Strange dibaryons in coupled-channel scattering from lattice QCD

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for HAL QCD Collaboration

HAL (Hadrons to Atomic nuclei from Lattice) QCD Collaboration

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Introduction

Dibaryon candidates

Several dibaryon candidates have been studied by model calculation

- **H-dibaryon**
  - **R.L.Jaffe PRL38(1977)**
- **N-Ω system**
  - **F.Wang et al. PRC51(1995)**
  - **Q.B.Li, P.N.Shen, EPJA8(2000)**
- **ΔΔ and ΩΩ system**
  - **F.J.Dyson,N-H.Xuong, PRL13(1964)**
  - **M.Oka, K.Yazaki, PLB 90(1980)**

- **Predicted B.E. and structures are highly depend on the model parameters.**
- **Some of them are still not confirmed in experiments.**

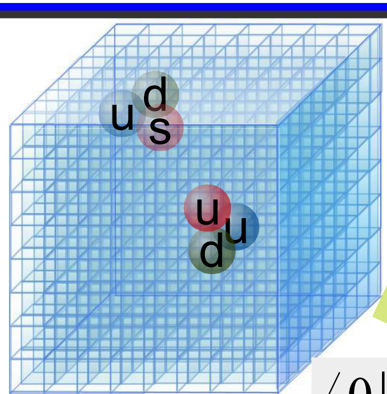
Lattice QCD study of hadron interactions is awaited.

HAL QCD method

Derivation of hadronic interaction from QCD

Start with the fundamental theory,QCD

Lattice QCD simulation



Lüscher's finite volume method

M. Lüscher, NPB354(1991)531

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

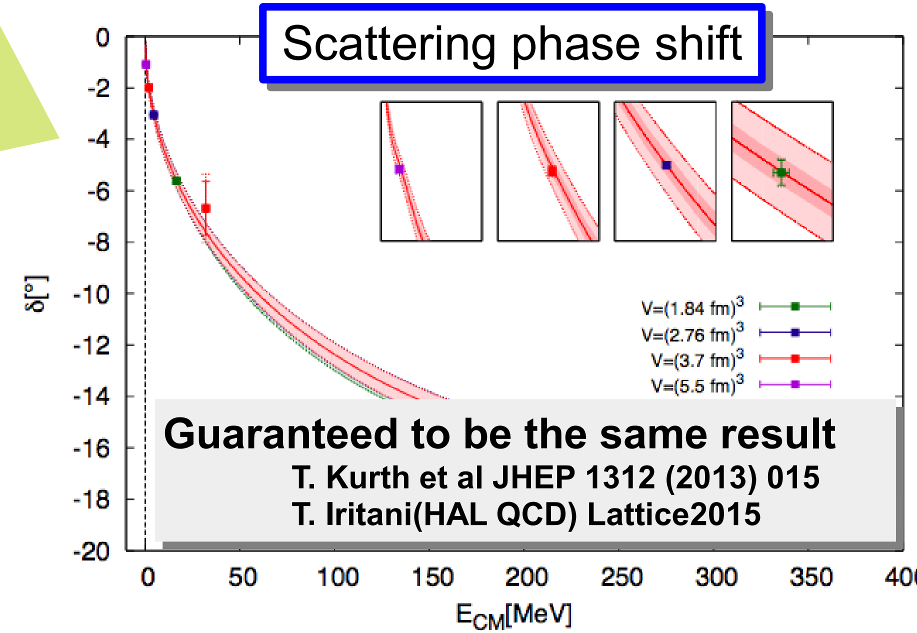
$$\langle 0|B_1 B_2(t,\vec{r})\bar{B}_2\bar{B}_1(t_0)|0\rangle = A_0\Psi(\vec{r},E_0)e^{-E_0(t-t_0)}+\cdots$$

HAL QCD method

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

1. Measure the NBS wave function, **Ψ**
2. Calculate potential, **V**, through Schrödinger eq.
3. Calculate observables by scattering theory

Scattering phase shift



Guaranteed to be the same result
T. Kurth et al JHEP 1312 (2013) 015
T. Iritani(HAL QCD) Lattice2015

BB interaction from NBS wave function

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

Derivative (velocity) expansion of U is performed to deal with its nonlocality.

- For the case of oct-oct system,

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

- For the case of dec-oct and dec-dec system,

$$U(\vec{r},\vec{r}\,') = \underbrace{\left[V_C(r)+S_{12}V_{T_1}(r)+S_{ii}V_{T_2}(r)+O(Spin\,op^3)\right]}_{\text{Leading order part}}+O(\nabla^2)$$

$$\left((\vec{r}\cdot\vec{S_1})^2-\frac{\vec{r}^{\,2}}{3}\vec{S_1}^2+(\vec{r}\cdot\vec{S_2})^2-\frac{\vec{r}^{\,2}}{3}\vec{S_2}^2\right)V_{T^2}(r)$$

$$\equiv\left[V_C^{eff}(r)\right]+O(\nabla^2)$$

We consider the effective central potential which contains not only the genuine central potential but also tensor parts.

HAL QCD method (coupled-channel)

NBS wave function

$$\Psi^{\alpha}(E_i,\vec{r})e^{-E_i t} = \langle 0|(B_1 B_2)^{\alpha}(\vec{r})\,|E_i\rangle$$

$$\Psi^{\beta}(E_i,\vec{r})e^{-E_i t} = \langle 0|(B_1 B_2)^{\beta}(\vec{r})\,|E_i\rangle$$

$$\int dr\,\tilde{\Psi}_{\beta}(E',\vec{r})\Psi^{\gamma}(E,\vec{r})=\delta(E'-E)\delta_{\beta}^{\gamma}$$

$$\boxed{R_E^{B_1 B_2}(t,\vec{r})=\Psi_{B_1 B_2}(\vec{r},E)e^{(-E+m_1+m_2)t}}$$

Leading order of velocity expansion and time-derivative method.

Modified coupled-channel Schrödinger equation

$$\begin{pmatrix} (-\frac{\partial}{\partial t}+\frac{\nabla^2}{2\mu_\alpha})R^{\alpha}_{E_0}(t,\vec{r}) \\ (-\frac{\partial}{\partial t}+\frac{\nabla^2}{2\mu_\beta})R^{\beta}_{E_0}(t,\vec{r}) \end{pmatrix} = \begin{pmatrix} V^{\alpha}{}_{\alpha}(\vec{r}) & V^{\alpha}{}_{\beta}(\vec{r})\Delta^{\alpha}{}_{\beta}(t) \\ V^{\beta}{}_{\alpha}(\vec{r})\Delta^{\beta}{}_{\alpha}(t) & V^{\beta}{}_{\beta}(\vec{r}) \end{pmatrix} \begin{pmatrix} R^{\alpha}_{E_0}(t,\vec{r}) \\ R^{\beta}_{E_0}(t,\vec{r}) \end{pmatrix}$$

$$\begin{pmatrix} \cdots \\ (-\frac{\partial}{\partial t}+\frac{\nabla^2}{2\mu_\beta})R^{\beta}_{E_1}(t,\vec{r}) \end{pmatrix} \cdots \begin{pmatrix} \cdots(\vec{r})\Delta^{\alpha}{}_{\beta}(t) \\ V^{\beta}{}_{\beta}(\vec{r}) \end{pmatrix} \begin{pmatrix} R^{\alpha}_{E_1}(t,\vec{r}) \\ R^{\beta}_{E_1}(t,\vec{r}) \end{pmatrix}$$

$$\boxed{\Delta^{\alpha}_{\beta}=\frac{\exp(-(m_{\alpha_1}+m_{\alpha_2})t)}{\exp(-(m_{\beta_1}+m_{\beta_2})t)}}$$

