Dibaryon search from Lattice QCD

Kenji Sasaki (*YITP, Kyoto University*)

for HAL QCD Collaboration

HAL (Hadrons to Atomic nuclei from Lattice) QCD Collaboration

S. Aoki (*YITP*)	**T. Doi** (*RIKEN*)	**F. Etminan** (*Birjand U.*)	**S. Gongyo** (*RIKEN*)	**T. Hatsuda** (*RIKEN*)
Y. Ikeda (*RCNP*)	**T. Inoue** (*Nihon U.*)	**N. Ishii** (*RCNP*)	**T. Iritani** (*RIKEN*)	**T. Miyamoto** (*YITP*)
K. Murano (*RCNP*)	**H. Nemura** (*RCNP*)	**T. Aoyama** (*YITP*)	**T.M. Doi** (*RIKEN*)	

Contents

- Introduction
- Baryon interaction from LQCD
  - HAL QCD method
- Results
  - ΔΔ, ΩΩ, NΩ system
  - H-dibaryon at the physical point
- Summary

Introduction

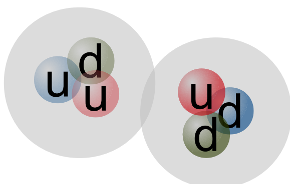
Introduction

- ***Dibaryon candidates?***

→ **Only one stable dibryon**
: deuteron

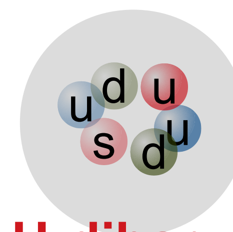
Two flavor (u, d) case

Three flavor (u, d, s) case



deuteron
Loosely bound state

Flavor symmetry extension



H-dibaryon
Tightly bound (six-quark) state predicted by Jaffe

- **Is H-dibaryon survive in SU(3) broken case?**
- **Is there another dibaryon in nature?**

We need deeper understandings of baryon-baryon interaction

How do we obtain the baryon force?

Clue to explore dibaryon candidates

Model approach to search for dibaryon

Experimental data are scarce to determine YN and YY interactions.

⇒ **Dibaryon predictions from model approaches are room for arguments**

Hints for dibaryon search from model approaches

- **Short range interaction in between two baryons could be a result of Pauli principle and color-magnetic interaction for the quarks.**
- **Symmetry of constituent quarks**
  - **Assuming that all quarks are in s-orbit,**
    Flavor SU(3) x Spin SU(2) x color SU(3)
    If totally anti-symmetric : Pauli allowed state
    If not : Pauli forbidden state
- **Gluonic interaction between quarks at short range region**
  - **Gluon exchange contribution generates a color magnetic interaction**

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

Dibaryon candidates

Possibility of dibaryon from view of constituent quarks

- **For octet-octet system**

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

Spin 0 → **Pauli allowed**, **Attractive color magnetic int.** → **H-dibaryon** (Coupled ΛΛ–NΞ–ΣΣ system)

- **For decuplet-octet system**

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

Spin 2 → **Pauli allowed**, **Attractive color magnetic int.** → **N-Ω system** (Ground state of coupled NΩ–ΛΞ*–ΣΞ*–ΞΣ* system)

- **For decuplet-decuplet system**

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

Spin 3 → **Pauli allowed**, **No color magnetic int.** → **ΔΔ system**

Spin 0 → **Pauli allowed**, **Repulsive color magnetic int.** → **ΩΩ system**

→ **Lattice QCD simulation**

Baryon interaction from LQCD

BB interaction from QCD

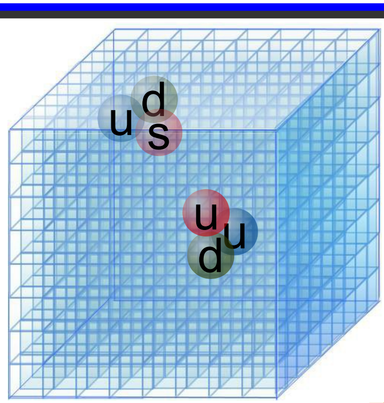
QCD is the fundamental theory of strong interactions

