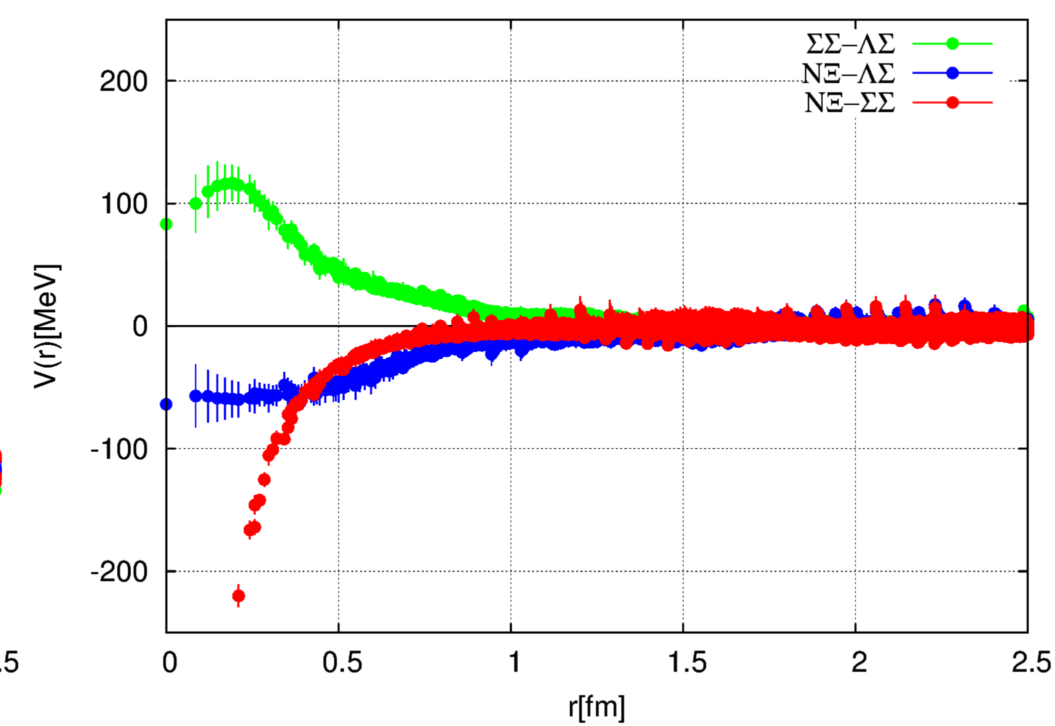
- All diagonal element are totally repulsive in whole range.
- Diagonal NΞ potential is strongly repulsive unlike the I=0 $^3S_1$ case.
  It means that the NΞ potential is strongly depend on the channel.

