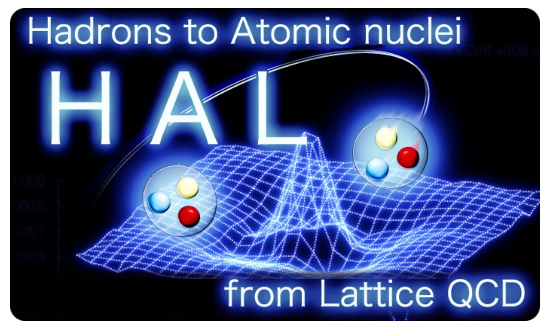
Lattice QCD study on YN / YY interactions

Kenji Sasaki (*YITP, Kyoto University*)

for HAL QCD Collaboration



HAL (Hadrons to Atomic nuclei from Lattice) QCD Collaboration

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Contents

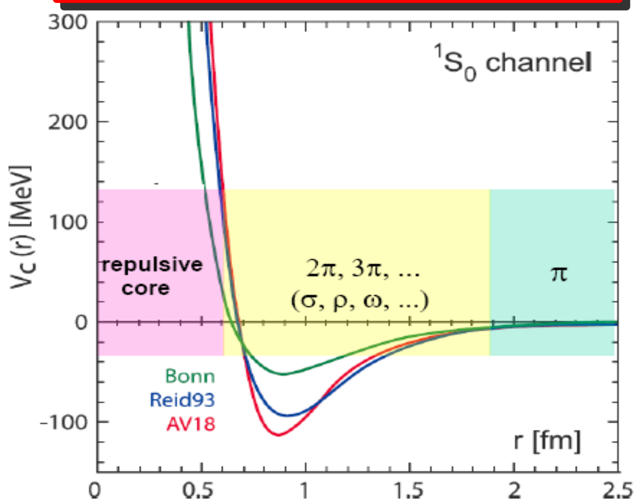
Introduction

Introduction

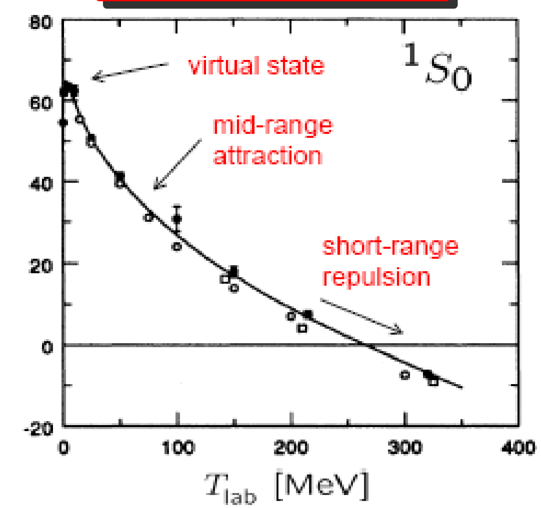
Baryon-baryon interactions are key to understand nuclear structures and astrophysical phenomena

Traditional way to research the BB interaction / potential

BB interaction (potential)



BB phase shift



NN interaction

Large amount of scattering data to determine theoretical parameters

YN / YY interaction

More strangeness, more difficult to access it experimentally. Experimental data are scarce.

Lattice QCD results for YN and YY interactions are highly awaited

Baryon interaction from QCD

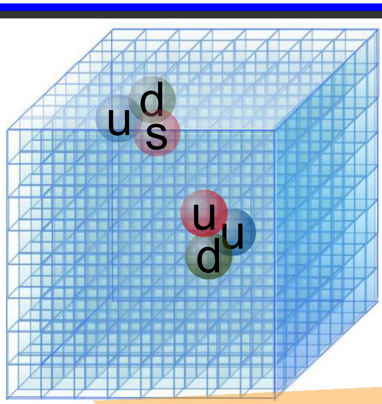
QCD is the fundamental theory of strong interactions

QCD Lagrangian

$$L_{QCD} = \bar{q}(i\gamma_\mu D^\mu - m)q + \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$$

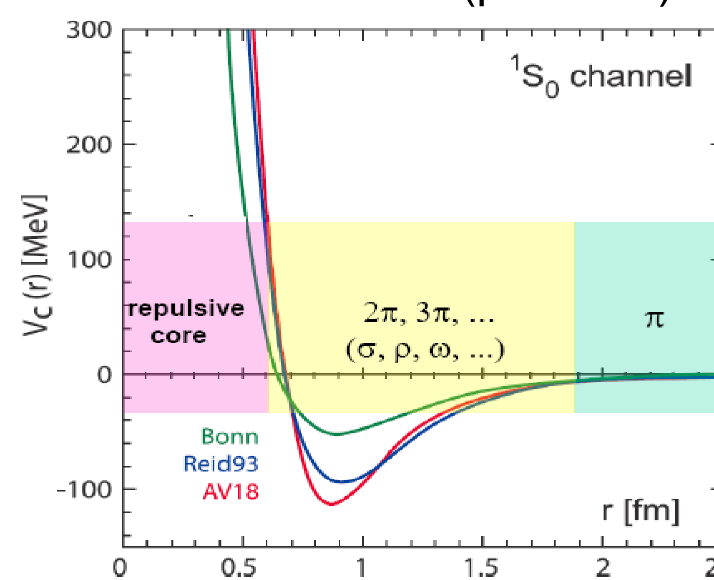
it is difficult to solve the dynamics of quarks and gluons because of its non-perturbative nature at low-energies.

Lattice QCD simulation



- **Non-perturbative calculation**
- **Hige computer resource is necessary**
- **Independent of experimental situation**

BB interaction (potential)

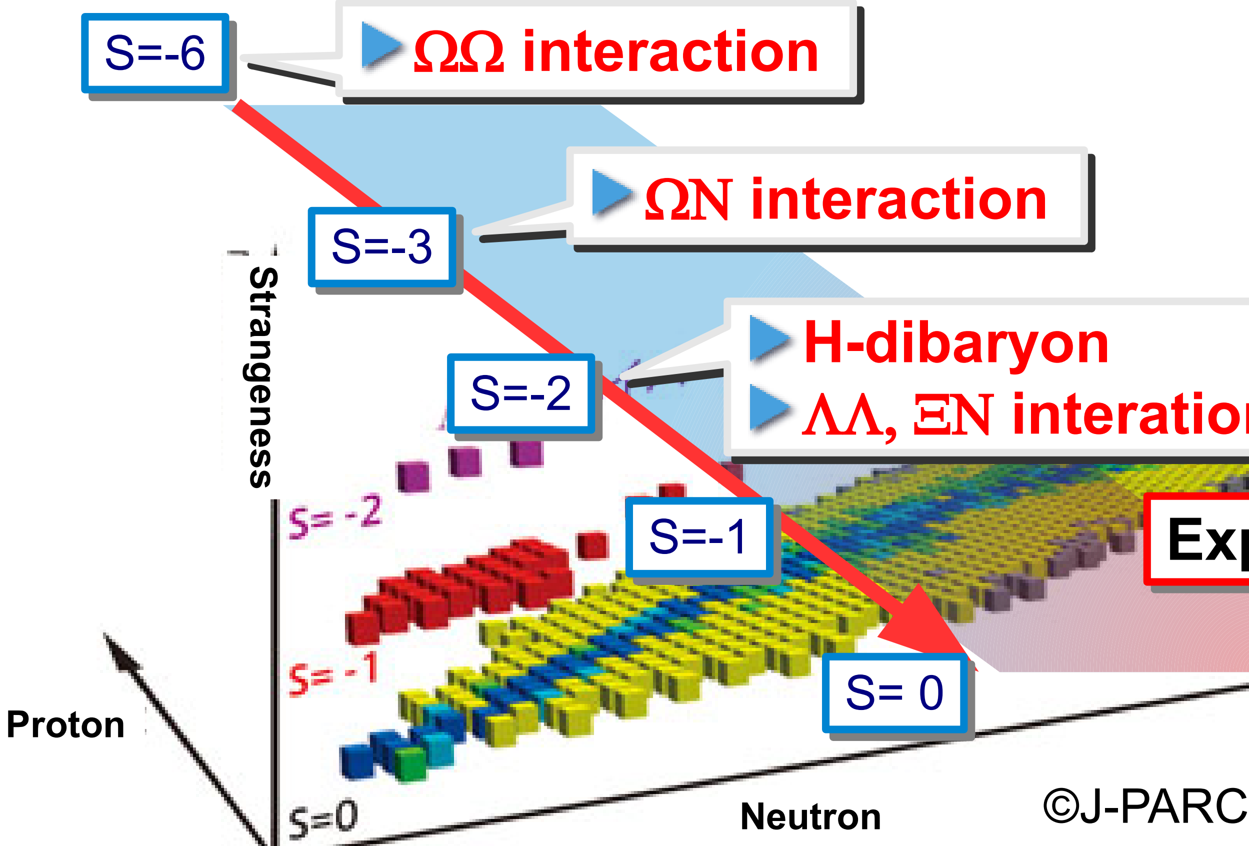


Introduction

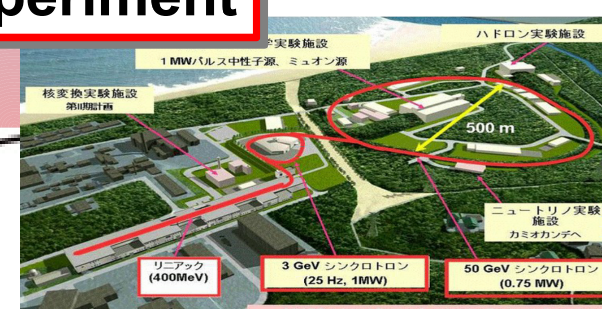
Aim : Nuclear structures and exotic states from QCD