S.Aoki et al [HAL QCD Collab.] Proc. Jpn. Acad., Ser. B, 87 509
K.Sasaki et al [HAL QCD Collab.] PTEP no 11 (2015) 113B01

Potential

Considering two different energy eigen states

$$\begin{pmatrix} V^{\alpha}{}_{\alpha}(\vec{r}) & V^{\alpha}{}_{\beta}(\vec{r})\Delta^{\alpha}_{\beta} \\ V^{\beta}{}_{\alpha}(\vec{r})\Delta^{\beta}_{\alpha} & V^{\beta}{}_{\beta}(\vec{r}) \end{pmatrix} = \begin{pmatrix} (\frac{\nabla^2}{2\mu_\alpha}-\frac{\partial}{\partial t})R^{\alpha}_{E0}(t,\vec{r}) & (\frac{\nabla^2}{2\mu_\beta}-\frac{\partial}{\partial t})R^{\alpha}_{E1}(t,\vec{r}) \\ (\frac{\nabla^2}{2\mu_\alpha}-\frac{\partial}{\partial t})R^{\beta}_{E0}(t,\vec{r}) & (\frac{\nabla^2}{2\mu_\beta}-\frac{\partial}{\partial t})R^{\beta}_{E1}(t,\vec{r}) \end{pmatrix} \begin{pmatrix} R^{\alpha}_{E0}(t,\vec{r}) & R^{\alpha}_{E1}(t,\vec{r}) \\ R^{\beta}_{E0}(t,\vec{r}) & R^{\beta}_{E1}(t,\vec{r}) \end{pmatrix}^{-1}$$

$S=-2$ BB interaction

--- focus on the H-dibaryon ---

Keys to understand H-dibaryon

A strongly bound state predicted by Jaffe in 1977 using MIT bag model.

H-dibaryon state is

- **SU(3) flavor singlet [uuddss], strangeness S=-2.**
- **spin and isospin equals to zero, and $J^P = 0^+$**

Strongly attractive interaction is expected in flavor singlet channel.

- **Short range one-gluon exchange contributions**

  Strongly attractive Color Magnetic Interaction

- **Symmetry of two-baryon system (Pauli principle)**

  Flavor singlet channel is free from Pauli blocking effect

	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)

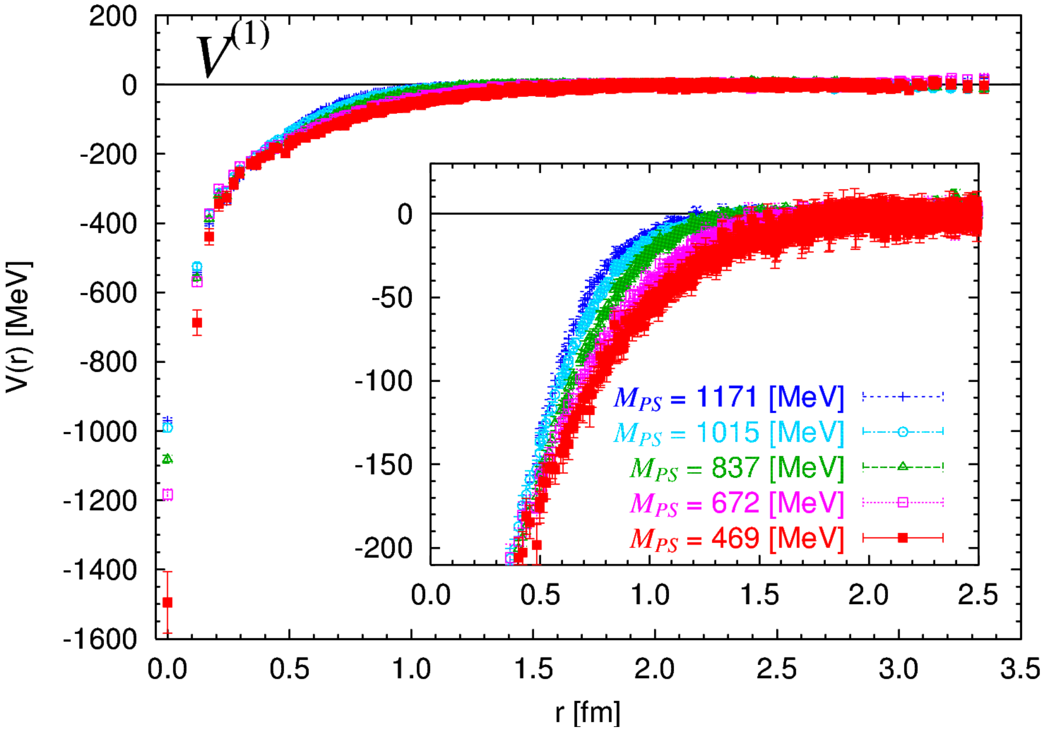
SU(3) breaking effects

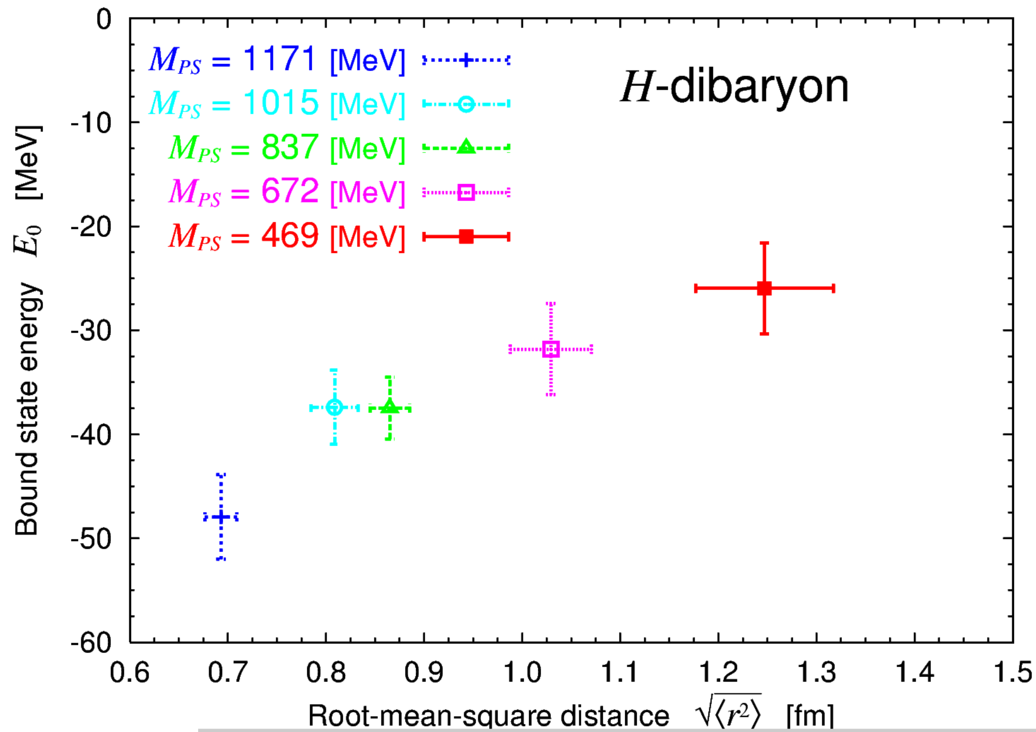
- **Threshold separation**
- **Changes of interactions**

