Dibaryon searches from lattice QCD

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for HAL QCD collaboration

HAL (Hadrons to Atomic nuclei from Lattice) QCD Collaboration

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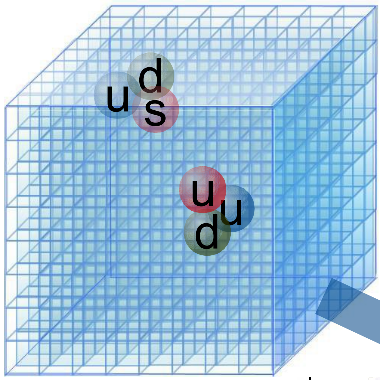
Introduction

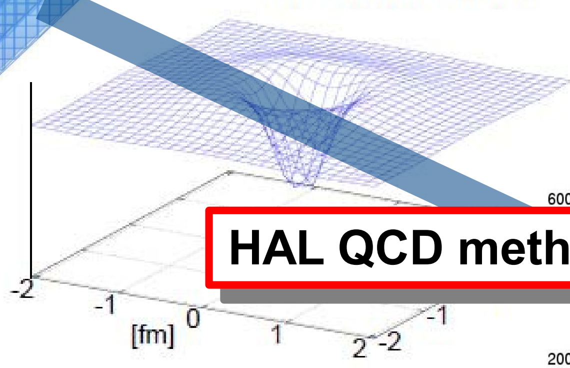
Ishii, Aoki, Hatsuda, PRL**99** (2007) 022001

Strategy of HAL QCD

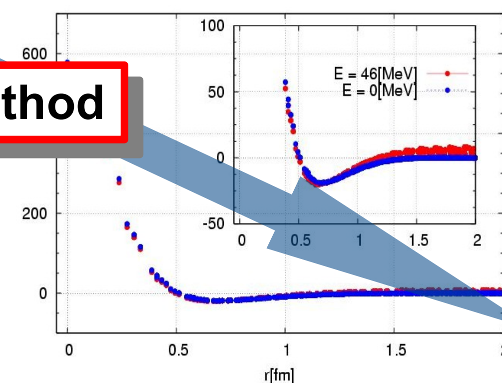
Technical improvements

- **Unified Contraction Algorithm,**
- **Time dependent method,**
- **Higher partial waves,**
- **Finite volume method vs potential**



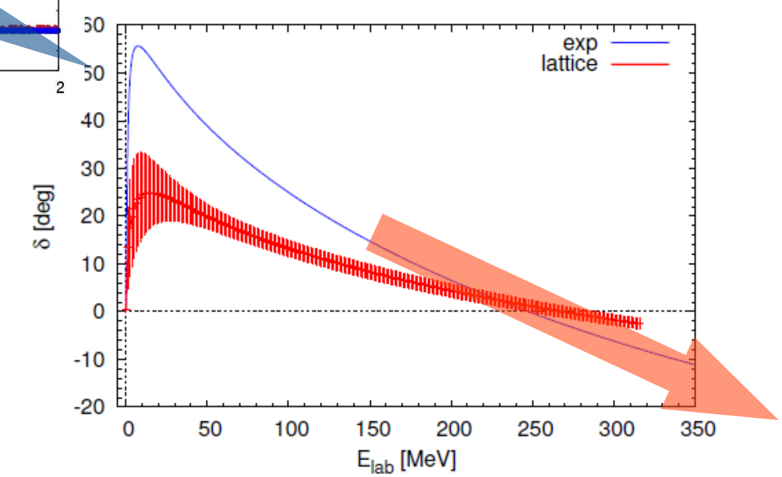


HAL QCD method



Applications

- **Few-body system**
- **Medium heavy system**
- **Neutron star EOS**



Extensions of the method

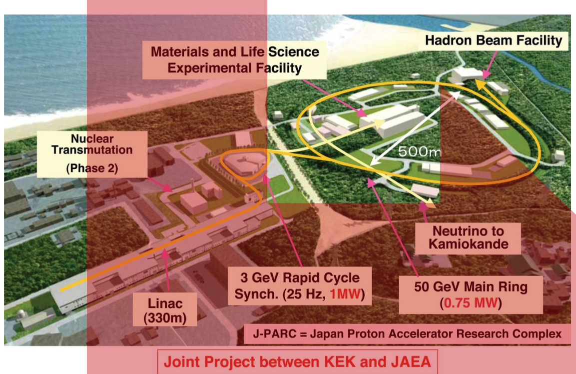
- **Generalized BB interaction**
- **Generalized Dec-Dec interaction**
- **Charmed baryon system**
- **Meson-meson,meson-baryon system**
- **Three-body interaction**

Role of our work

Study of BB interaction and search for dibaryon state

Experiment

- **Advantageous for less strange quarks**
- **Collision experiment getting more difficult as increasing the number of strange quarks due to short lifetime of flavored quarks**



Lattice QCD simulation

- **Advantageous for more strange quarks**
- **Signals getting worse as increasing the number of light quarks due to suffering statistical noise.**
- **Complementary role to experiment.**

It is best to collaborate to yield a high quality BB potential

Dibaryon candidates

Some dibaryon candidates are predicted by model calculations

- **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 found in experiments.**

Lattice QCD study of hadron interactions is awaited.

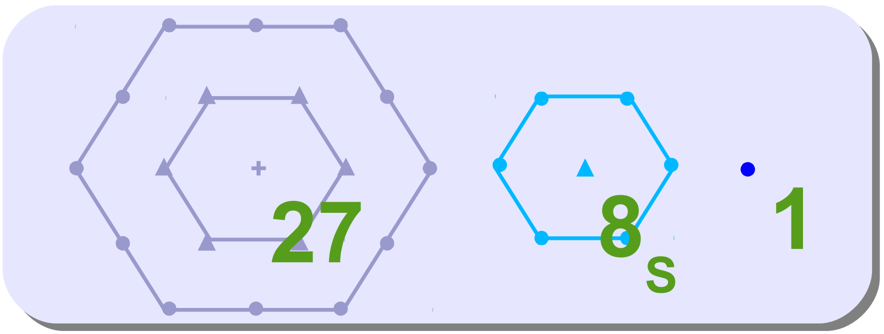
S=-2 BB interaction

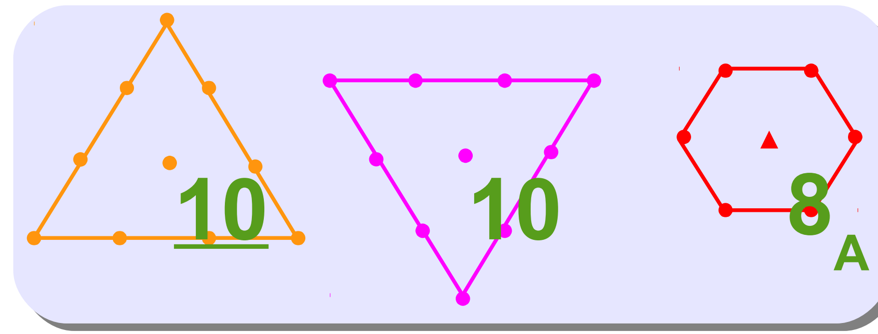
--- focus on the H-dibaryon ---

SU(3) feature of BB interaction

SU(3) classification

$8 \times 8 = 27 + 8_s + 1 + \overline{10} + 10 + 8_A$





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.**
- **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.**