Lattice QCD simulation

- **Advantageous for more strange quarks**
- **Noises are getting larger as increasing the number of light quarks.**
- **Complementary role to experiment.**



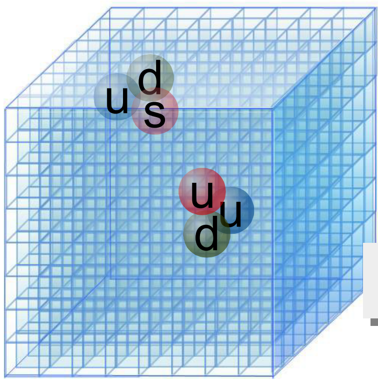
Experiment



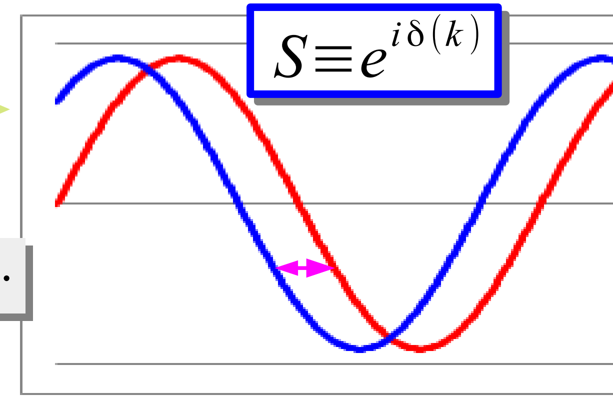
Baryon interaction from LQCD

Hadron interaction from Lattice QCD

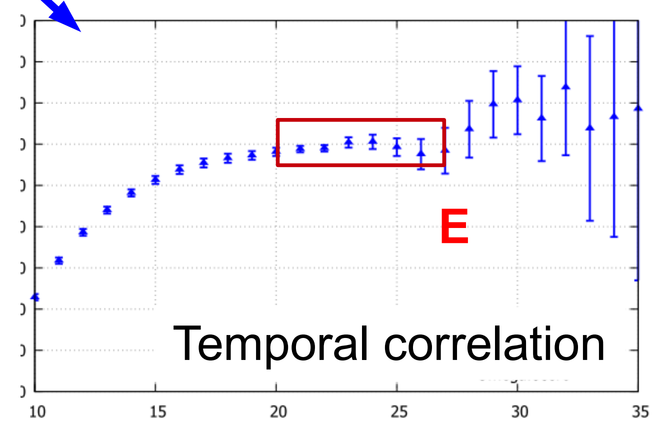
Lattice QCD simulation



Scattering S-matrix



$$\langle 0 | B_1 B_2(t, \vec{r}) \bar{I}(t_0) | 0 \rangle = A_0 \Psi(\vec{r}, E_0) e^{-E_0(t-t_0)} + \cdots$$



Eigen energy is extracted from plateau region

Issue of mirage plateau

T. Iritani et al. (HAL), JHEP1610(2016)101

Lüscher's finite volume method

M. Lüscher, NPB354(1991)531

1. Measure the discrete energy spectrum, **E**
2. Put the **k** from E into the formula which connects **k** and **δ**

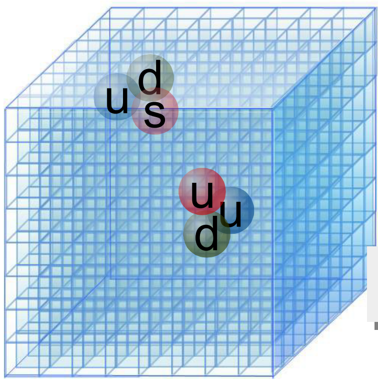
$$k_n \cot \delta(k_n) = \frac{4\pi}{L^3} \sum_{m \in \mathbb{Z}^3} \frac{1}{\vec{p}_m^2 - k_n^2}$$

Scattering phase shift

HAL QCD method

Hadron interaction from LQCD

Lattice QCD simulation

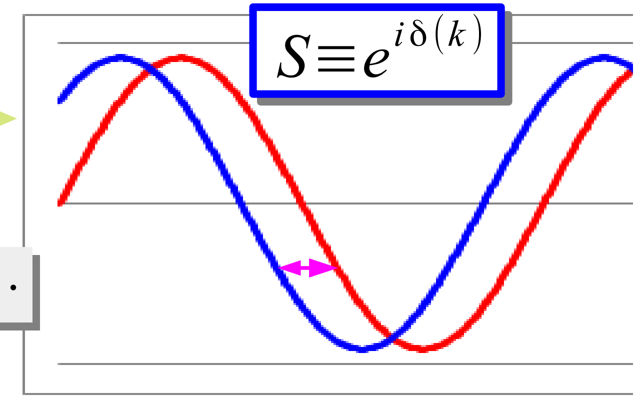


HAL QCD method

Ishii, Aoki, Hatsuda, PRL**99** (2007) 022001

Scattering S-matrix

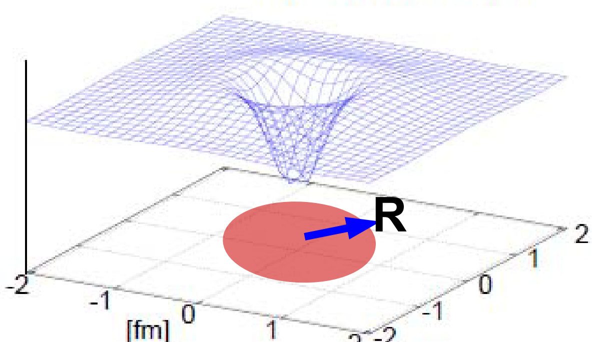
$$S \equiv e^{i\delta(k)}$$



$$\langle 0 | B_1 B_2(t, \vec{r}) \bar{I}(t_0) | 0 \rangle = A_0 \Psi(\vec{r}, E_0) e^{-E_0(t-t_0)} + \cdots$$

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

NBS wave function



$$\left(p^2 + \nabla^2\right) \Psi(\vec{r}, E) = 0, (r > R)$$

$$\Psi(\vec{r}, E) \simeq A \frac{\sin(pr + \delta(E))}{pr}$$

Phase shift is embedded in NBS w.f.

- **Inside of "interacting region"**

$$\left(p^2 + \nabla^2\right) \Psi^\alpha(E, \vec{x}) \equiv \int d^3 y\, U^\alpha_\alpha(\vec{x}, \vec{y}) \Psi^\alpha(E, \vec{y})$$

- **U(x,y) is faithful to the S-matrix.**
- **U(x,y) is not an observable.**
- **U(x,y) is energy independent but non-local.**

Time-dependent Schrödinger like equation

Start with the normalized four-point correlator.

$$R_I^{B_1 B_2}(t,\vec{r}) = F^{B_1 B_2}{}_I(t,\vec{r})\, e^{(m_1+m_2)t}$$

$$= A_0 \Psi(\vec{r},E_0)\, e^{-(E_0-m_1-m_2)t} + A_1 \Psi(\vec{r},E_1)\, e^{-(E_1-m_1-m_2)t} + \cdots$$

$$\left(\frac{p_0^2}{2\mu}+\frac{\nabla^2}{2\mu}\right)\Psi(\vec{r},E_0) = \int U(\vec{r},\vec{r}\,')\Psi(\vec{r}\,',E_0)\, d^3r'$$

$$E_n - m_1 - m_2 \approx \frac{p_n^2}{2\mu}$$

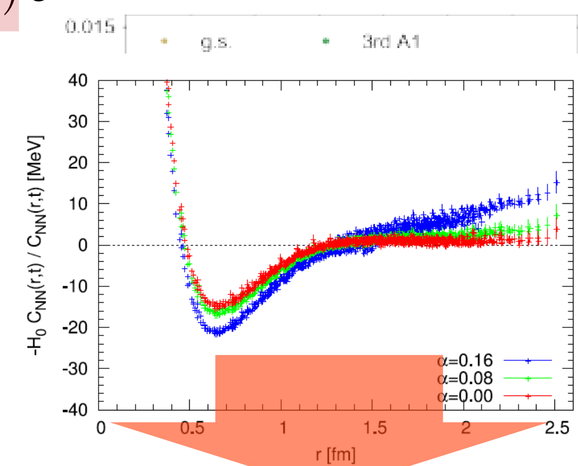
$$\left(\frac{p_1^2}{2\mu}+\frac{\nabla^2}{2\mu}\right)\Psi(\vec{r},E_1) = \int U(\vec{r},\vec{r}\,')\Psi(\vec{r}\,',E_1)\, d^3r'$$

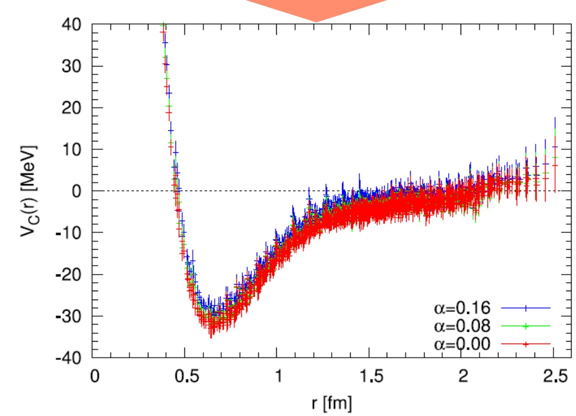
A single state saturation is not required!!