QCD Lagrangian

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

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

Lattice QCD simulation



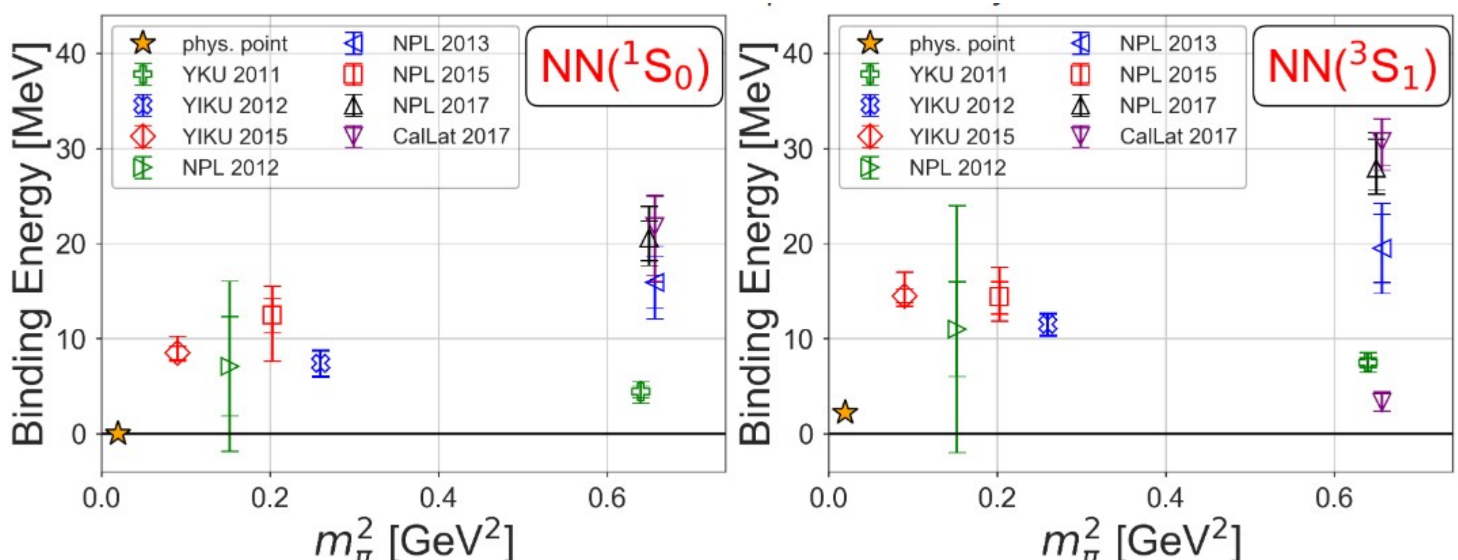
- **Non-perturbative calculation.**
- **Huge computer resource is required.**

BB interaction

Independent of experimental situation.

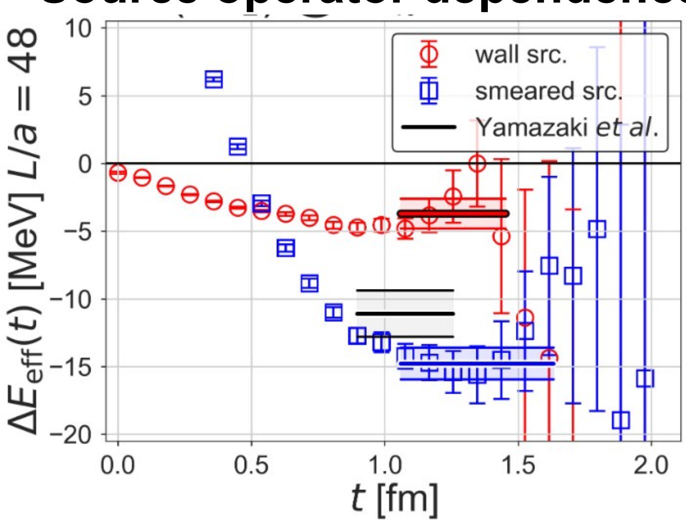
Fake plateau problem

For m_π>300MeV deeply bound dineutron & deuteron are observed



Is di-neutron exist?

Source operator dependence



Discrepancy between two results

Mixture of excited states

Ground state saturation?

Iritani et al JHEP 1610(2016)101

Consistency check by finite volume formula

Iritani et al PRD96(2017)034521

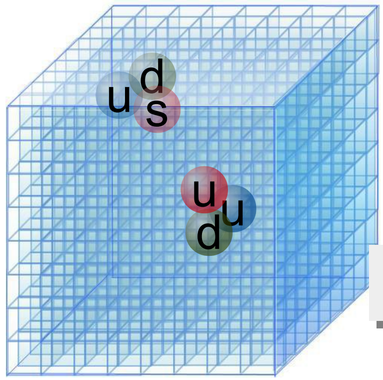
Is plateau mirage??