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

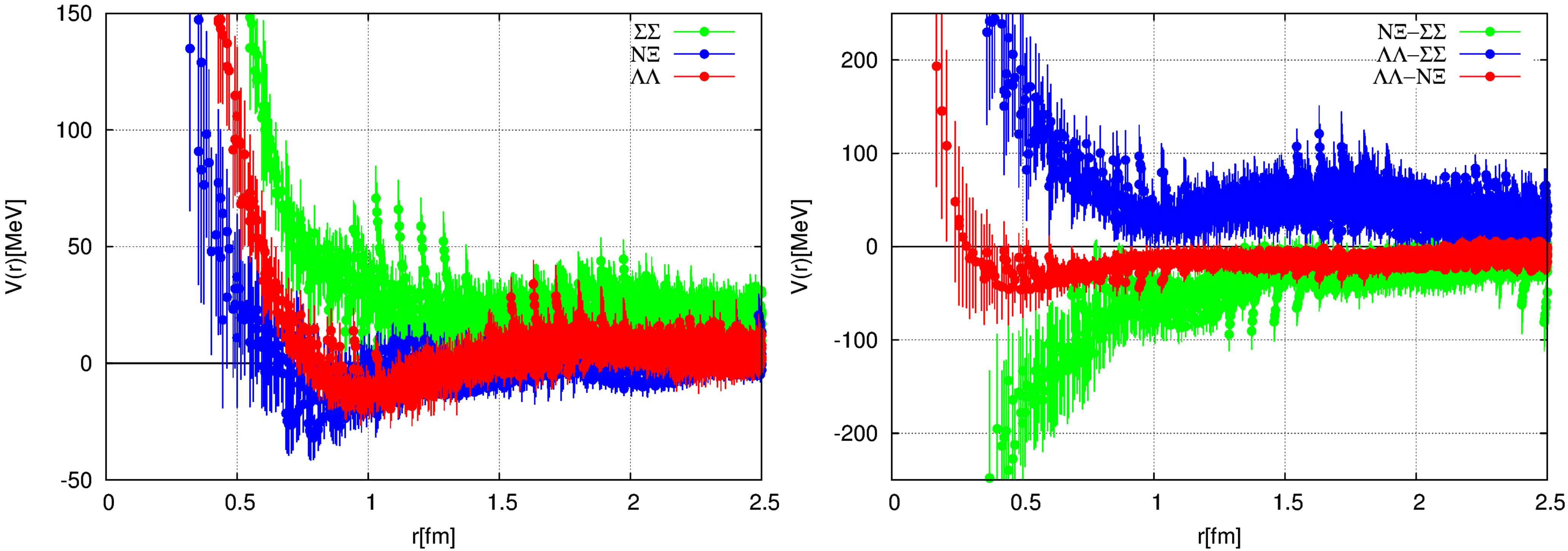
Oka, Shimizu and Yazaki NPA464 (1987)

ΛΛ, NΞ, ΣΣ (I=0) $^1S_0$ channel near the physical point

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

Preliminary!

Diagonal elements | **Off-diagonal elements**



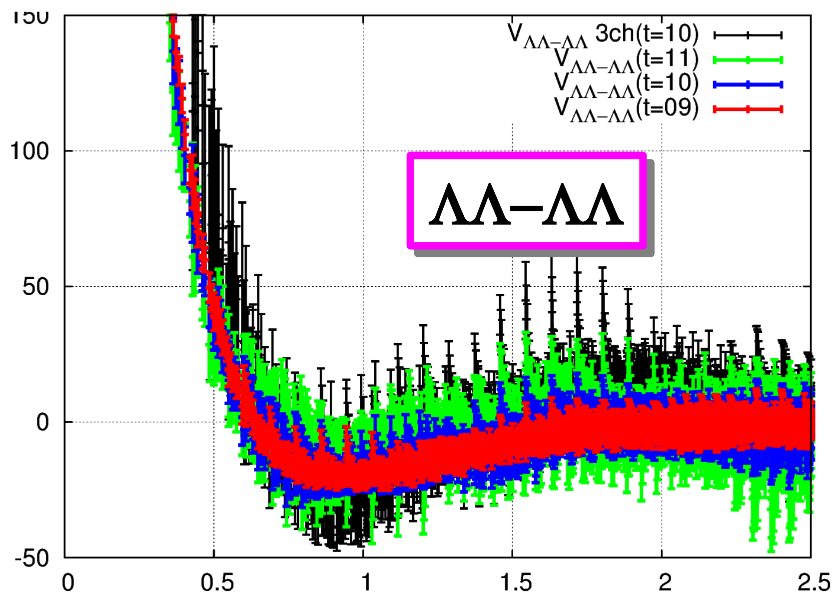
- All diagonal element have a repulsive core ΣΣ–ΣΣ potential is strongly repulsive.
- **Diagonal NΞ potential is more attractive than the ΛΛ potential.**
- We need more statistics to discuss physical observables through this potential.

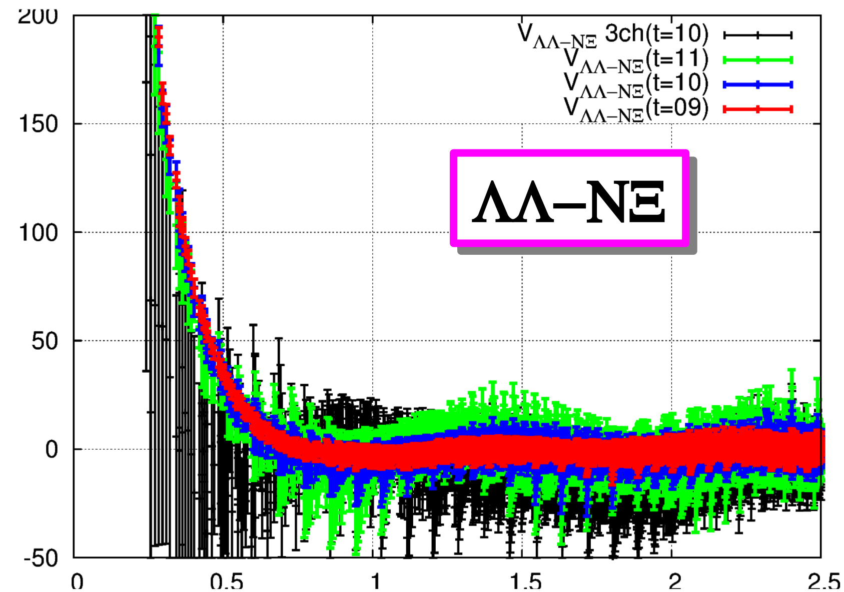
H-dibaryon channel (2-ch calculation)