$$\left(-\frac{\partial}{\partial t}+\frac{\nabla^2}{2\mu}\right) R_I^{B_1 B_2}(t,\vec{r}) = \int U(\vec{r},\vec{r}\,') R_I^{B_1 B_2}(t,\vec{r})\, d^3r'$$

Derivative (velocity) expansion of U

$$U(\vec{r},\vec{r}\,') = \left[V_C(r) + S_{12} V_T(r)\right] + \left[\vec{L}\cdot\vec{S}_s V_{LS}(r) + \vec{L}\cdot\vec{S}_a V_{ALS}(r)\right] + O(\nabla^2)$$





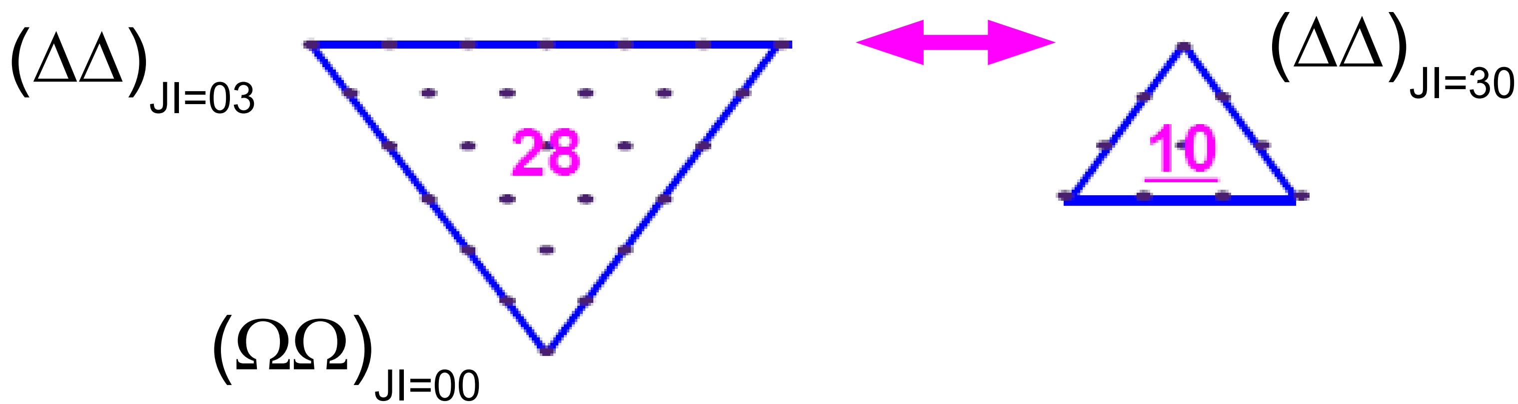
ΩΩ interaction

Decuplet-Decuplet interaction

- **Flavor symmetry aspect**

Decuplet-Decuplet interaction can be classified as

$$10 \otimes 10 = 28 \oplus 27 \oplus 35 \oplus \overline{10}$$



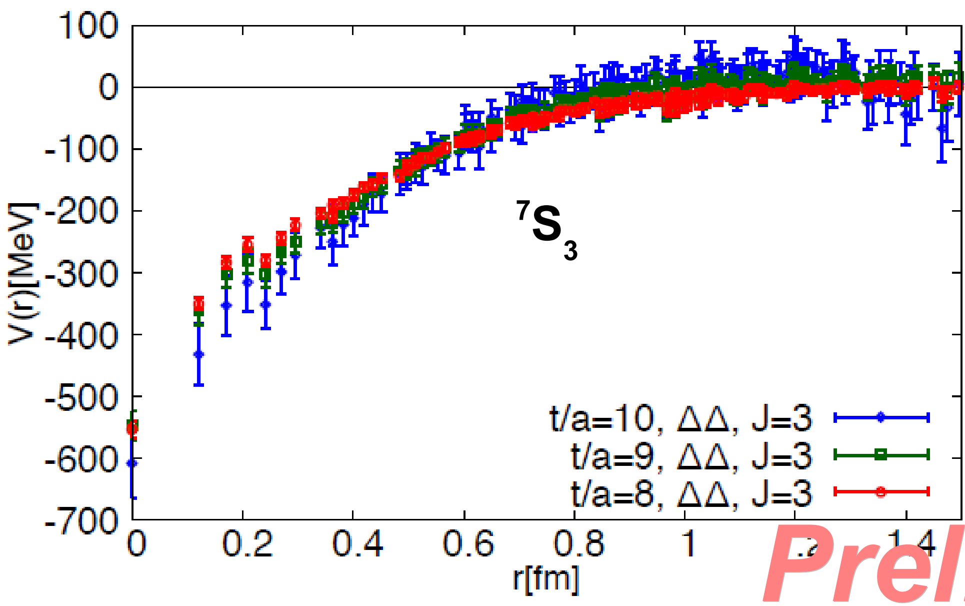
	28plet (0^+)	10*plet (3^+)
Pauli	**allowed**	**allowed**
CMI	**repulsive**	**No**

- **Δ–Δ(J=3) : Bound (resonance) state was found in experiment.**
- **Δ–Δ(J=0) [and Ω–Ω(J=0)] : Mirror of Δ–Δ(J=3) state**

S. Gongyo, K. Sasaki (HAL QCD)

Decuplet-Decuplet interaction in SU(3) limit

▶ N_f = 3 full QCD with L = 1.93fm, *m_π = 1015 MeV* *m_Δ = 2225 MeV*



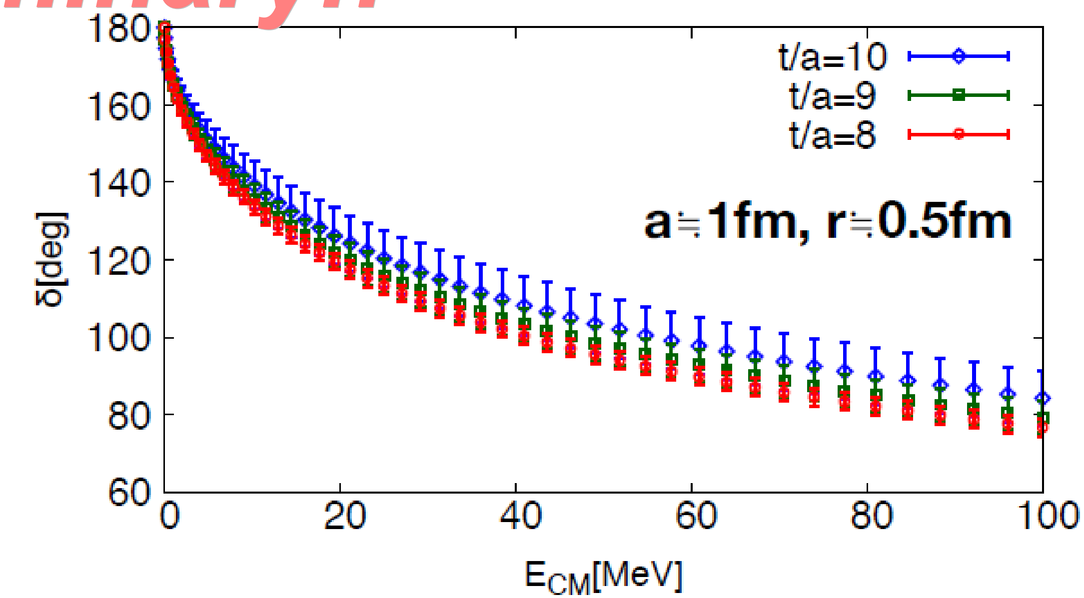
Δ–Δ(J=3) **10*plet**

- **Interaction in 10*plet [$J^p(I)=3^+(0)$] is strongly attractive.**
- **There is no repulsive core at short distances**

Preliminary!!

Bound ΔΔ state is found.

- **Decay to NN($^3D_3$) is neglected.**
- **Δ baryon can not decay into N+π in this lattice setup**