Non-trivial contributions

Hunting for H-dibaryon in SU(3) limit

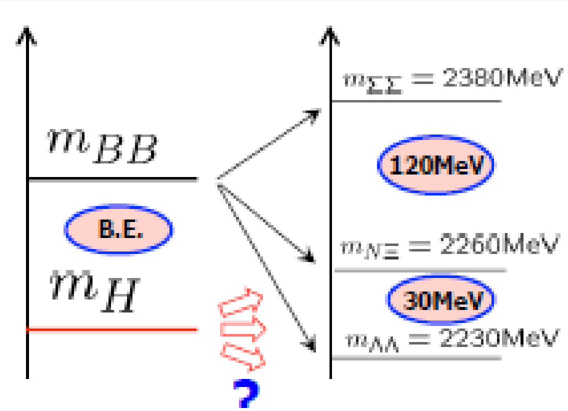
Strongly attractive interaction is expected in flavor singlet channel.





T.Inoue et al[HAL QCD Coll.] NPA881(2012) 28

- **Strongly attractive potential was found in the flavor singlet channel.**
- **Bound state was found in this mass range with SU(3) symmetry.**



What happens at the physical point?

Works on H-dibaryon state

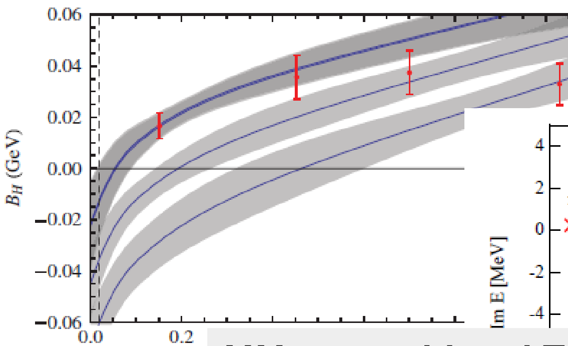
Theoretical status

Several sort of calculations and results
(bag models, NRQM, Quenched LQCD….)

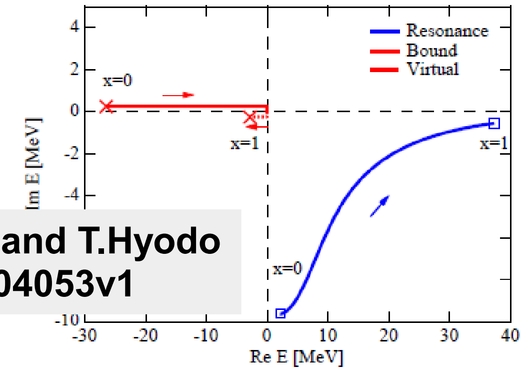
There were no conclusive result.

Chiral extrapolations of recent LQCD data

Unbound or resonance



P. E. Shanahan et al
PRL 107(2011) 092004



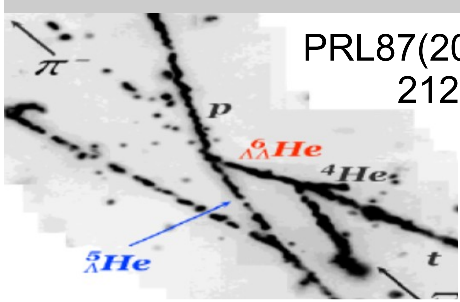
Y.Yamaguchi and T.Hyodo
hep-ph:1607.04053v1

Experimental status

"NAGARA Event"

K.Nakazawa et al
KEK-E176 & E373 Coll.

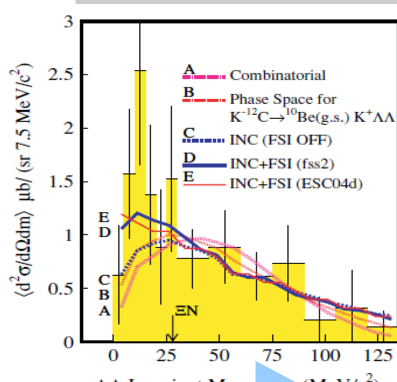
PRL87(2001) 212502



Deeply bound dibaryon state is ruled out

"^{12}C(K^-,$K^+\Lambda\Lambda$) reaction"

C.J.Yoon et al KEK-PS E522 Coll.



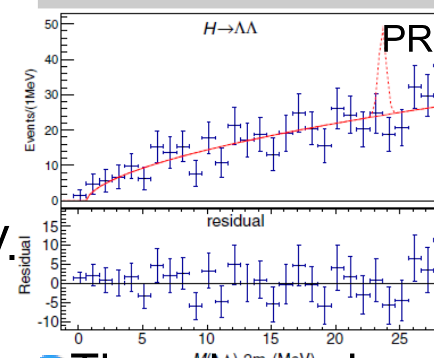
PRC75(2007) 022201(R)

Significance of enhancements below 30 MeV.

Larger statistics
J-PARC E42

"Y(1S) and Y(2S) decays"

B.H. Kim et al Belle Coll.



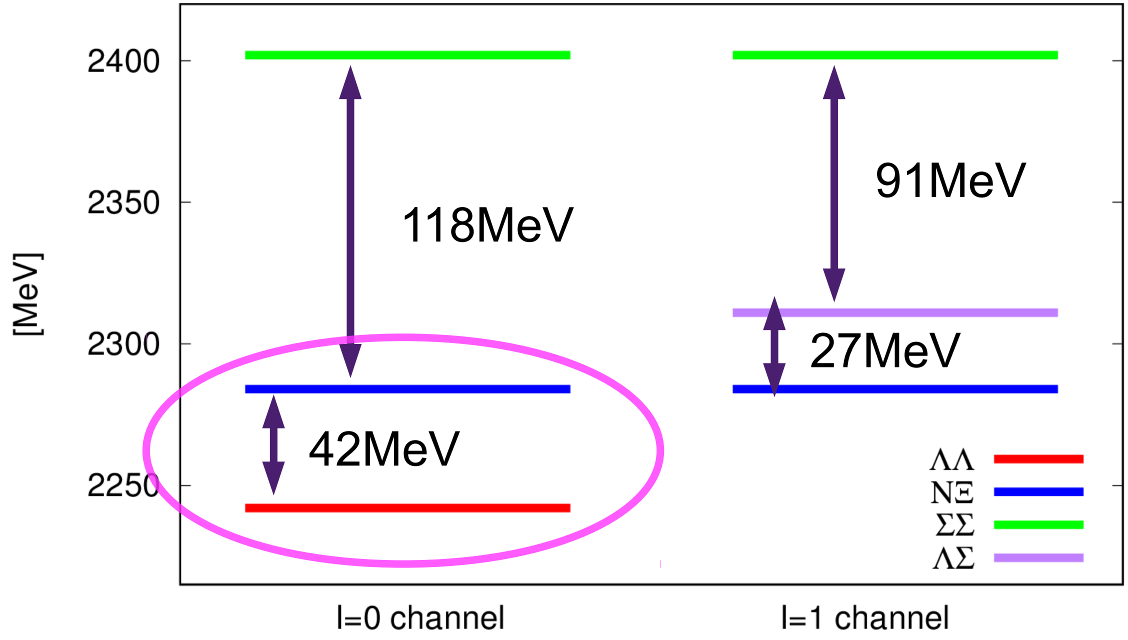
PRL110(2013) 222002

There is no sign of near threshold enhancement.