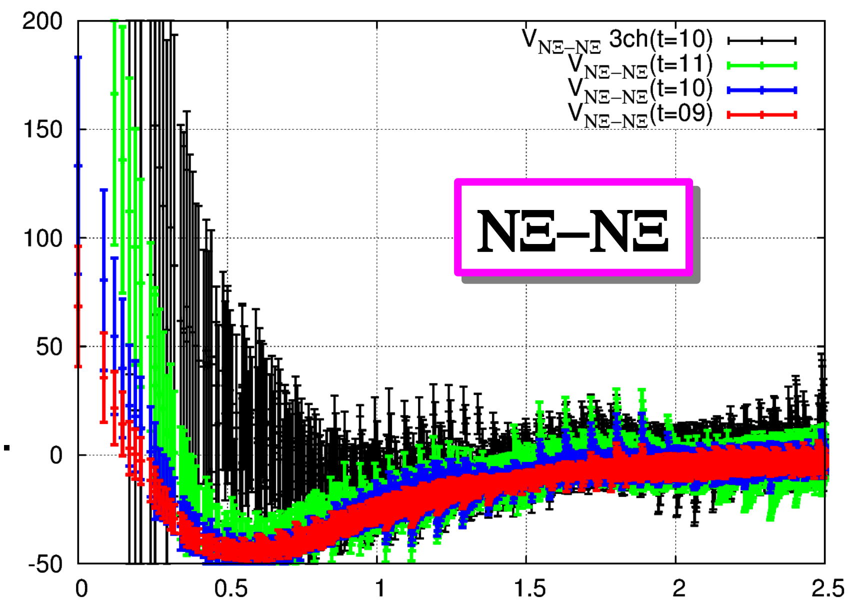
ΛΛ, NΞ (I=0) $^1S_0$ potential (2ch calc.)

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

Preliminary!







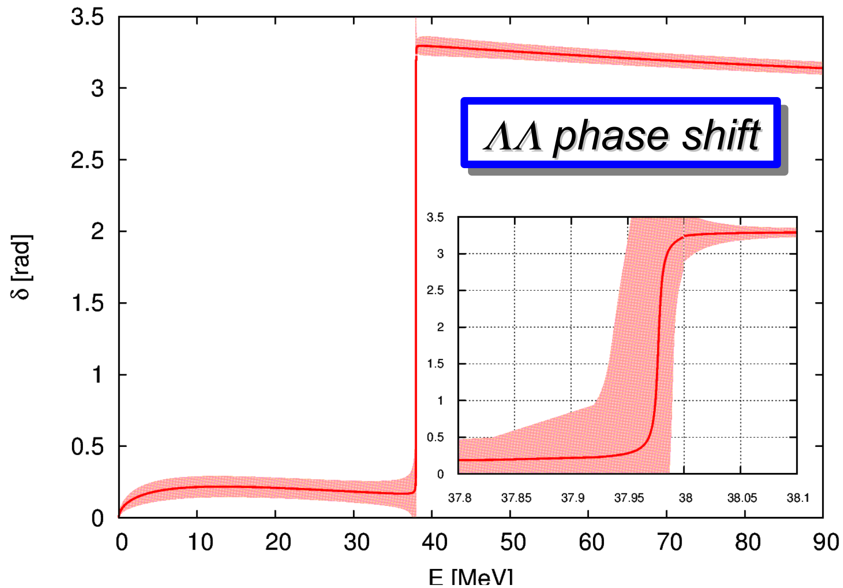
- Potential calculated by only using ΛΛ and NΞ channels
- Deviation from potential in 3ch calc. can be seen mainly in r<1fm.
- The same scattering phase shift would be expected in low energy region.

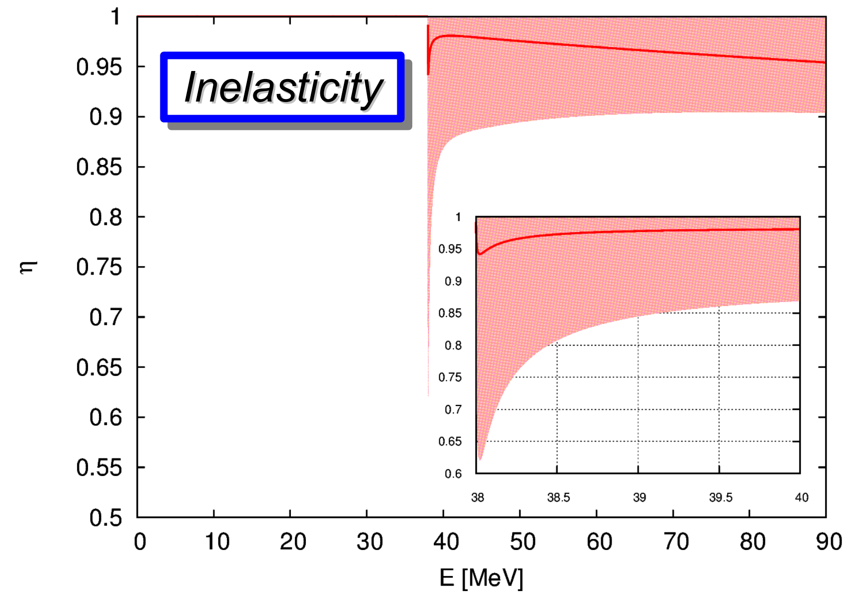
$\Lambda\Lambda$ and $N\Xi$ phase shift and inelasticity

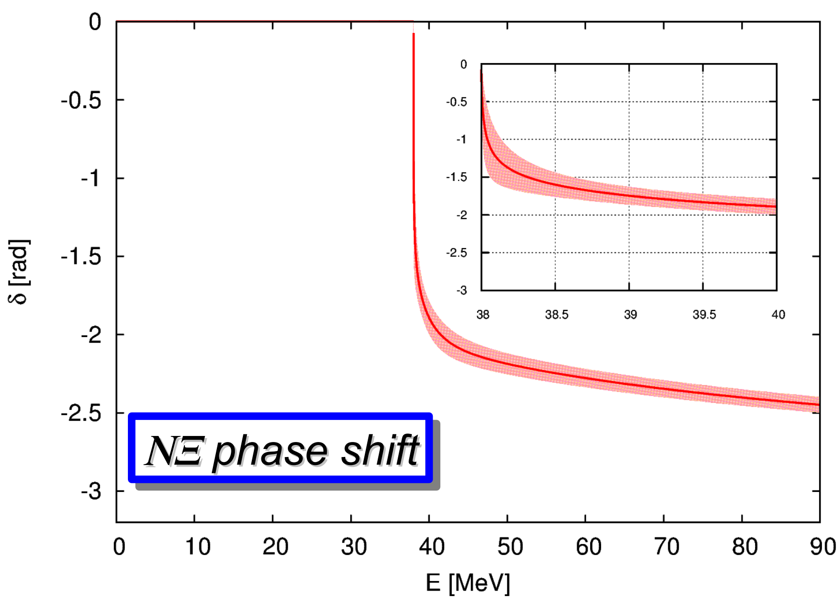
t=10

Preliminary!