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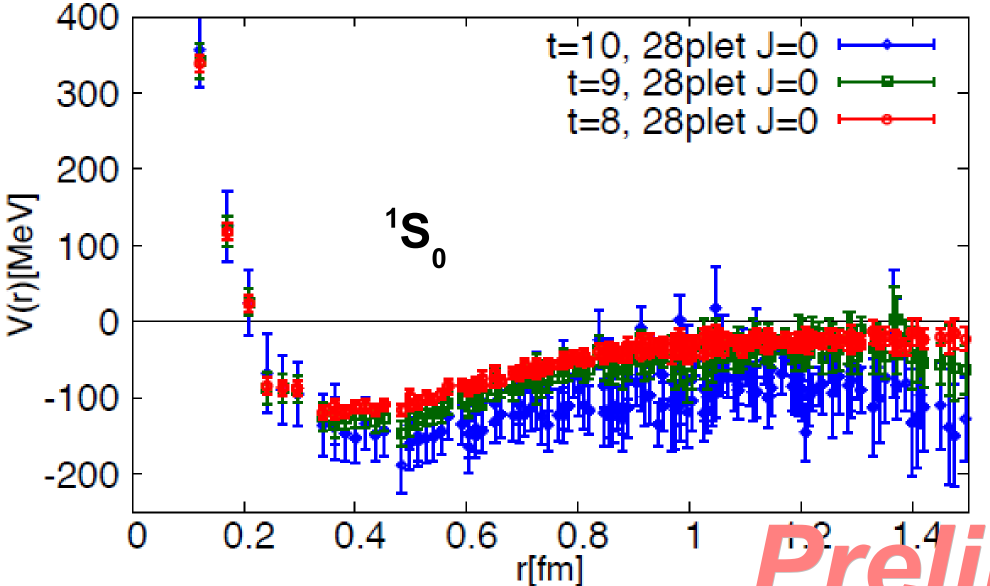
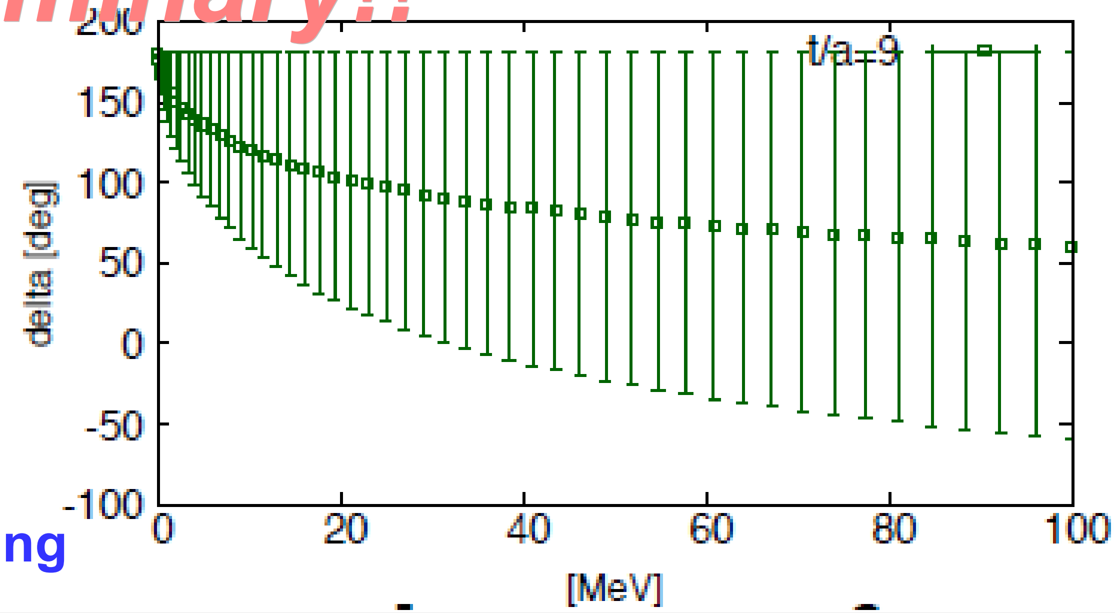


Δ−Δ(J=0) 28plet

- Repulsive core is surrounded by attractive pocket in 28plet [ΔΔ $J^p(I)=0^+(3)$] and [ΩΩ $J^p(I)=0^+(0)$].

Preliminary!!



Phase shift shows that the system is in the unitary limit.

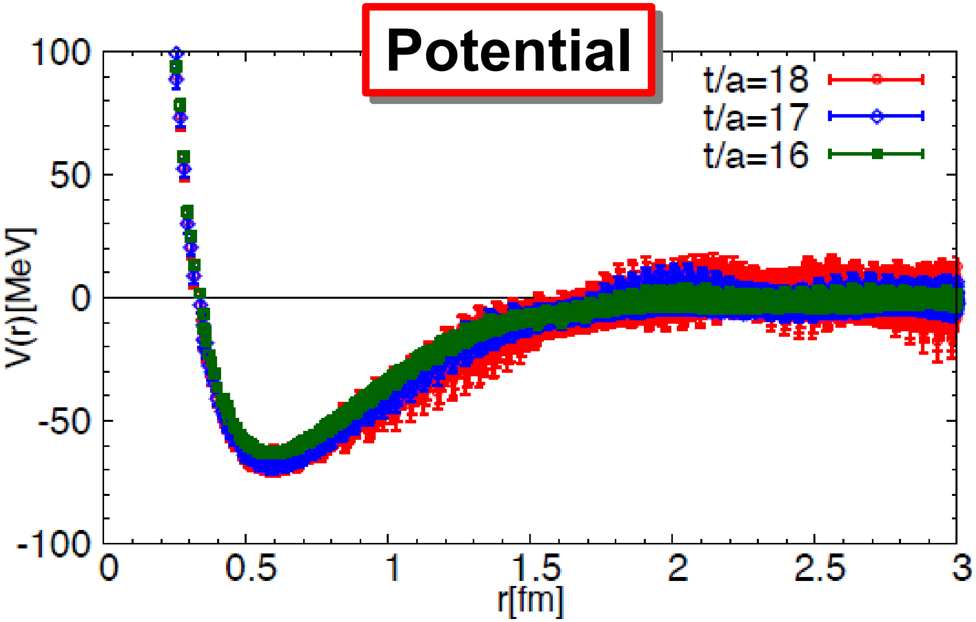
- Δ baryon can not decay into N+π in this lattice setup

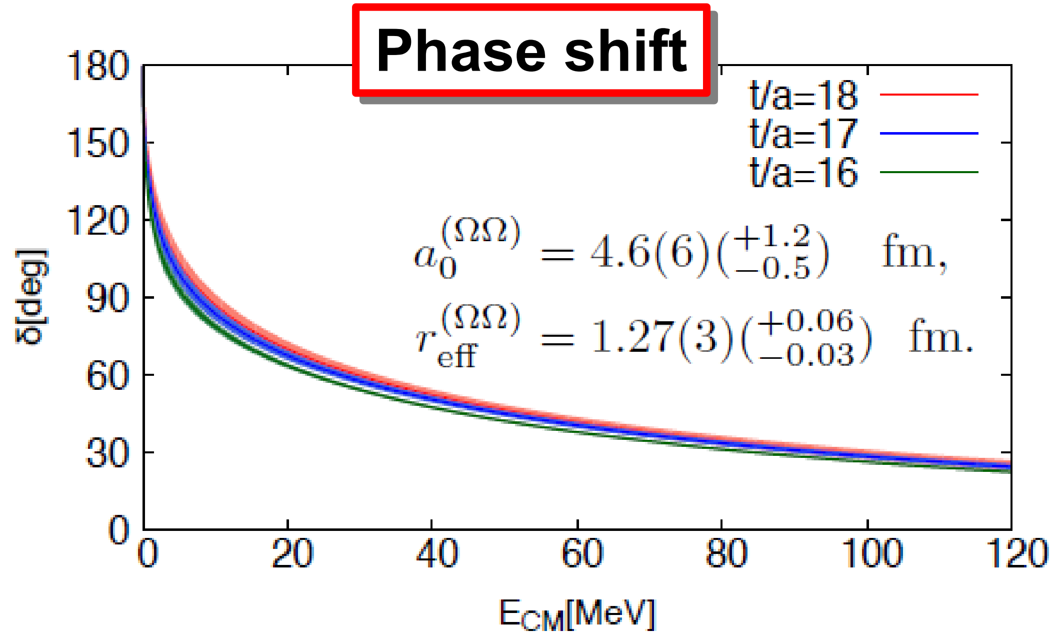
Go to the lighter quark mass region with consideration of SU(3) breaking

S. Gongyo, K. Sasaki (HAL QCD)arXiv:1709.00654

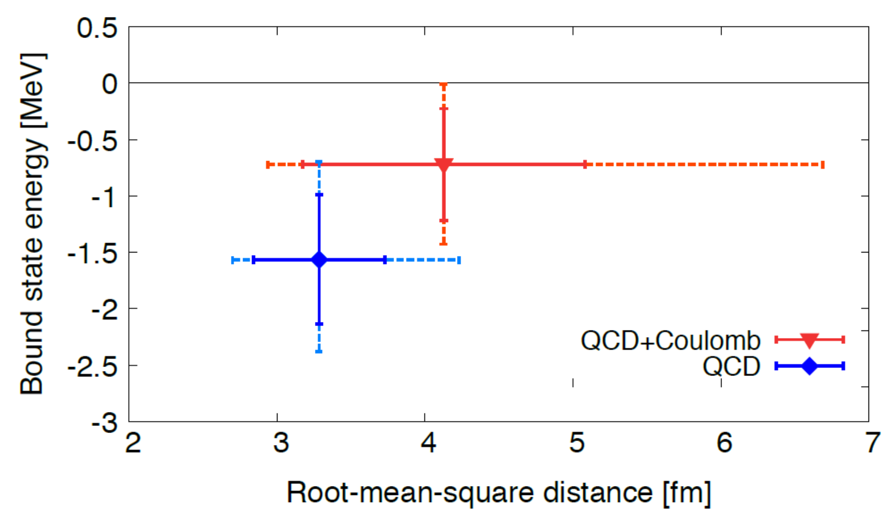
$\Omega\Omega$ $J^P(I) = 0^+(0)$ state near the physical point

- N_f = 2+1 full QCD with L = 8fm, m_π = 146 MeV m_Ω = 1712 MeV





- Short range repulsion and attractive pocket is found.
- Calculated phase shift indicates a bound $\Omega\Omega$ state **[Most strange dibaryon].**
- **Physical $\Omega\Omega$ state in $J^P(I) = 0^+(0)$ is very close to unitary region.**