NΞ, ΛΣ, ΣΣ (I=1) $^3S_1$ *channel*

Diagonal elements



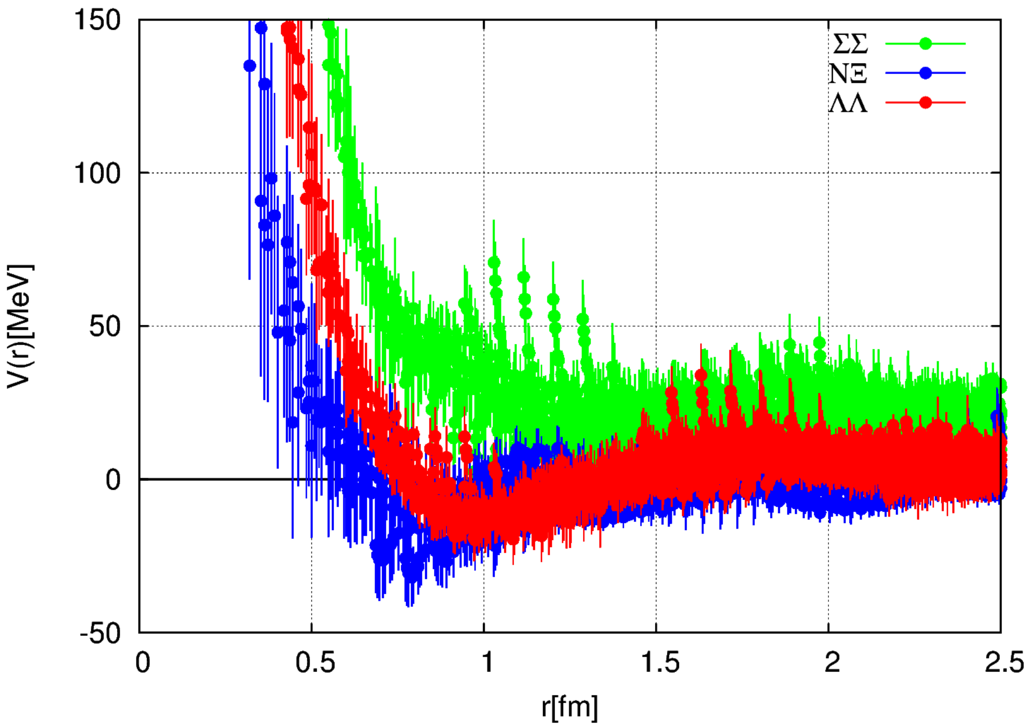
Off-diagonal elements



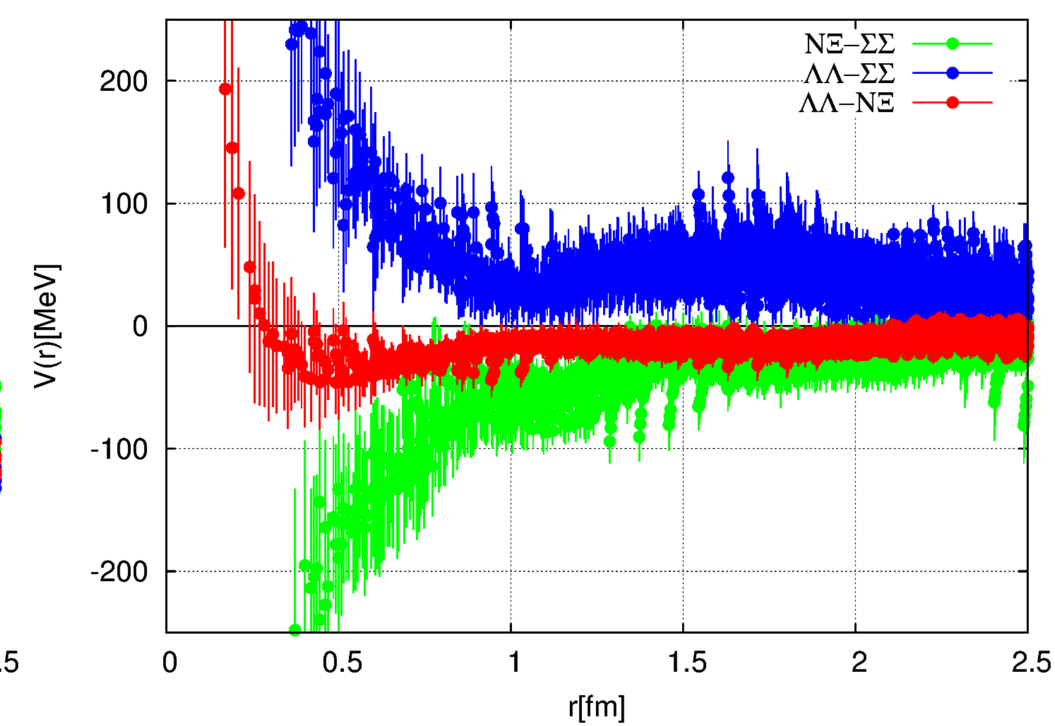
- All diagonal element have a repulsive core and shallow attractive pocket.
- Diagonal ΣΣ potential is most attractive within them.
- We find that NΞ–ΣΣ transition potential is relatively strong comparing to the other transition potentials

ΛΛ, NΞ, ΣΣ (I=0) $^1S_0$ channel

Diagonal elements



Off-diagonal elements



- All diagonal element have a repulsive core ΣΣ–ΣΣ potential is strongly repulsive.
- Off-diagonal potentials are relatively strong except for ΛΛ–NΞ transition
- We need more statistics to discuss physical observables through this potential.

Comparison of potential matrices

Transformation of potentials
from the particle basis to the SU(3) irreducible representation (irrep) basis.

SU(3) Clebsh-Gordan coefficients

$$\begin{pmatrix} |1\rangle \\ |8\rangle \\ |27\rangle \end{pmatrix} = U \begin{pmatrix} |\Lambda\Lambda\rangle \\ |N\Xi\rangle \\ |\Sigma\Sigma\rangle \end{pmatrix}, \quad U \begin{pmatrix} V^{\Lambda\Lambda} & V^{\Lambda\Lambda}_{N\Xi} & V^{\Lambda\Lambda}_{\Sigma\Sigma} \\ V^{N\Xi}_{\Lambda\Lambda} & V^{N\Xi} & V^{N\Xi}_{\Sigma\Sigma} \\ V^{\Sigma\Sigma}_{\Lambda\Lambda} & V^{\Sigma\Sigma}_{N\Xi} & V^{\Sigma\Sigma} \end{pmatrix} U^t \longrightarrow \begin{pmatrix} V_1 & & \\ & V_8 & \\ & & V_{27} \end{pmatrix}$$