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





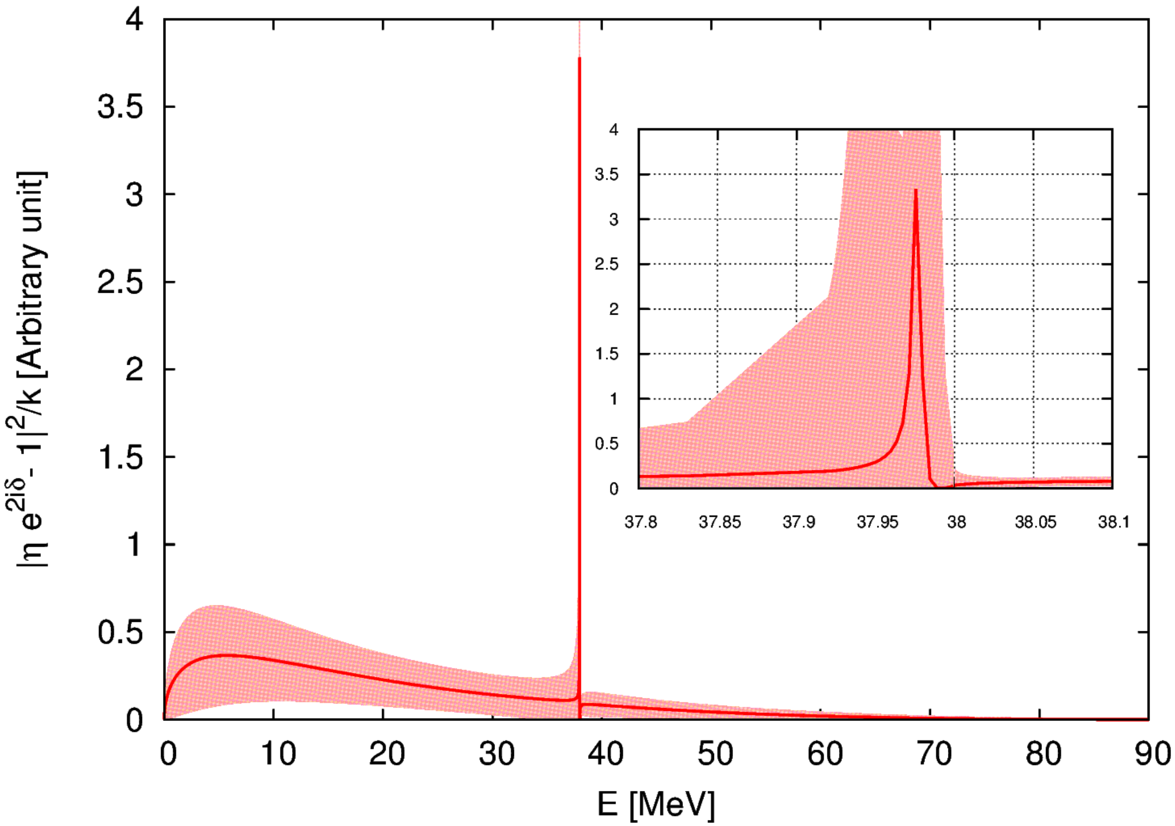


- **$\Lambda\Lambda$ and $N\Xi$ phase shift is calculated by using 2ch effective potential.**
- **A sharp resonance below the $N\Xi$ threshold**
- **Inelasticity is small.**

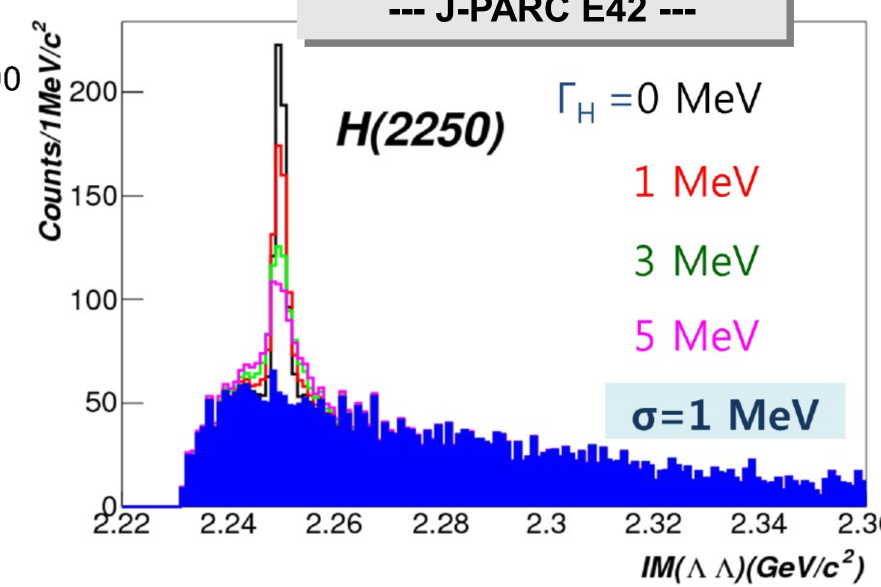
Breit-Wigner mass and width

$$E_R = 37.977 \pm 0.092 \ [MeV]$$
$$\Gamma = 0.0054 \pm 0.0576 \ [MeV]$$

Invariant mass spectrum of ΛΛ channel



- **Sharp peak below NΞ threshold**



- **Time slice saturation should be checked.**
- **3ch calculation(need more statistics)**