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 = 8.24 [fm].
  - 414 confs x 28 sources x 4 rotations.
- Flat wall source is considered to produce S-wave B-B state.

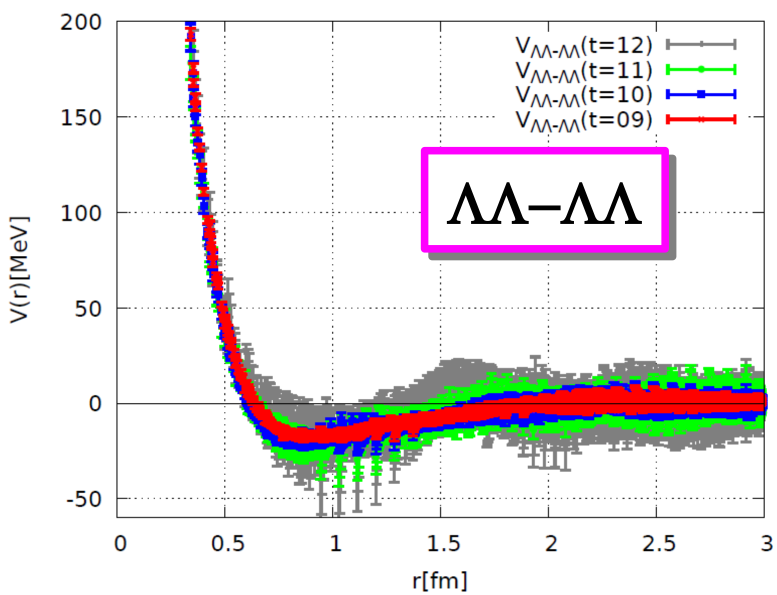
	Mass [MeV]
π	146
K	525
m_π/m_K	0.28
N	956±12
Λ	1121±4
Σ	1201±3
Ξ	1328±3

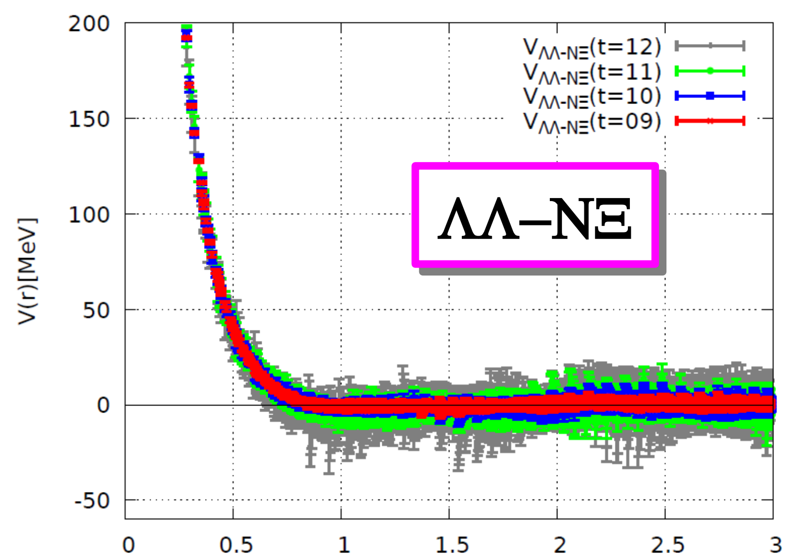


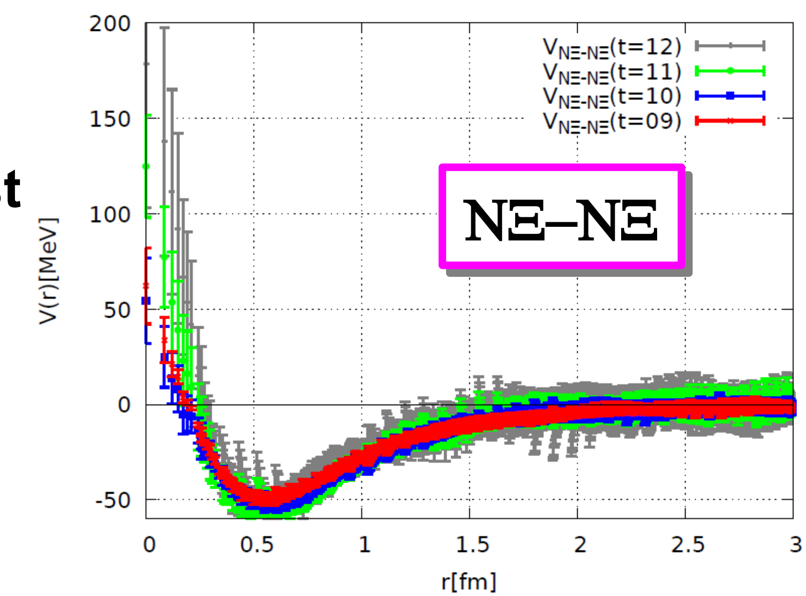
$\Lambda\Lambda$, $N\Xi$ (I=0) $^1S_0$ potential (2ch calc.)

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

Preliminary!