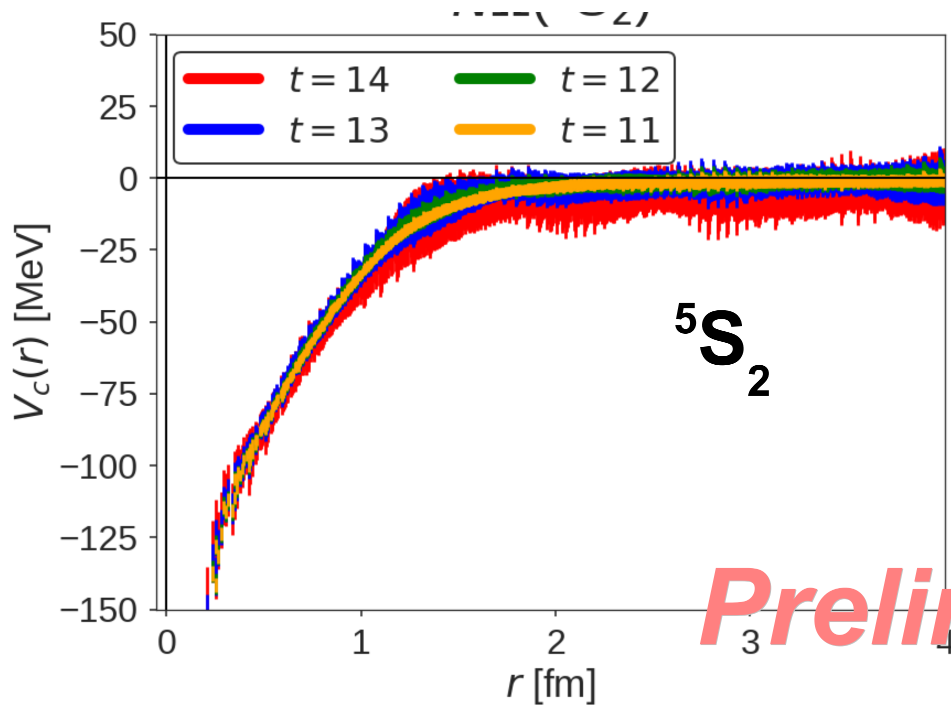


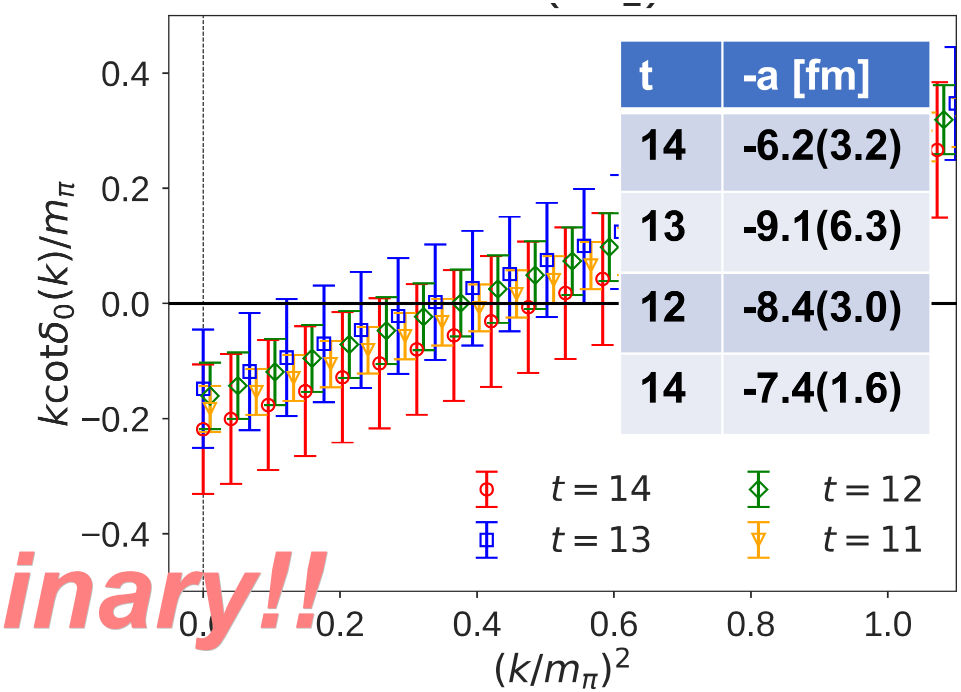
NΩ interaction

T. Iritani, T. Doi et al(HAL QCD), arxiv[1711.01952]

NΩ system $J^p=2^+$ near the physical point

- N_f = 2+1 full QCD with L = 8fm, ***m_π = 146 MeV***





t	-a [fm]
14	-6.2(3.2)
13	-9.1(6.3)
12	-8.4(3.0)
14	-7.4(1.6)

Preliminary!!

NΩ state decay into ΛΞ (D-wave) state is suppressed.

- **The system is bound (compared to the NΩ threshold) within the errors because of the strongly attractive potential.**
  → **The doorway to the S=-3 nuclear system.**
- **Measurement of strong NΩ attraction at RHIC and LHC is expected.**

K.Morita et al PRC94(2016)031901

S=-2 baryon-baryon potentials

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.

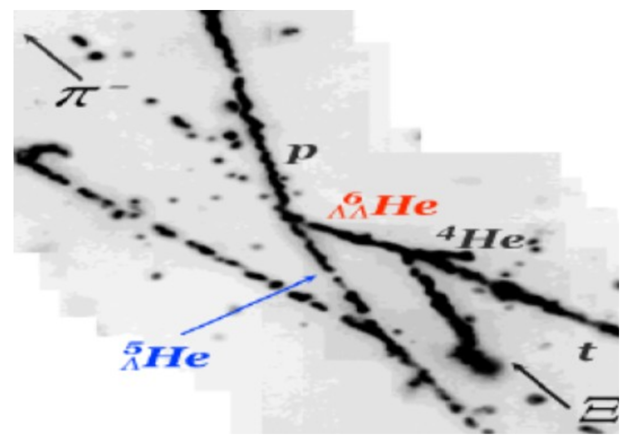
Double-Λ hypernucleus

- Conclusions of the "NAGARA Event"

K.Nakazawa and KEK-E176 & E373 Collaborators

Λ–Λ weak attraction

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

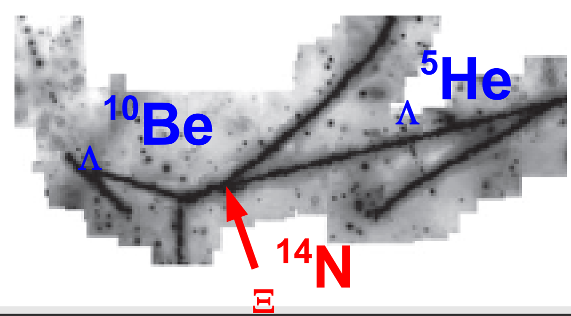


Ξ hypernucleus

- Conclusions of the "KISO Event"

K.Nakazawa and KEK-E373 Collaborators

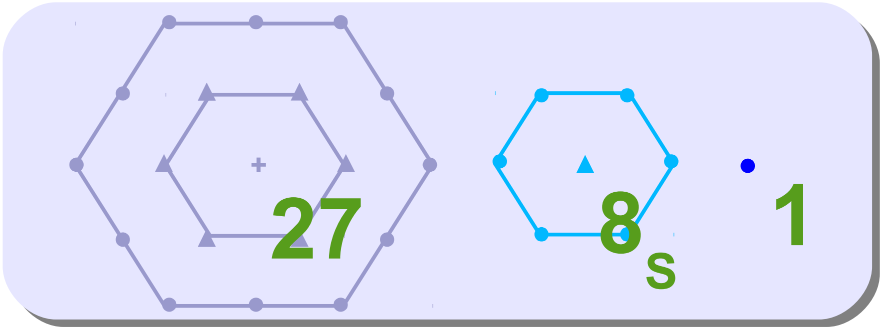
Ξ–N attraction

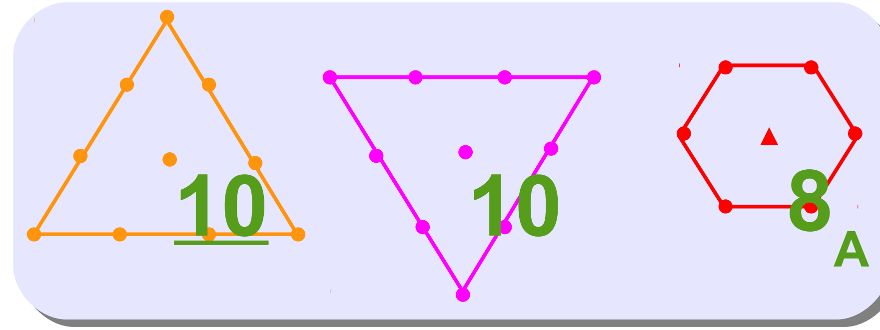


SU(3) feature of BB interaction

SU(3) classification

$8 \times 8 = 27 + 8_S + 1 + \underline{10} + 10 + 8_A$





In view of quark degrees of freedom

- **Short range repulsion in BB interaction could be a result of Pauli principle and color-magnetic interaction for the quarks.**

$$V_{OGE}^{CMI} \propto \frac{1}{m_{q1} m_{q2}} \langle \lambda_1 \cdot \lambda_2 \sigma_1 \cdot \sigma_2 \rangle f(r_{ij})$$