Interactions of decuplet baryons

SU(3) aspects of BB interaction

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

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

H-dibaryon

Nuclear force

Inclusion of decuplet baryons

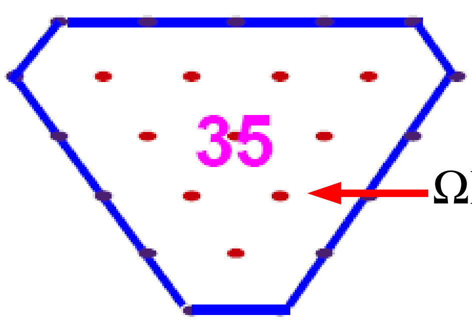
For decuplet-octet system

$$10 \otimes 8 = 35 \oplus 8 \oplus 10 \oplus 27$$

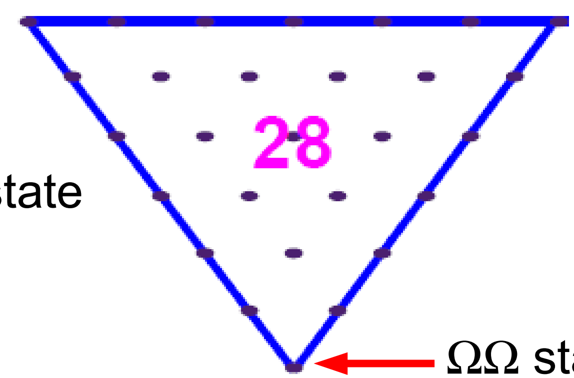
For decuplet-decuplet system

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

ΔΔ state (I=0,J=3)



ΩN state



ΩΩ state (pure 28plet)

Alternative source of generalized baryon-baryon interactions

$N\Omega$ interaction

NΩ system from quark model

- One of di-baryon candidate T.Goldman et al PRL59(1987)627
- (Quasi-)Bound state is reported with J=2, I=1/2

- Constituent quark model M.Oka PRD38(1988)298
  - CMI does not contribute for this system because of no quark exchange between baryons.
  - Coupled channel effect is important.

- Chiral quark model Q.B.Li, P.N.Shen, EPJA8(2000)
  - Strong attraction yielded by scalar exchange

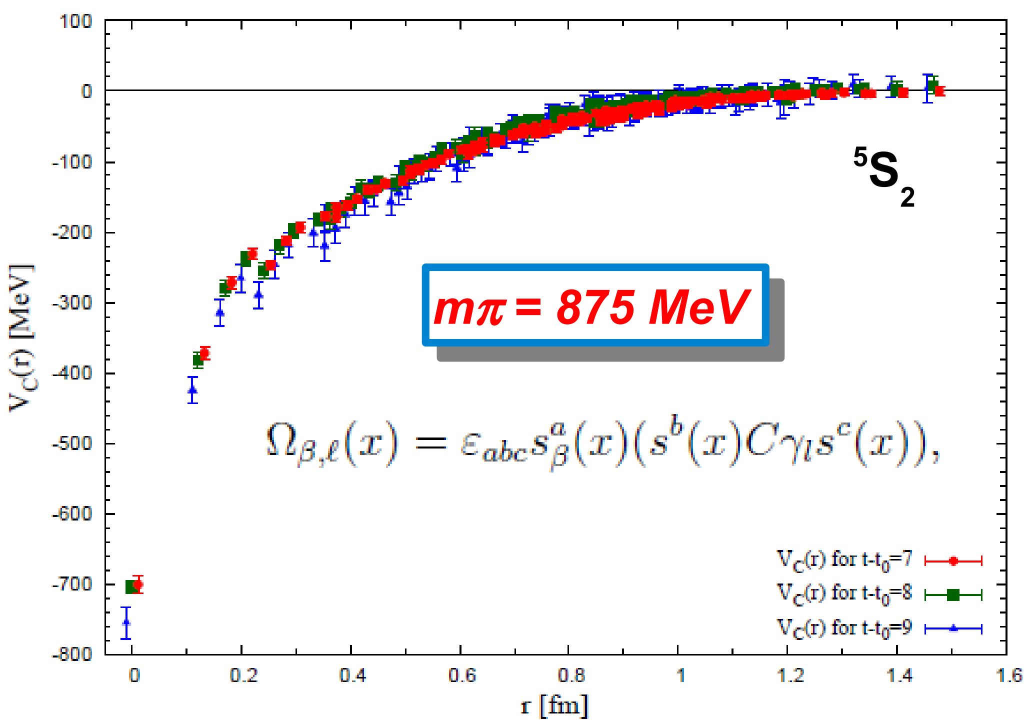
NΩ $J^p(I) = 2^+(1/2)$ is considered

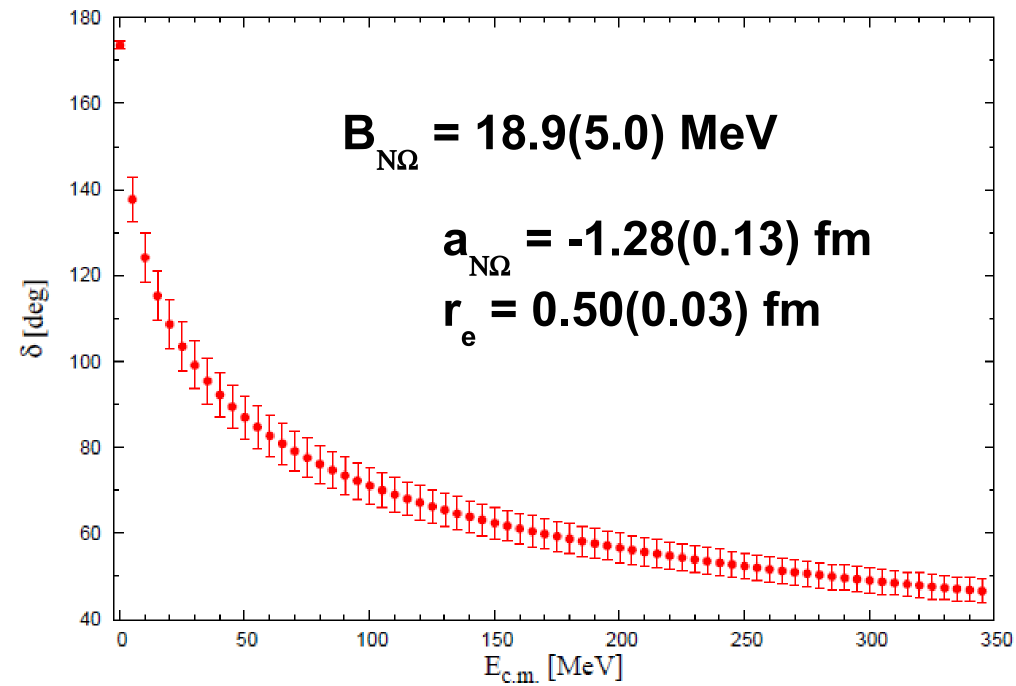
- Easy to tackle it by lattice QCD simulation
  - Lowest state in J=2 coupled channel
    - NΩ–ΛΞ*–ΣΞ*–ΞΣ*
  - Multi-strangeness reduces a statistical noise
  - Wick contraction is very simple