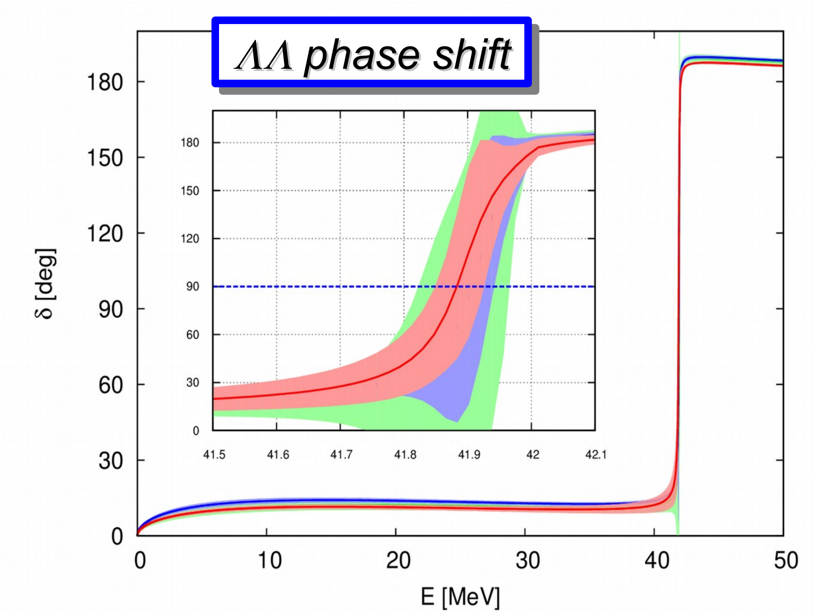


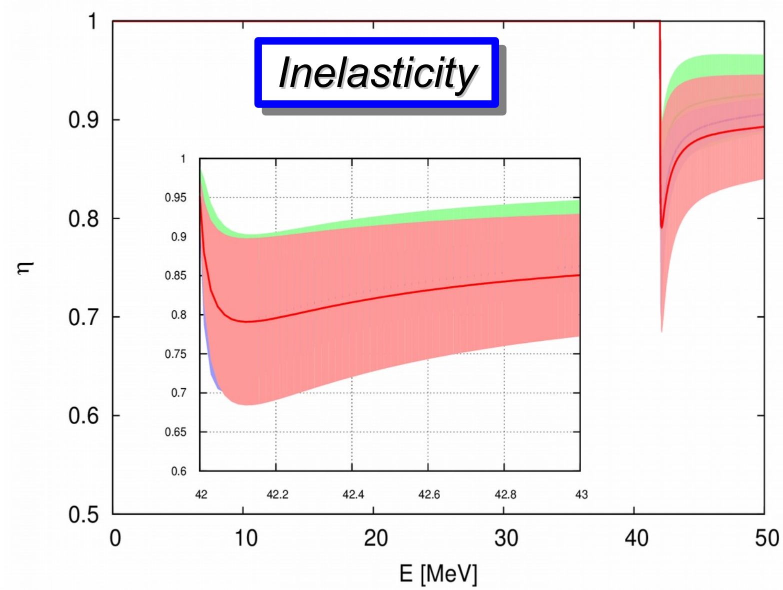
- Potential calculated by only using $\Lambda\Lambda$ and $N\Xi$ channels.
- Long range part of potential is almost stable against the time slice.
- Short range part of $N\Xi$ potential changes as time t goes.
- $\Lambda\Lambda$–$N\Xi$ transition potential is quite small in r > 0.7fm region

$\Lambda\Lambda$ and $N\Xi$ phase shift and inelasticity T-dep

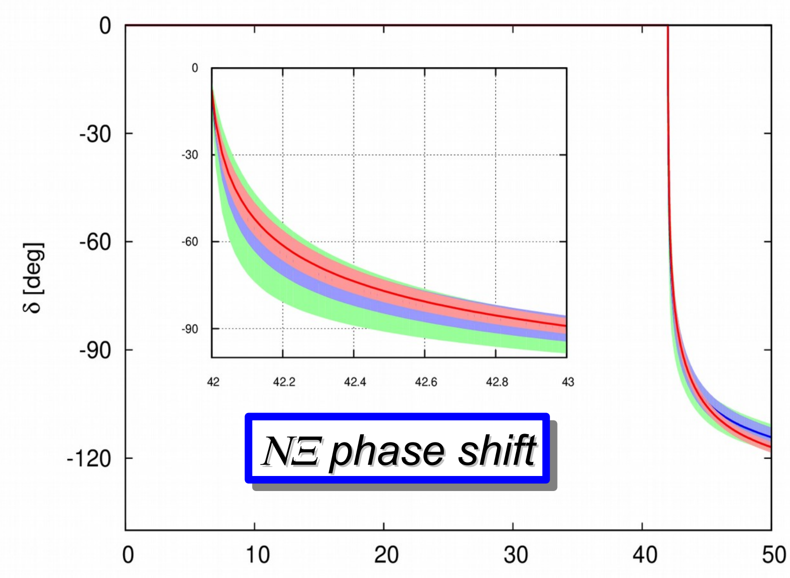
▶ N_f = 2+1 full QCD with L = 8fm, ***m_π = 146 MeV***

Preliminary!





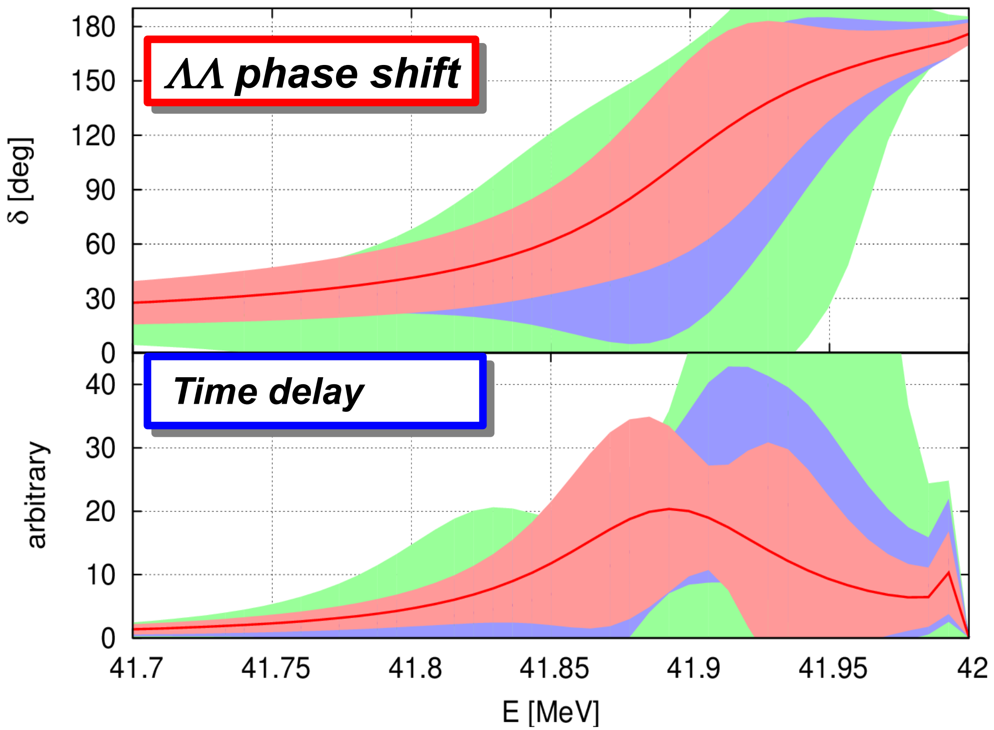
- **$\Lambda\Lambda$ and $N\Xi$ phase shift is calculated by using 2ch effective potential.**
- **A sharp resonance is found just below the $N\Xi$ threshold.**
- **Inelasticity is small.**



Breit-Wigner mass and width

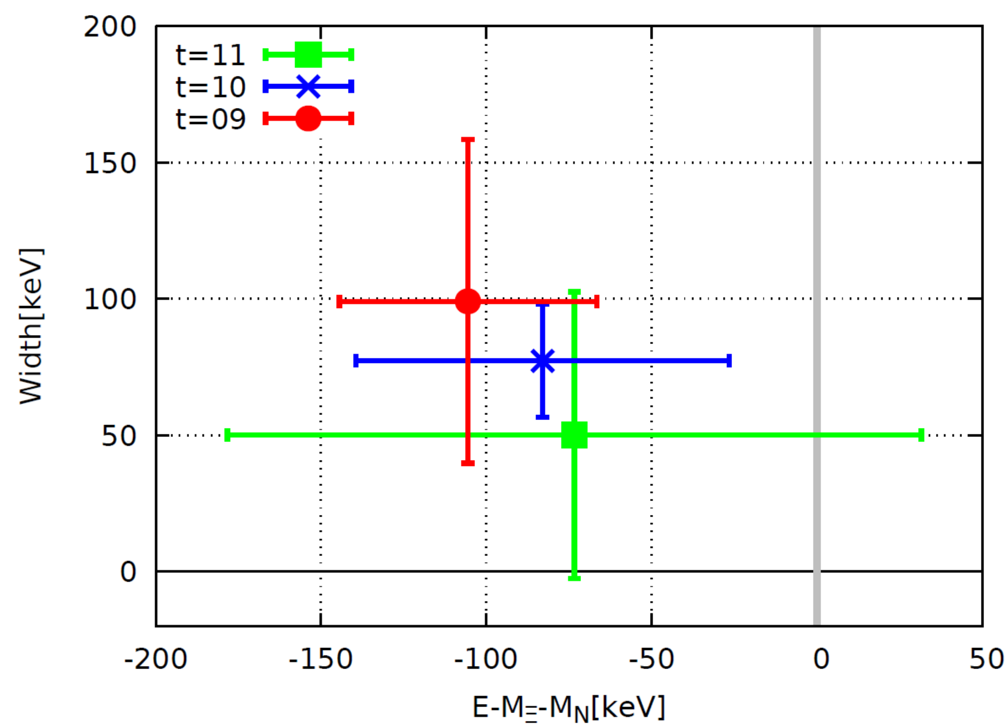
▶ N_f = 2+1 full QCD with L = 8fm, m_π = 146 MeV

Preliminary!