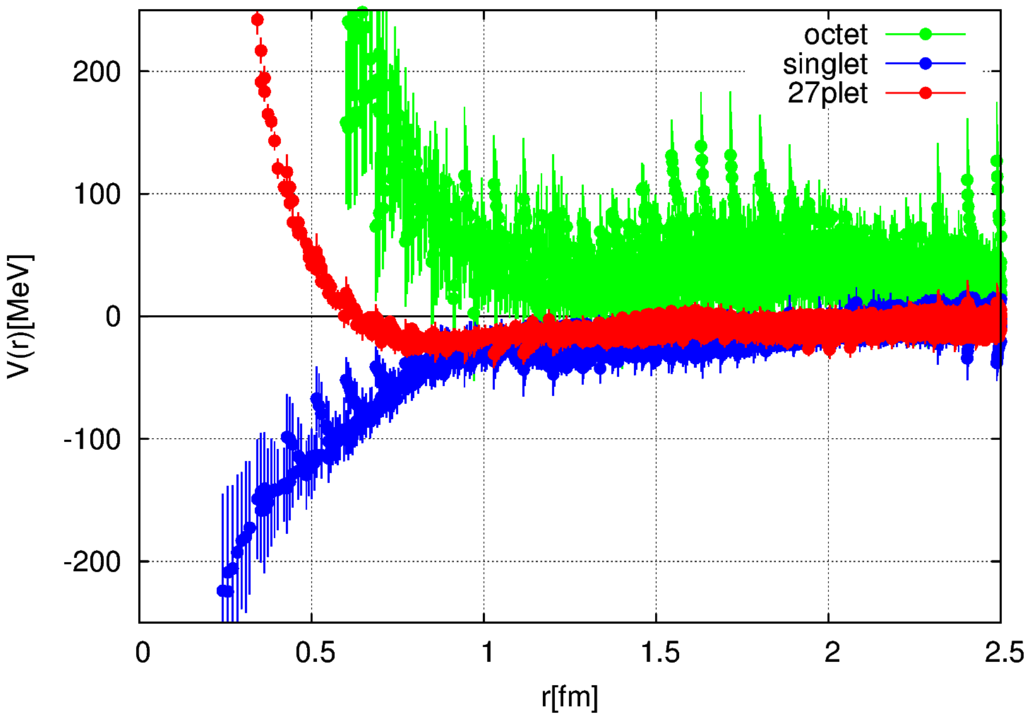
In the SU(3) irreducible representation basis,
the potential matrix should be diagonal in the SU(3) symmetric configuration.

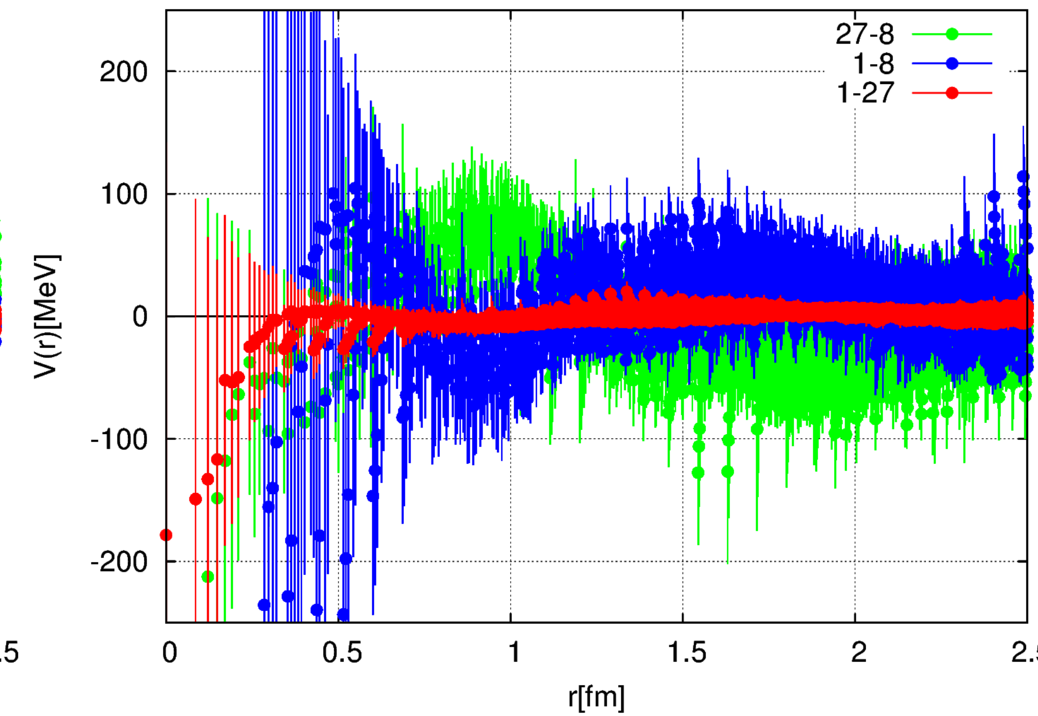
Off-diagonal part of the potential matrix in the SU(3) irrep basis
would be an effectual measure of the SU(3) breaking effect.