$N\Omega$ system $J^p(I) = 2^+(1/2)$

- **N_f = 2+1 full QCD with L = 1.9fm**

F.Etminan(HAL QCD), NPA928(2014)89





$N\Omega$ state cannot decay into $\Lambda\Xi$ (D-wave) state in this setup

- **Strongly attractive S-wave effective potential in $J^p(I) = 2^+(1/2)$**
- **Good baseline to explore S=-3 baryonic system**

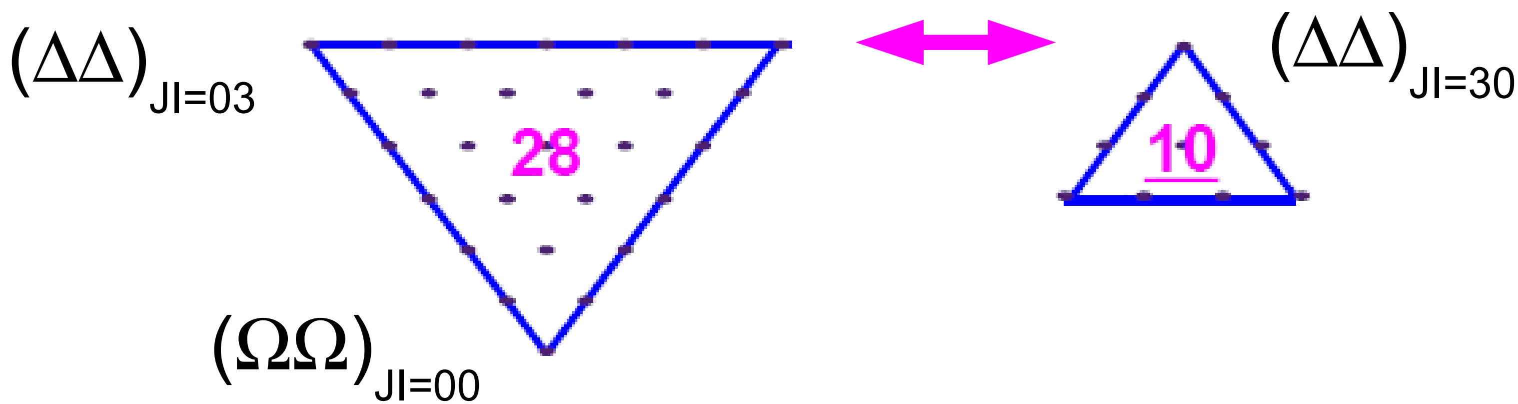
Decuplet-Decuplet interactions

Decuplet-Decuplet interaction

- **Flavor symmetry aspect**

  Decuplet-Decuplet interaction can be classified as

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



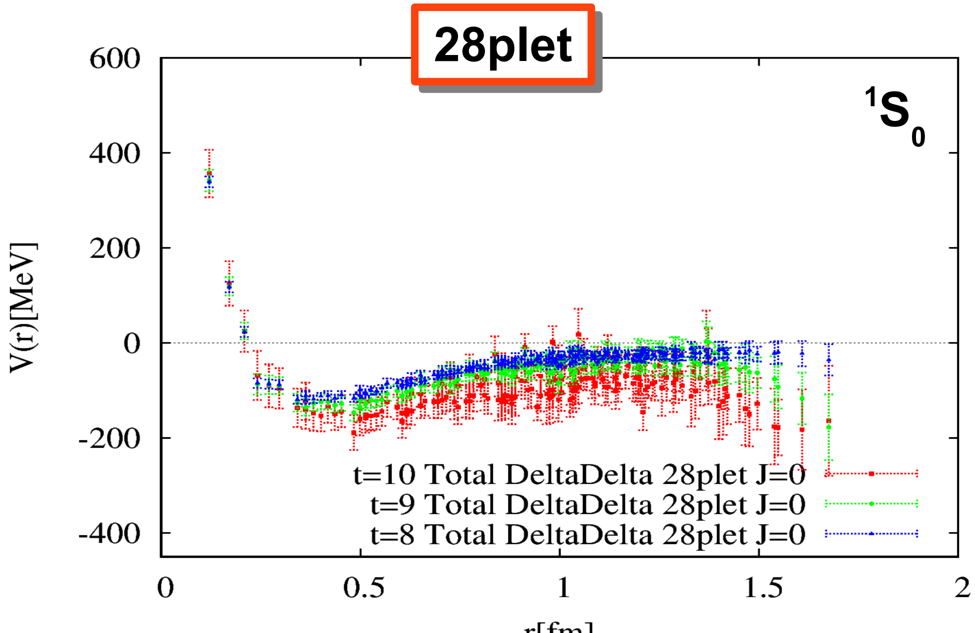
	28plet (0^+)	28plet (2^+)	10*plet (1^+)	10*plet (3^+)
Pauli	**allowed**	**forbidden**	---	**allowed**
CMI	**repulsive**	---	---	**Not attractive**

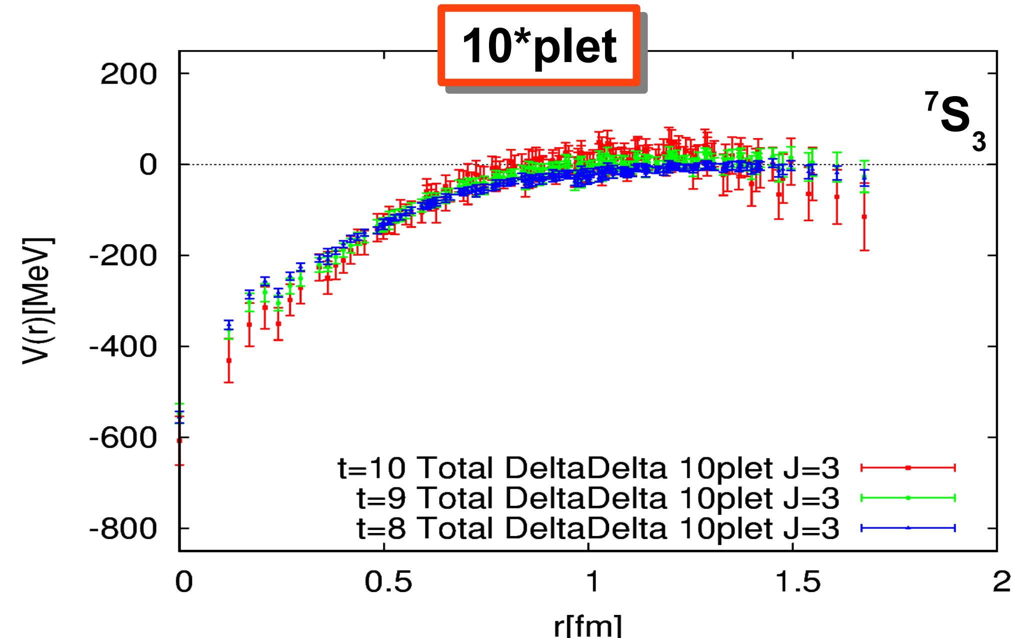
- **Δ–Δ(J=3) : Bound (resonance) state was found in experiment.**
- **Δ–Δ(J=0) [and Ω–Ω(J=0)] : Mirror of Δ–Δ(J=3) state**