- Fitting the time delay of ΛΛ scattering by the Breit-Wigner type finction,

Resonance enargy and width



- In the vicinity of resonance point,

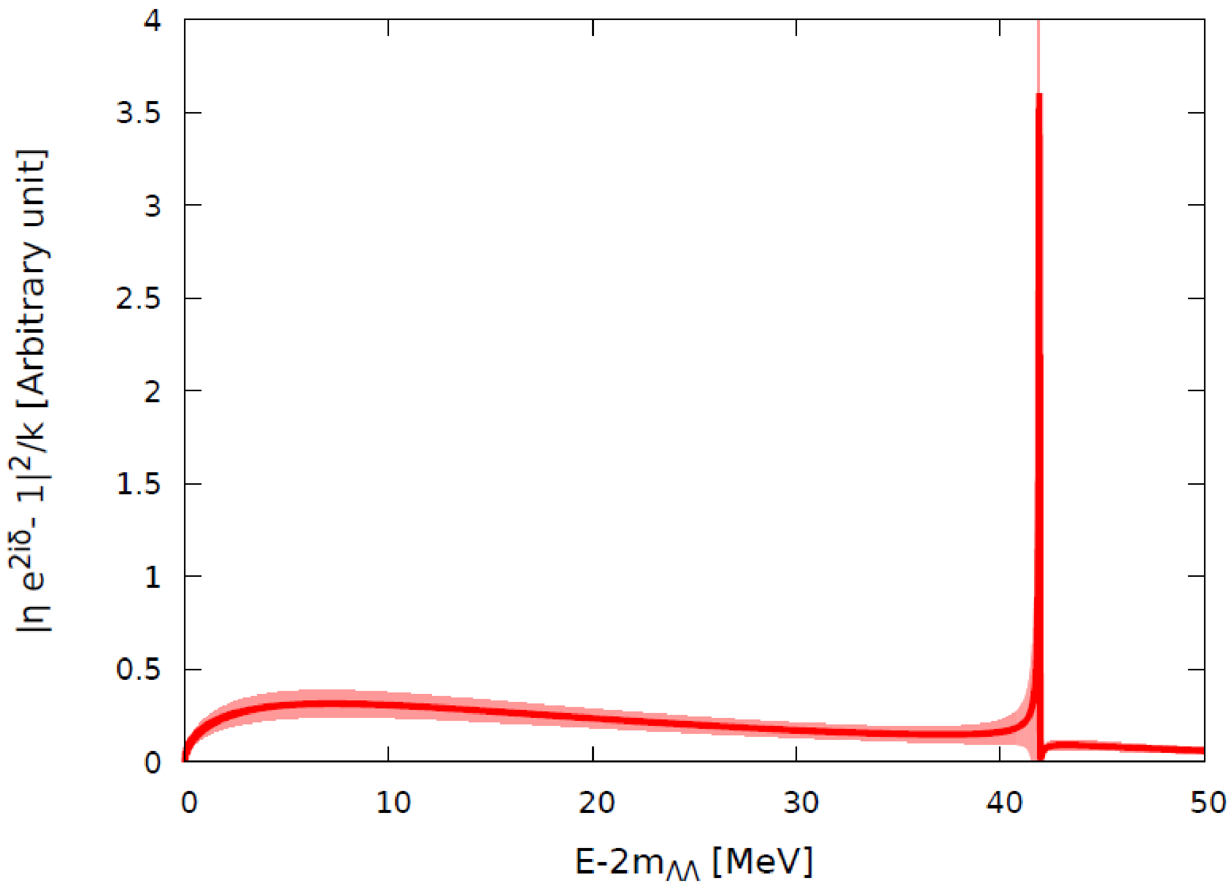
$$\delta(E) = \delta_B - \arctan\left(\frac{\Gamma/2}{E - E_r}\right)$$

thus

$$\frac{d\,\delta(E)}{d\,E} = \frac{\Gamma/2}{(E - E_r)^2 + (\Gamma/2)^2}$$

Invariant mass spectrum of $\Lambda\Lambda$ channel

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



- **Sharp peak below $N\Xi$ threshold**
- **Direct comparison with our simulation results and experimental data will be performed in near future?**

Interactions of decuplet baryons

SU(3) aspects of BB interaction

We have succeeded to evaluate potentials
between ground state baryons directly from QCD.

$$8\otimes 8 = 1\oplus 8_s \oplus \boxed{27} \oplus 8_a \oplus 10 \oplus \boxed{\overline{10}}$$

H-dibaryon

Nuclear force

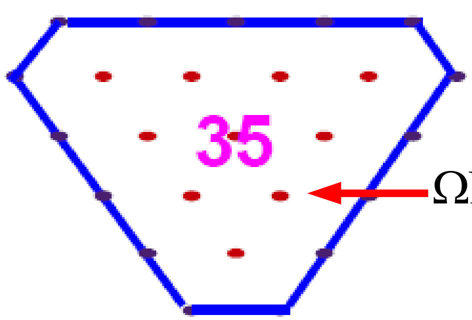
Inclusion of decuplet baryons

- **For decuplet-octet system**

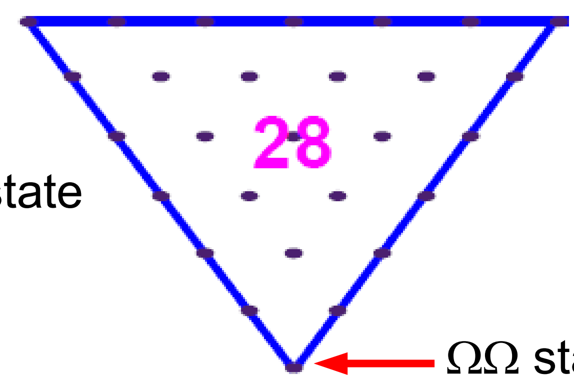
$$10\otimes 8 = \boxed{35} \oplus 8 \oplus 10 \oplus 27$$

- **For decuplet-decuplet system**

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



ΩN state



ΔΔ state (I=0,J=3)

ΩΩ state (pure 28plet)