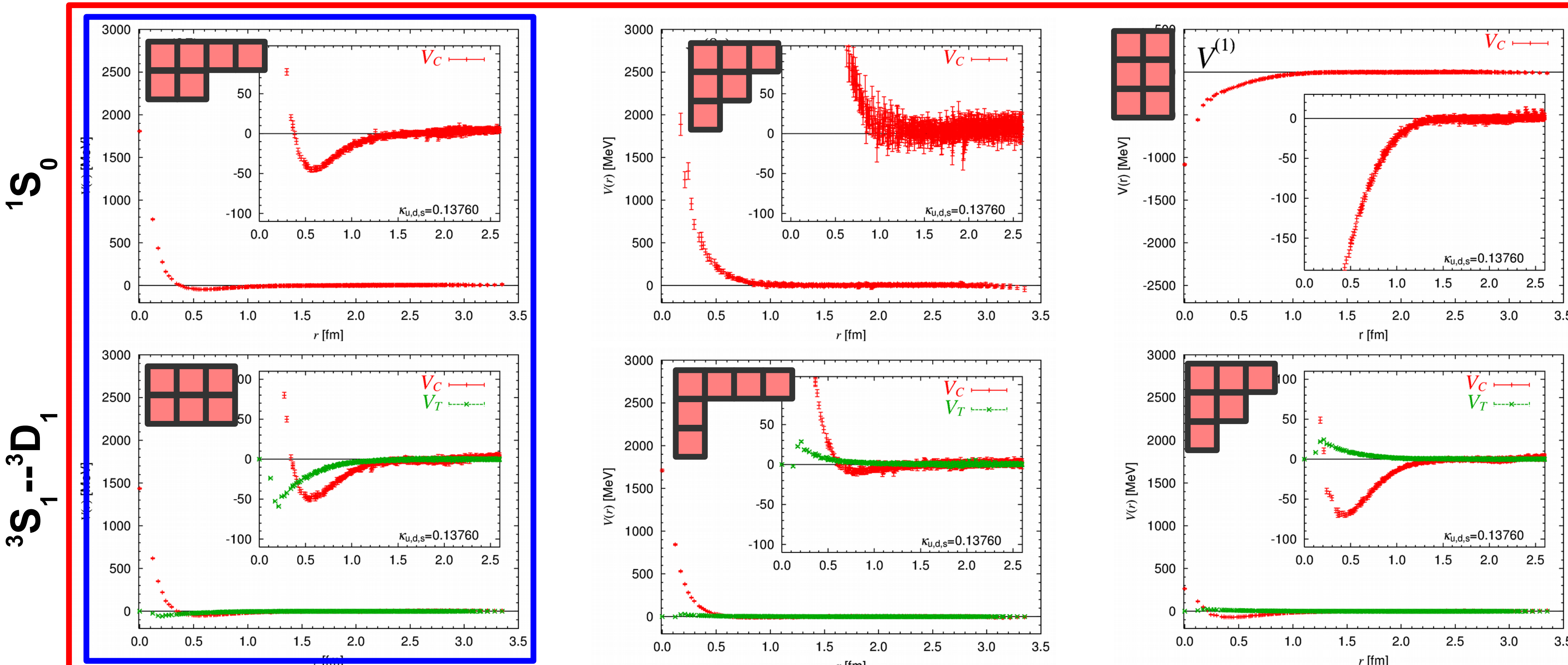
- **For the s-wave BB system, no repulsive core is predicted in flavor singlet state which is known as H-dibaryon channel.**

	Flavor symmetric states			Flavor anti-symmetric states		
	27	8	1	$\underline{10}$	10	8
Pauli	mixed	forbidden	allowed	mixed	forbidden	mixed
CMI	repulsive	repulsive	attractive	repulsive	repulsive	repulsive

Oka, Shimizu and Yazaki NPA464 (1987)

B-B potentials in SU(3) limit

m_π= 469MeV



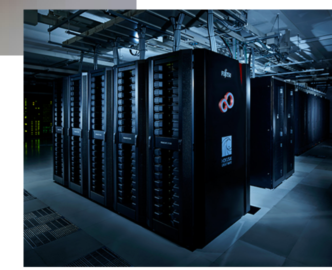
Two-flavors | Three-flavors

- Quark Pauli principle can be seen at around short distances
  - No repulsive core in flavor singlet state
  - Strongest repulsion in flavor 8s state
- **Possibility of bound H-dibaryon in flavor singlet channel.**

H-dibaryon channel

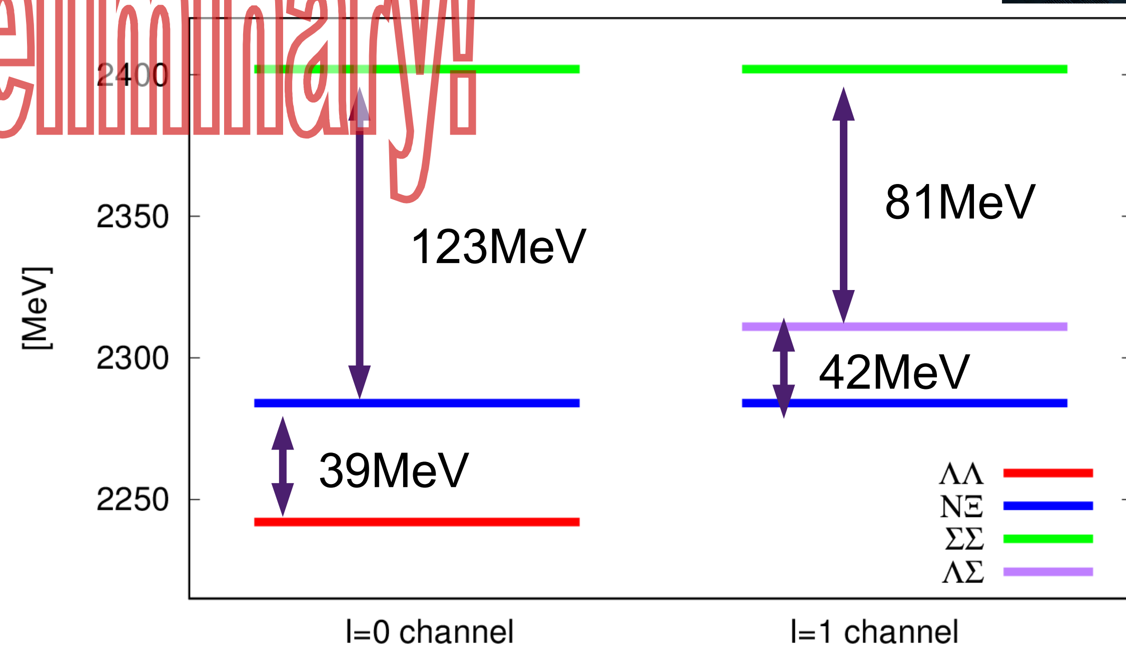
Numerical setup

- 2+1 flavor gauge configurations.
  - Iwasaki gauge action & O(a) improved Wilson quark action
  - a = 0.085 [*fm*], a^{-1} = 2.300 GeV.
  - 96^3x96 *lattice*, *L* = 8.21 [*fm*].
  - 414 confs x 84 sources x 4 rotations.
- Wall source is considered to produce S-wave B-B state.



Preliminary!

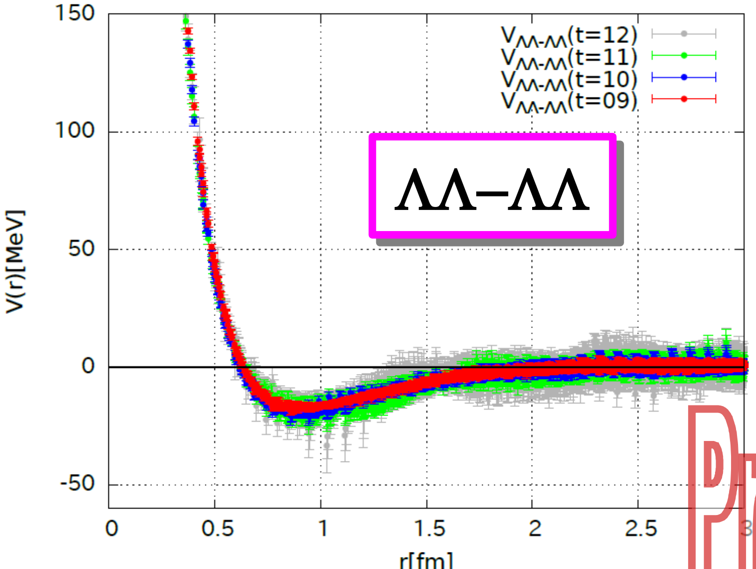
	Mass [MeV]
π	146
K	525
m_π/m_K	0.28
N	953±7
Λ	1123±3
Σ	1204±1
Ξ	1332±2