S. Gongyo, K. Sasaki (HAL QCD)

Decuplet-Decuplet interaction in SU(3) limit

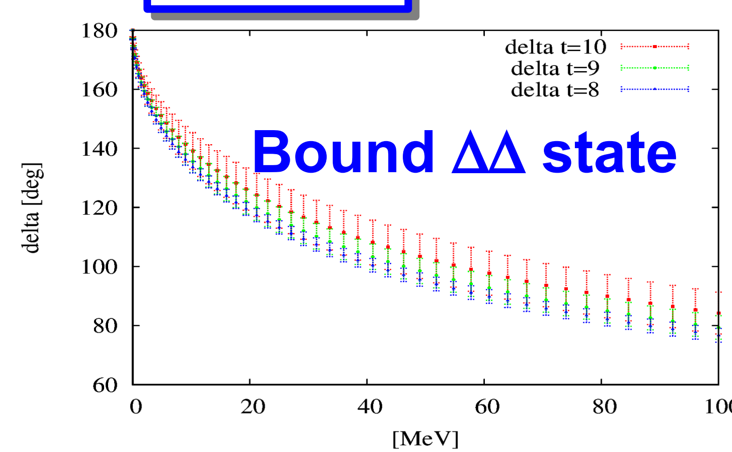
▶ **N_f = 2+1 full QCD with L = 1.93fm, *m_π = 1015 MeV*** **Preliminary!**





Δ–Δ(J=0) and Ω–Ω(J=0)

Δ–Δ(J=3)



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

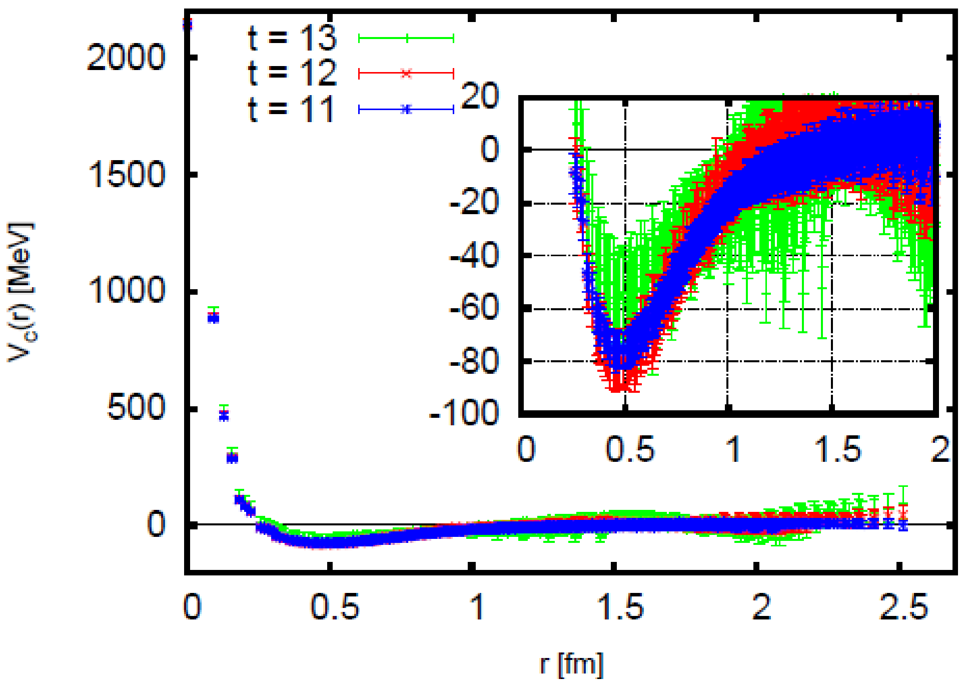
M. Yamada et al(HAL QCD), accepted in PTEP

$\Omega\Omega$ $J^p(I) = 0^+(0)$ state in unphysical region

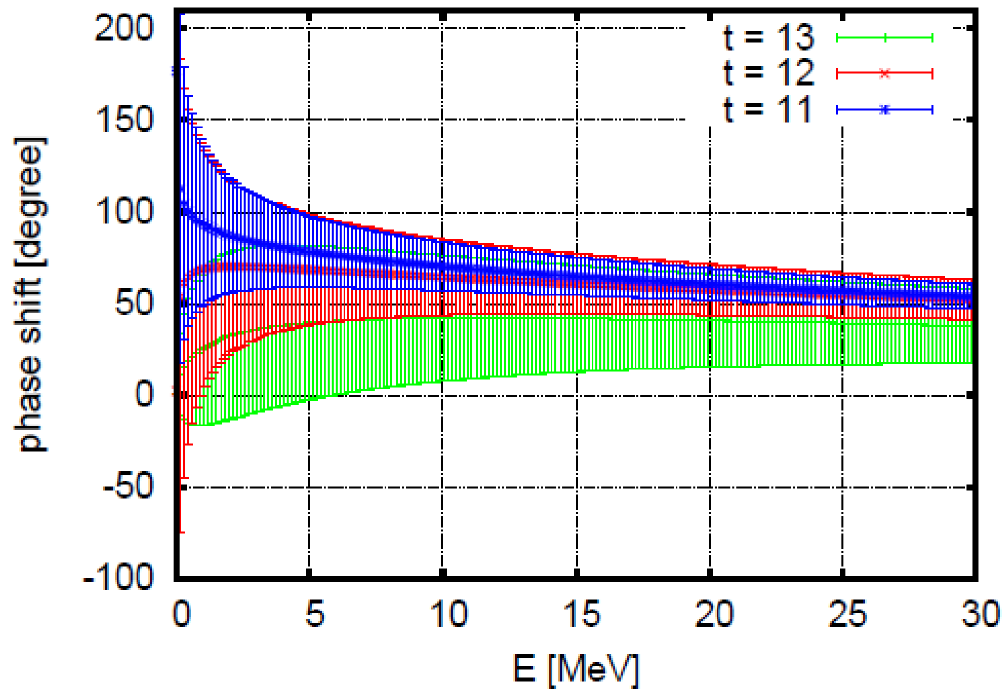
- N_f = 2+1 full QCD with L = 3fm, m_π = 700 MeV

The ΩΩ state is stable against the strong interaction.