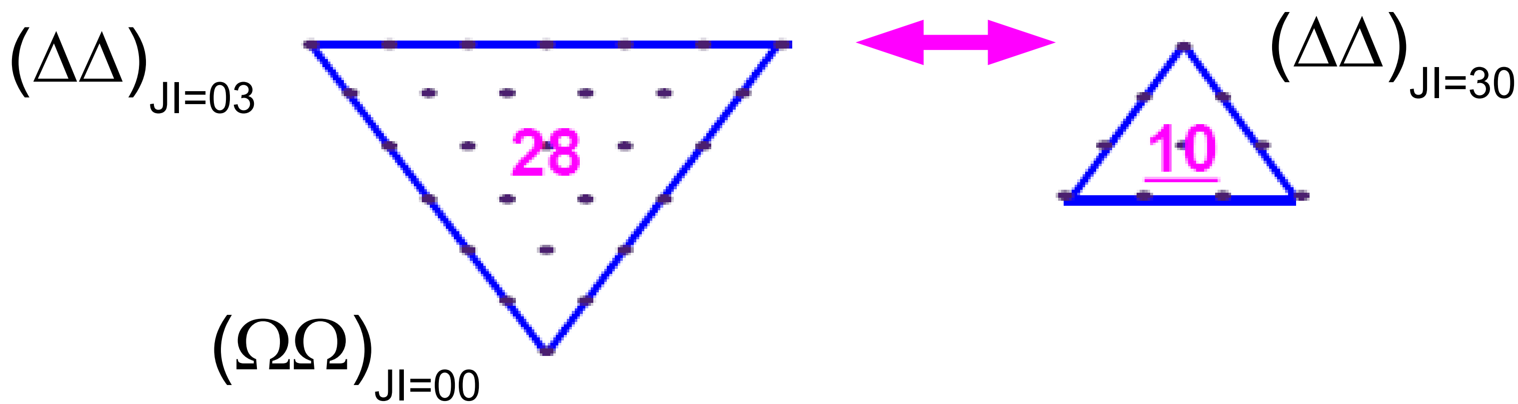
Alternative source of generalized baryon-baryon interactions

Decuplet-Decuplet interaction

- **Flavor symmetry aspect**

  Decuplet-Decuplet interaction can be classified as

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



	28plet (0^+)	~~28plet (2^+)~~	~~10*plet (1^+)~~	10*plet (3^+)
Pauli	**allowed**	~~**forbidden**~~	~~---~~	**allowed**
CMI	**repulsive**	~~---~~	~~---~~	**Not attractive**

- **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**

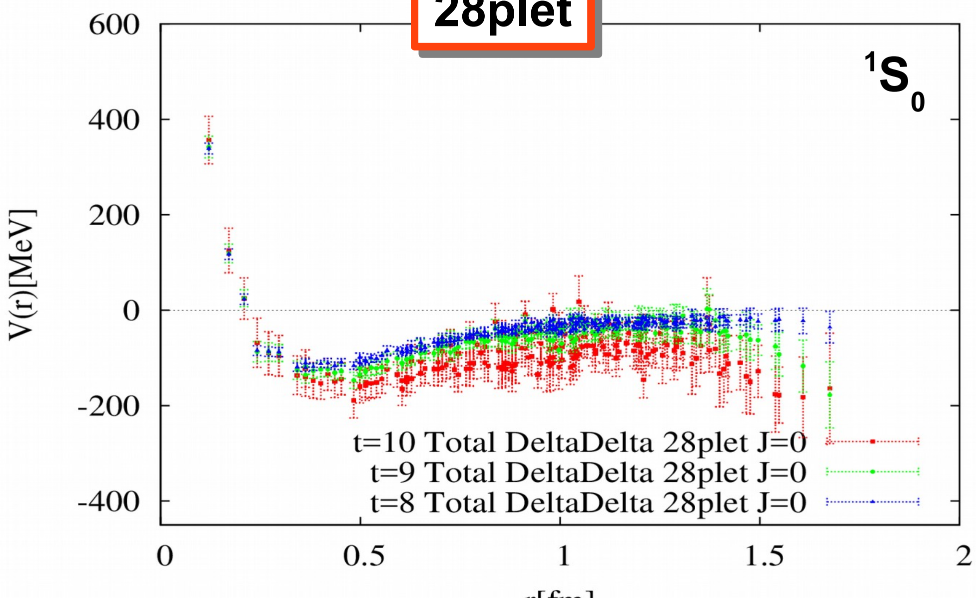
S. Gongyo, K. Sasaki (HAL QCD)

Decuplet-Decuplet interaction in SU(3) limit

- **N_f = 2+1 full QCD with L = 1.93fm, *m_π = 1015 MeV***

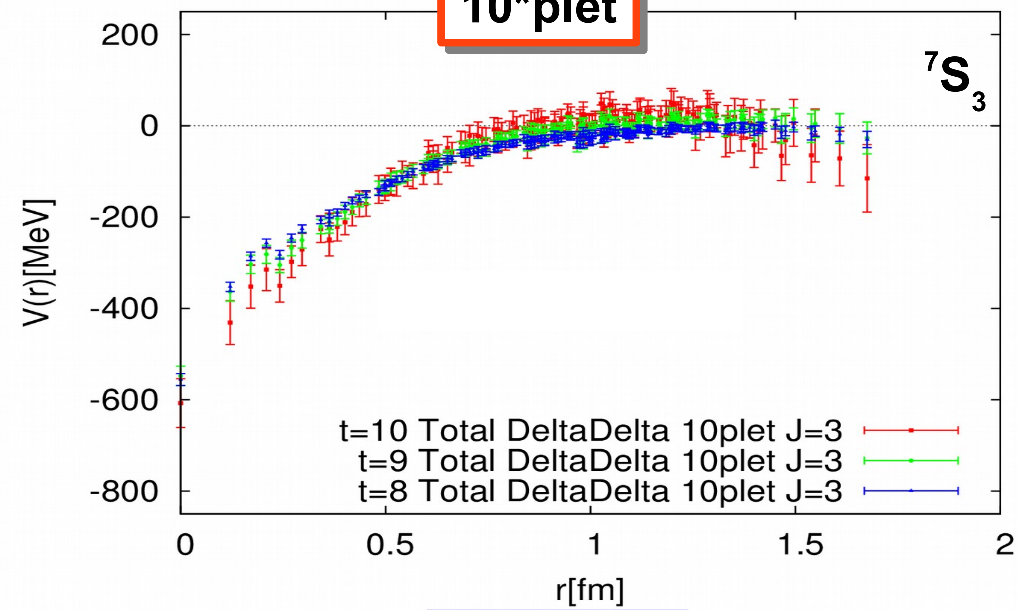
Preliminary!

28plet

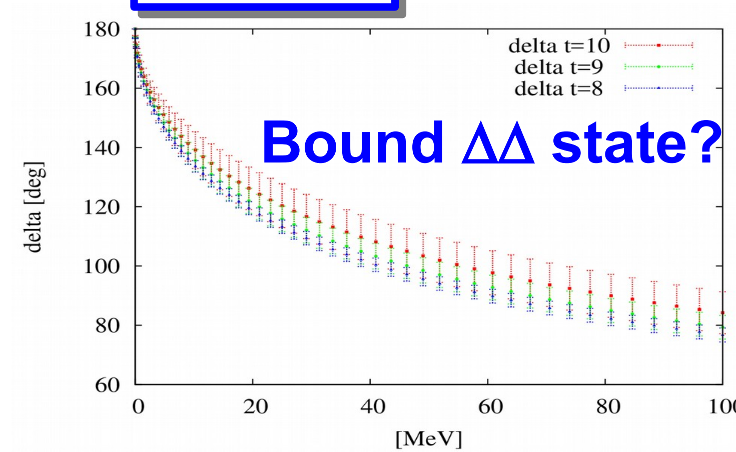


Δ–Δ(J=0) and Ω–Ω(J=0)