1, 8s, 27plet $^1S_0$ channel

Diagonal elements

Off-diagonal elements





- Potential of flavor singlet channel does not have a repulsive core
- Potential of flavor octet channel is strongly repulsive which reflect a Pauli effect.
- Off-diagonal potentials are visible only in r<1fm region.

Summary and outlook

- We have investigated S=-2 BB interactions from lattice QCD near the physical point.

- We find that
  - Potential in $\Lambda\Lambda$ $^1S_0$ channel is weakly attractive.
  - $N\Xi$ potential is largely depends on its channel.
  - Potential in flavor singlet $^1S_0$ channel is strongly attractive.

- It is not enough statistics to calculate several observables and to discuss the fate of H-dibayon.

- Further investigation will be performed with high statistics data.

Backup slides

Coupled channel Schrödinger equation

Preparation for the NBS wave function

Two-channel coupling case

$$\Psi^{\alpha}(E,t,\vec{r}) = \sum_{\vec{x}} \langle 0|(B_1 B_2)^{\alpha}(t,\vec{r})|E\rangle$$

$$\Psi^{\beta}(E,t,\vec{r}) = \sum_{\vec{x}} \langle 0|(B_1 B_2)^{\beta}(t,\vec{x})|E\rangle$$

The same “in” state

Inside the interaction range

In the *leading order of velocity expansion* of non-local potential,

Coupled channel Schrödinger equation.

Factorization of interaction kernel

$$\left(\frac{p_{\alpha}^2}{2\mu_{\alpha}} + \frac{\nabla^2}{2\mu_{\alpha}}\right)\psi^{\alpha}(\vec{x},E) = V^{\alpha}{}_{\alpha}(\vec{x})\psi^{\alpha}(\vec{x},E) + V^{\alpha}{}_{\beta}(\vec{x})\psi^{\beta}(\vec{x},E)$$

μ_{α} : *reduced mass*

p_{α} : asymptotic momentum.

Asymptotic momentum are replaced by the time-derivative of *R*.

$$R_I^{B_1 B_2}(t,\vec{r}) = \sum_{\vec{x}} \langle 0|B_1(t,\vec{x}+\vec{r})B_2(t,\vec{x})\bar{I}(0)|0\rangle e^{(m_1+m_2)t}$$

$$\begin{pmatrix} V^{\alpha}{}_{\alpha}(\vec{r}) & V^{\alpha}{}_{\beta}(\vec{r})x \\ V^{\beta}{}_{\alpha}(\vec{r})x^{-1} & V^{\beta}{}_{\beta}(\vec{r}) \end{pmatrix} = \begin{pmatrix} (\frac{\nabla^2}{2\mu_{\alpha}} - \frac{\partial}{\partial t})R_{I1}^{\alpha}(\vec{r},E) & (\frac{\nabla^2}{2\mu_{\beta}} - \frac{\partial}{\partial t})R_{I2}^{\beta}(\vec{r},E) \\ (\frac{\nabla^2}{2\mu_{\alpha}} - \frac{\partial}{\partial t})R_{I1}^{\alpha}(\vec{r},E) & (\frac{\nabla^2}{2\mu_{\beta}} - \frac{\partial}{\partial t})R_{I2}^{\beta}(\vec{r},E) \end{pmatrix} \begin{pmatrix} R_{I1}^{\alpha}(\vec{r},E) & R_{I1}^{\beta}(\vec{r},E) \\ R_{I2}^{\alpha}(\vec{r},E) & R_{I2}^{\beta}(\vec{r},E) \end{pmatrix}^{-1}$$

$$x = \frac{\exp(-(m_{\alpha_1}+m_{\alpha_2})t)}{\exp(-(m_{\beta_1}+m_{\beta_2})t)}$$