Potential



Phase shift



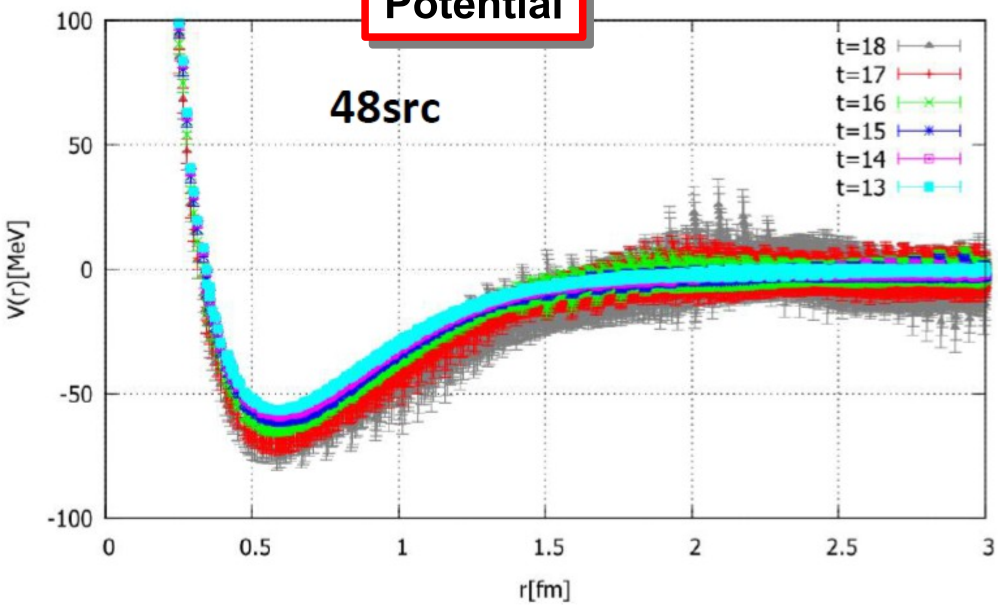
- **Short range repulsion and attractive pocket are found.**
- **Potential is nearly independent on "t" within statistical error.**
- **The system may appear close to the unitary limit.**

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

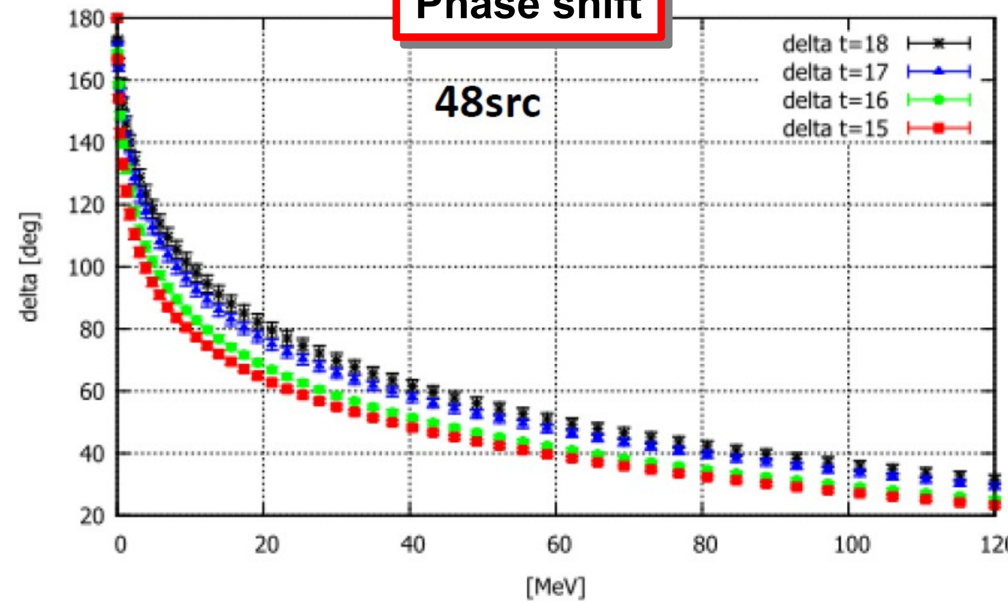
ΩΩ $J^p(I) = 0^+(0)$ state near the physical point

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

Potential



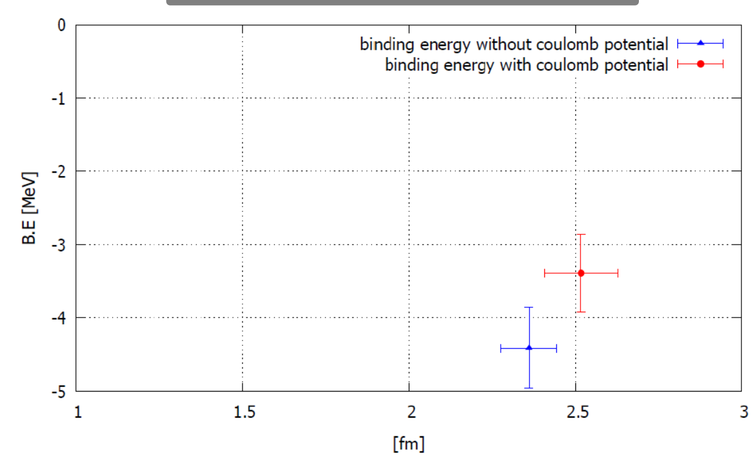
Phase shift



The ΩΩ state is stable against the strong interaction.

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

Binding energy and rms



Summary and outlook

- **We have studied exotic candidate states**
  - **H-dibaryon channel**
    - **Sharp resonance just below the $N\Xi$ threshold was found.**
    - **Breit-Wigner mass and width are**

$$E_R = 37.977 \pm 0.092 \ [MeV]$$
$$\Gamma = 0.0054 \pm 0.0576 [MeV]$$

Preliminary!!

  - **$N\Omega$ state with $J^p=2^+$**
    - **It is strongly attractive without short range repulsion.**
    - **It forms a bound state with about 20MeV B.E..**
    - **$\Omega N - \Xi * \Sigma - \Xi * \Lambda - \Sigma * \Xi$ coupled channel calculation is necessary.**
  - **$\Delta\Delta$ and $\Omega\Omega$ states**
    - **$\Delta\Delta$(I=0) have strongly attractive potential.**
    - **$\Delta\Delta$(I=3) and $\Omega\Omega$ potential have repulsive core and attractive pocket.**
    - **Both channels form (quasi-)bound state???**

- **BB-BD-DD coupling channel treatment**

- **Dibaryon search at the physical point**