10*plet



Δ–Δ(J=3)

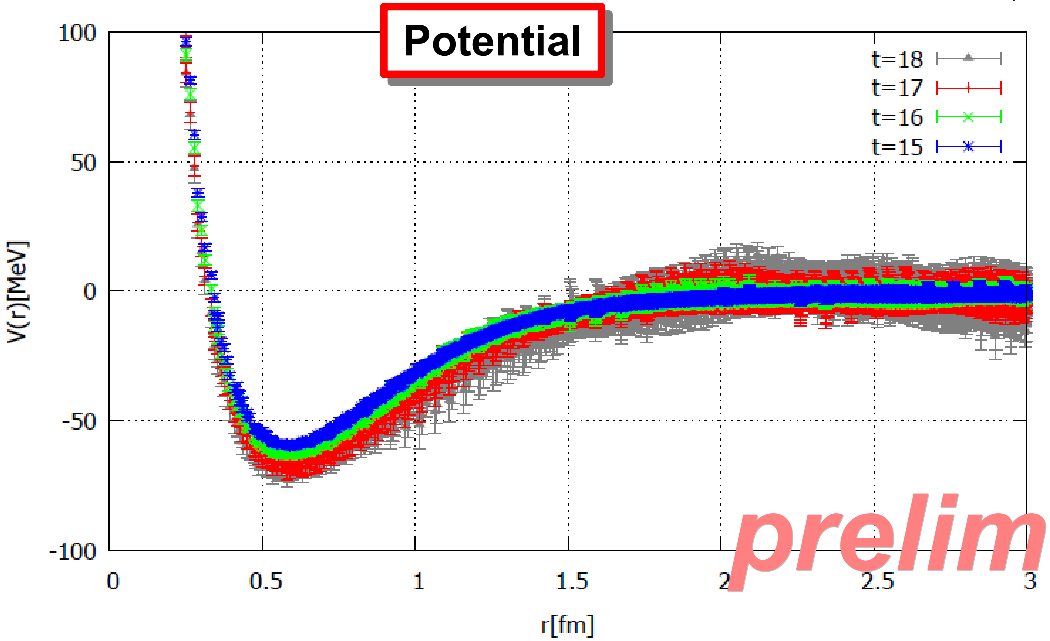


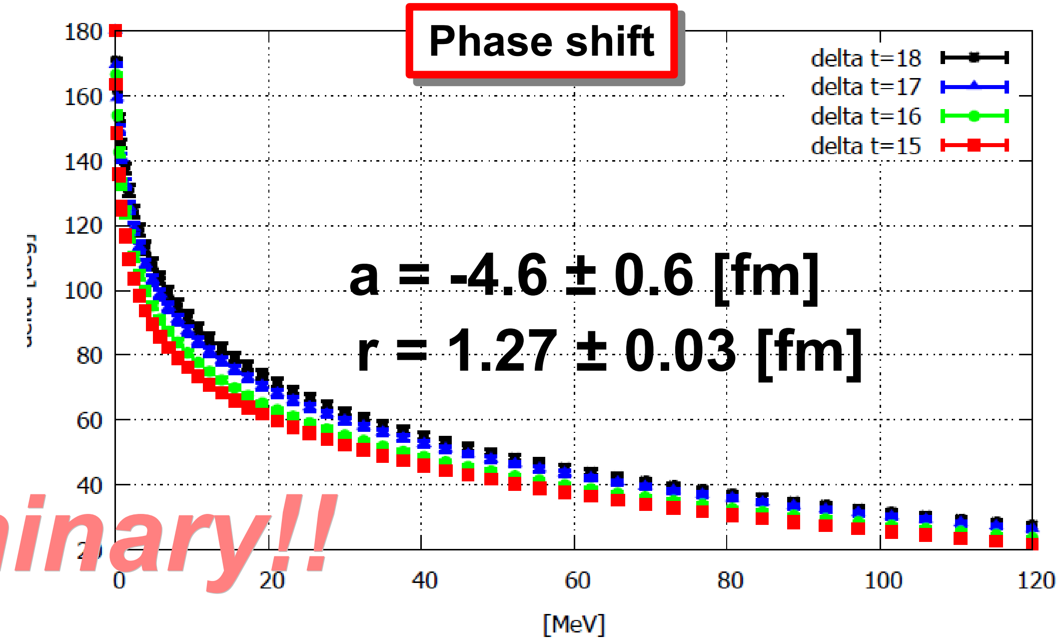
- **Short range repulsion and attractive pocket are found in 28plet.**
- **10*plet [$J^p(I)=3^+(0)$] is strongly attractive.**

S. Gongyo, M. Yamada, K. Sasaki (HAL QCD)

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

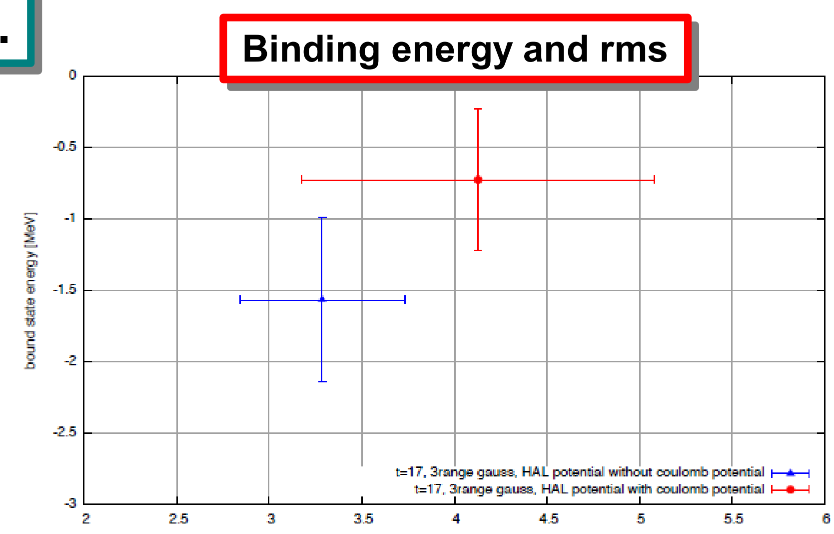
- N_f = 2+1 full QCD with L = 8fm, m_π = 145 MeV





The $\Omega\Omega$ state is stable against the strong interaction.

- **Short range repulsion and attractive pocket are found.**
- **Physical $\Omega\Omega$ state would form a bound state.**
- **Coulomb repulsion**
  - **reduces binding energy.**
  - **is not enough to untie two-Ωs.**



Summary and outlook

- **We have investigated coupled channel baryonic interactions from lattice QCD.**

- **We have studied dibaryon candidate states**
  - **H-dibaryon channel**
    - **We perform $\Lambda\Lambda$–$N\Xi$ coupled channel calculation.**
    - **Sharp resonance is found just below the $N\Xi$ threshold. (Time slice saturation is not achieved yet.)**
  - **$\Delta\Delta$ and $\Omega\Omega$ states**
    - **$\Delta\Delta$(I=0) has strongly attractive potential**
    - **$\Delta\Delta$(I=3) has repulsive core and attractive pocket**
    - **$\Omega\Omega$ potential has repulsive core and attractive pocket**
      - **$\Omega\Omega$ would form the bound state.**
  - **We continue to study it by using higher statistical data.**