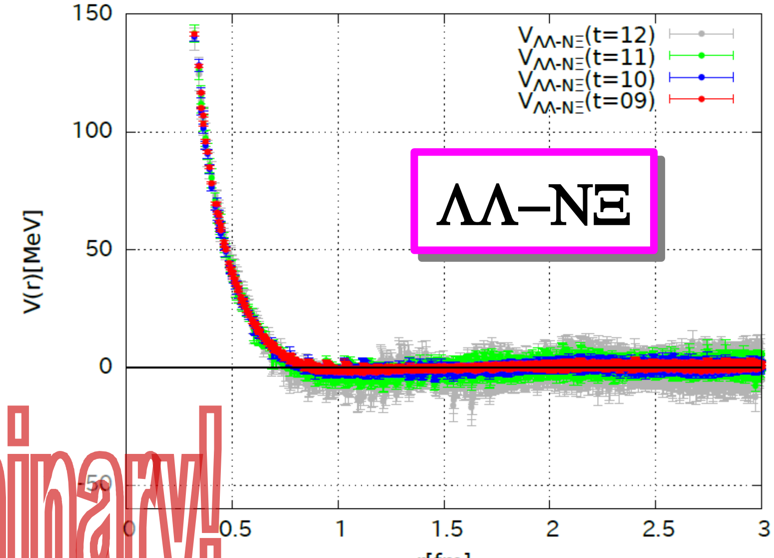


ΛΛ, NΞ (I=0) $^1S_0$ potential

t=09
t=10
t=11
t=12

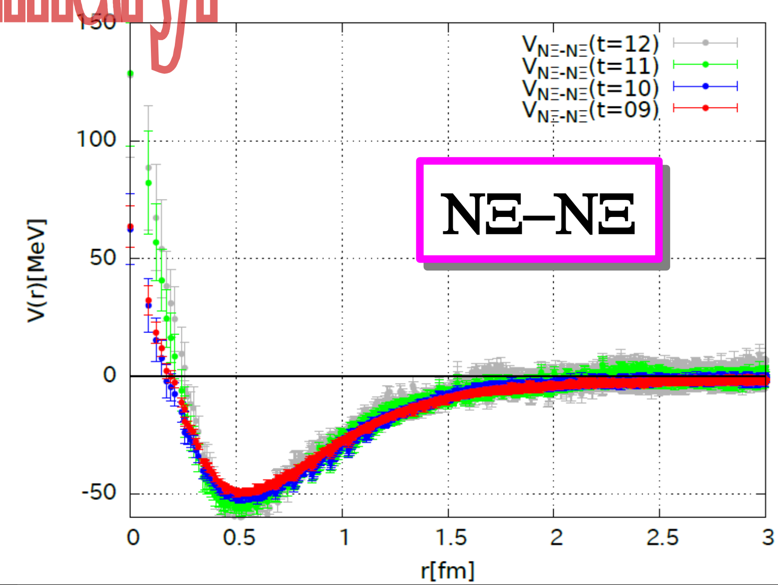
- **N_f = 2+1 full QCD with L = 8.1fm, *m_π = 146 MeV***





Preliminary!

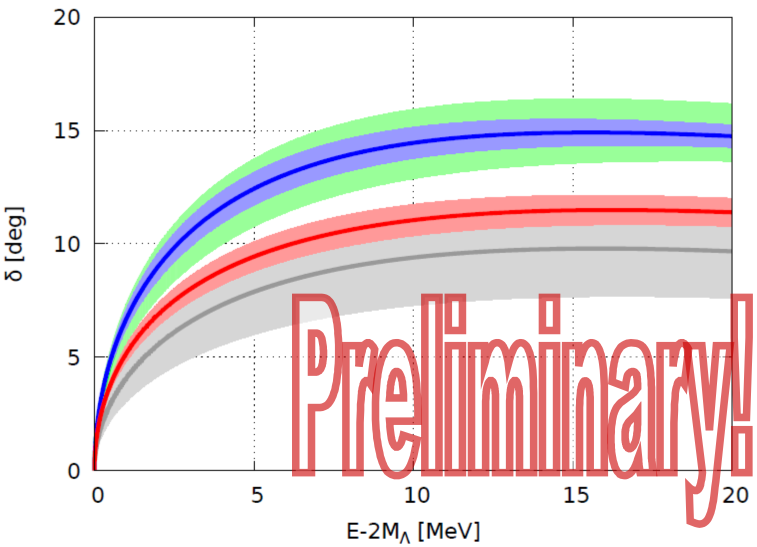
- **ΛΛ and NΞ potential have attractive pocket and repulsive core.**
- **Short range part of NΞ potential shows a "t" dependence.**
- **ΛΛ−NΞ transition potential is quite small in r > 0.7fm region**



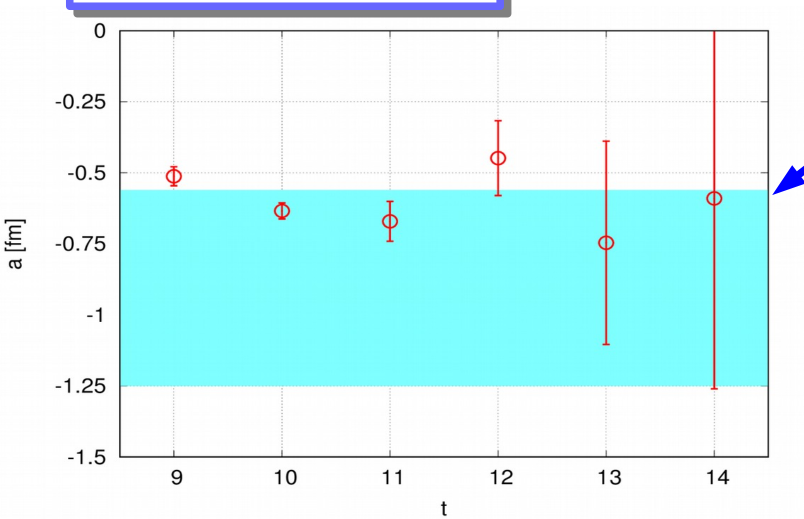
ΛΛ scattering length

t=09
t=10
t=11
t=12

Phase shift



Scattering length



Λ		NLO			
		500	550	600	650
ΛΛ	a_{1S0}	−0.62	−0.61	−0.66	−0.70
	r_{1S0}	6.95	6.06	5.05	4.56

J. Haidenbauer et al, NPA954(2016)273

$a_{\Lambda\Lambda}=-0.821$fm Y.Fujiwara et al, PPNP58(2007)439

$a_{\Lambda\Lambda}=-0.97$fm Th.A.Rijken et al, Few-Body Syst 54(2013)801

$-1.25 < a_{\Lambda\Lambda} < -0.56$fm (or 0fm)

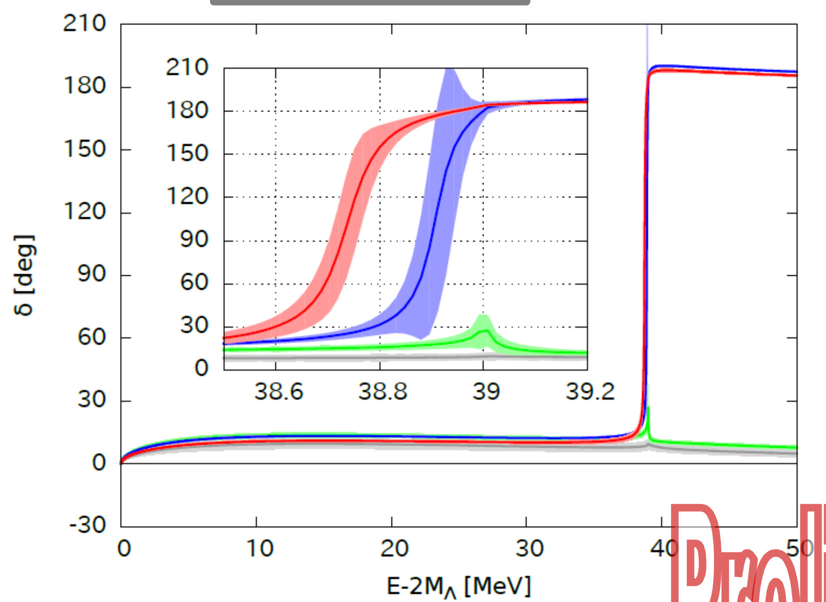
K.Morita et al, PRC91 (2015)024916
K.Morita, private communication

- **Scattering length in ΛΛ (I=0) is almost saturated.**
- **Attraction is a little bit weaker than the phenomenological values.**

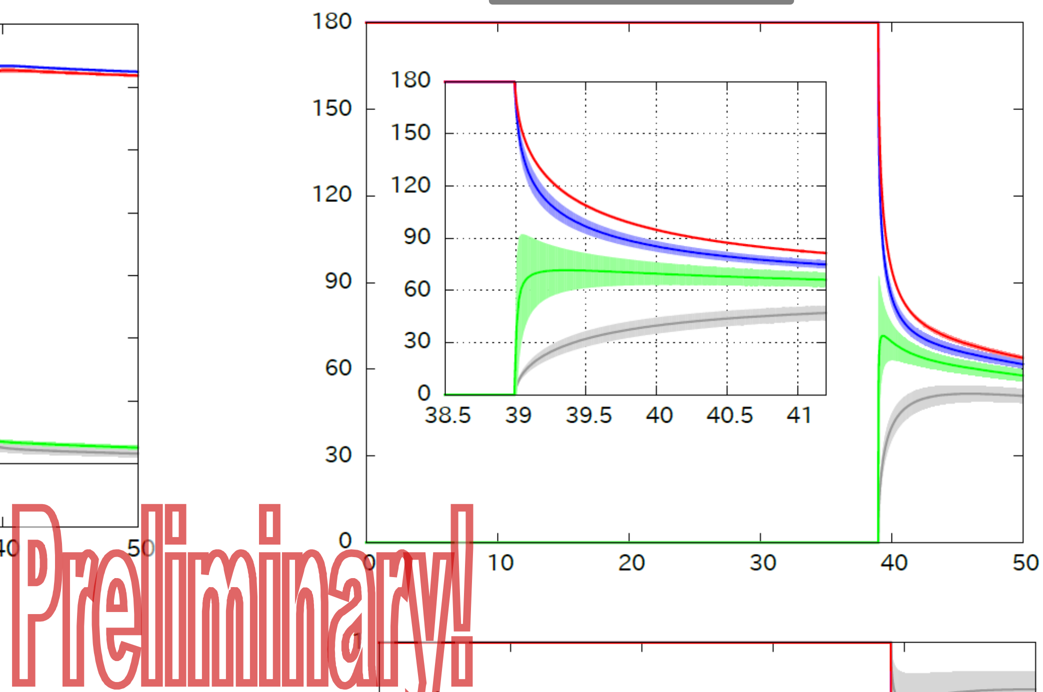
ΛΛ and NΞ phase shift and inelasticity

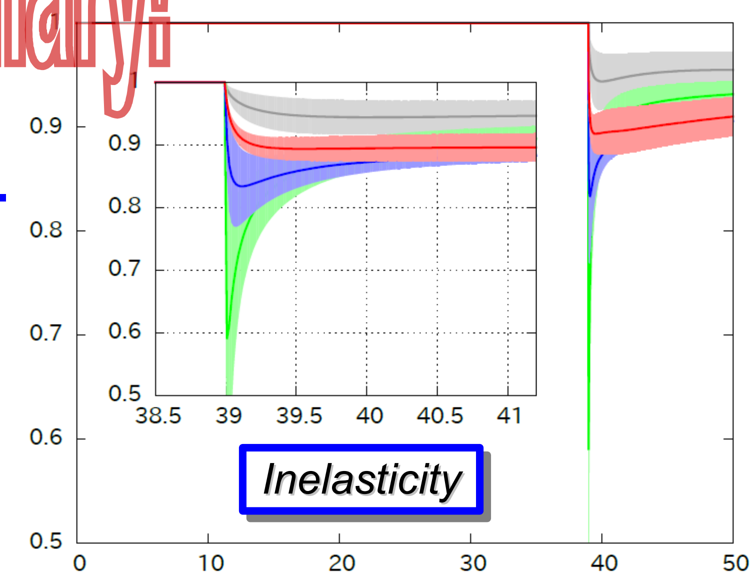
t=09
t=10
t=11
t=12

ΛΛ phase shift



NΞ phase shift





Inelasticity

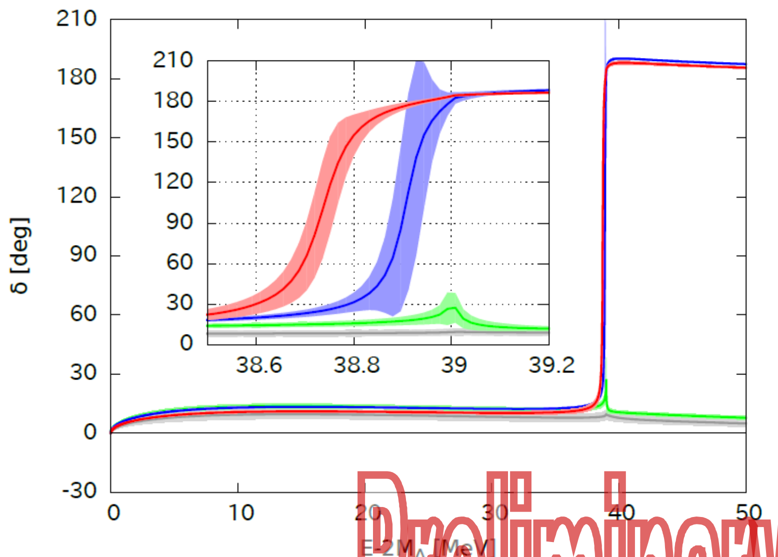
- **A sharp resonance is found below the NΞ threshold for t=9 and 10.**

- **Strength of NΞ attraction could be key to understand the H-dibaryon at the physical point.**

ΛΛ and NΞ phase shift –comparison--

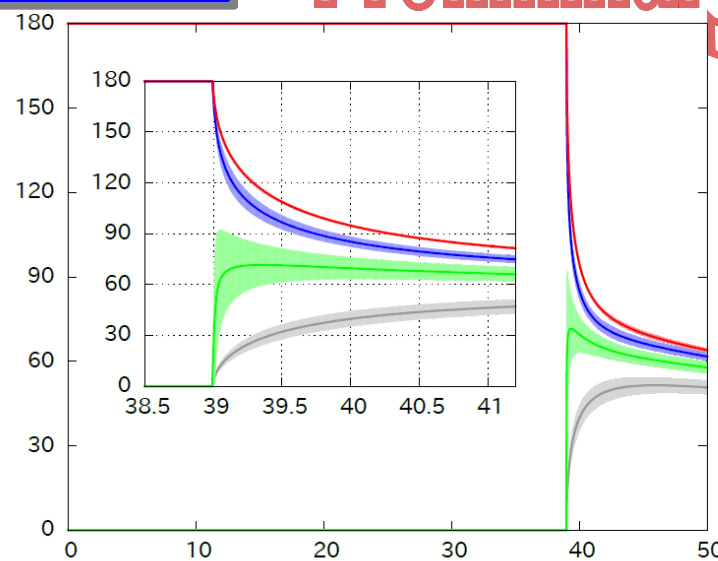
t=09
t=10
t=11
t=12

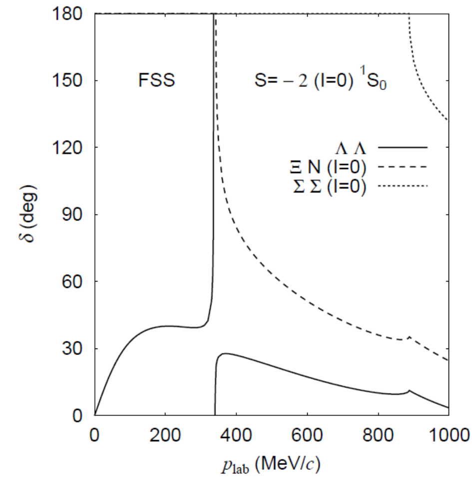
ΛΛ phase shift

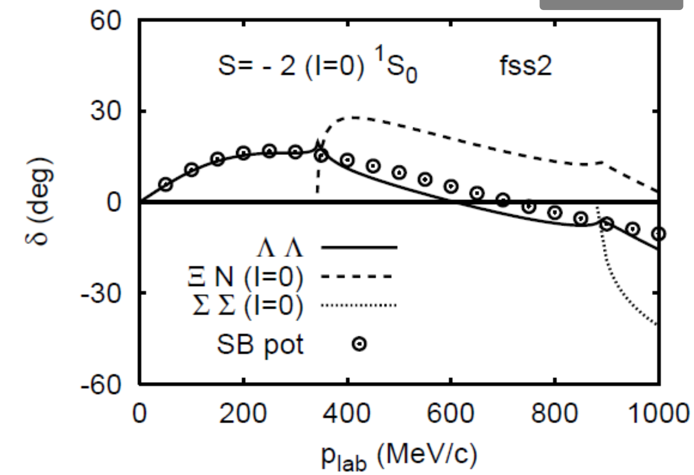


Preliminary!

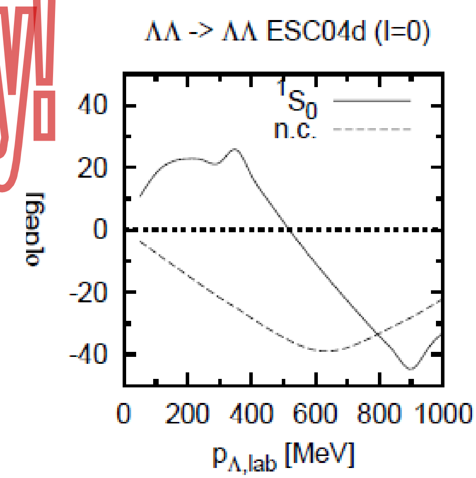
NΞ phase shift



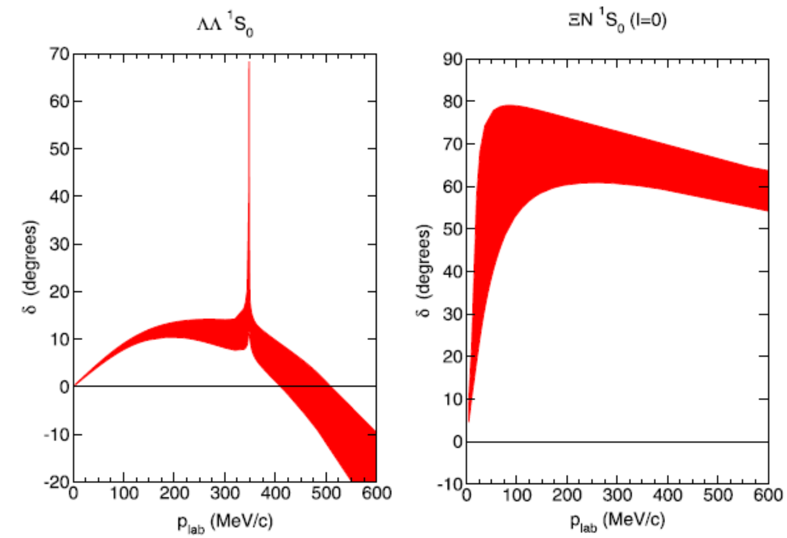




Y.Fujiwara et al, PPNP58(2007)439



Th.A. Rijken, nucl-th/060874



J. Haidenbauer et al, NPA954(2016)273

- Our results are compatible with the phenomenological ones.

Summary

- We have investigated YN / YY interaction from LQCD

  - ΩΩ (and ΔΔ) state
    - ΔΔ(I=0) have strongly attractive potential.
    - ΔΔ(I=3) and ΩΩ potential have repulsive core and attractive pocket.
    - Physical ΩΩ system in J=0 forms the most strange dibaryon (or unitary region...)

  - NΩ state with $J^p=2^+$
    - Interaction is strongly attractive and no short range repulsion.
    - It forms a bound state with about a few MeV B.E..

  - H-dibaryon channel
    - We found a strong attraction in NΞ J=0 with I=0.
    - It is still difficult to conclude the fate of H-dibayon.