Difficulty of direct measurement of eigen energies

HAL QCD method

Hadron interaction from LQCD

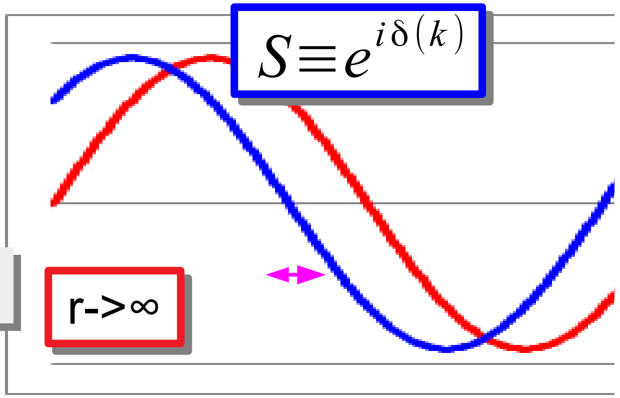
Lattice QCD simulation



HAL QCD method

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

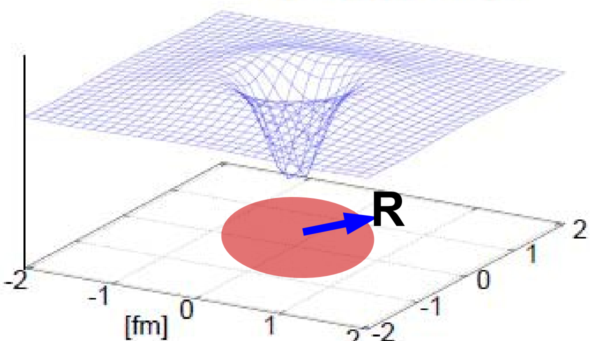
Scattering S-matrix



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

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

NBS wave function



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

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

- **Inside of "interacting region"**

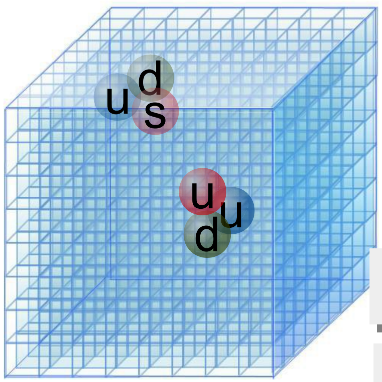
$$\left(p^2 + \nabla^2\right) \Psi^\alpha(E, \vec{x}) \equiv \int d^3y\, U_\alpha^\alpha(\vec{x}, \vec{y}) \Psi^\alpha(E, \vec{y})$$

- **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.**

Phase shift is embedded in NBS w.f.

Hadron interaction (coupled-channel)

Lattice QCD simulation



HAL QCD method

S.Aoki et al [HAL] Proc. Jpn. Acad.,Ser.B,87 509

Scattering S-matrix

$$S(E)=\begin{pmatrix} \eta e^{2i\delta_1} & i\sqrt{1-\eta^2}\, e^{i(\delta_1+\delta_2)} \\ i\sqrt{1-\eta^2}\, e^{i(\delta_1+\delta_2)} & \eta e^{2i\delta_2} \end{pmatrix}$$

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

$$\langle 0|(B_1 B_2)^{\beta}(t,\vec{r})\bar{I}(t_0)|0\rangle = C_0 \Psi^{\beta}(\vec{r},E_0)e^{-E_0(t-t_0)}+\cdots$$

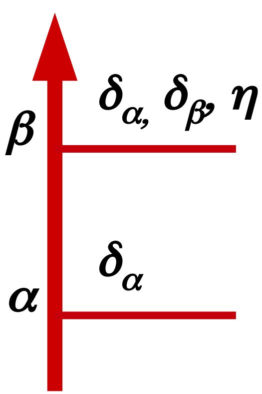
NBS wave function for each channel

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

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

Coupled-channel Schrödinger equation

$$\left(p_{\alpha}^2+\nabla^2\right)\Psi^{\alpha}(E,\vec{x}) \equiv \int d^3y\, U_{\beta}^{\alpha}(\vec{x},\vec{y})\,\Psi^{\beta}(E,\vec{y})$$



$\delta_\alpha, \delta_\beta, \eta$ ← $\Psi_{sc}^{\alpha}(\vec{r}),\ \Psi_{sc}^{\beta}(\vec{r})$

δ_α ← $\Psi_{sc}^{\alpha}(\vec{r})$

- **U(x,y) is faithful to the S-matrix beyond the threshold of channel β.**
- **U(x,y) is energy independent until the higher energy thershold opens.**
- **Derivative (velocity) expansion is used.**

N. Ishii et al Phys. Lett. B712(2012)437

Time-dependent HAL QCD method

Considering the normalized four-point correlator,

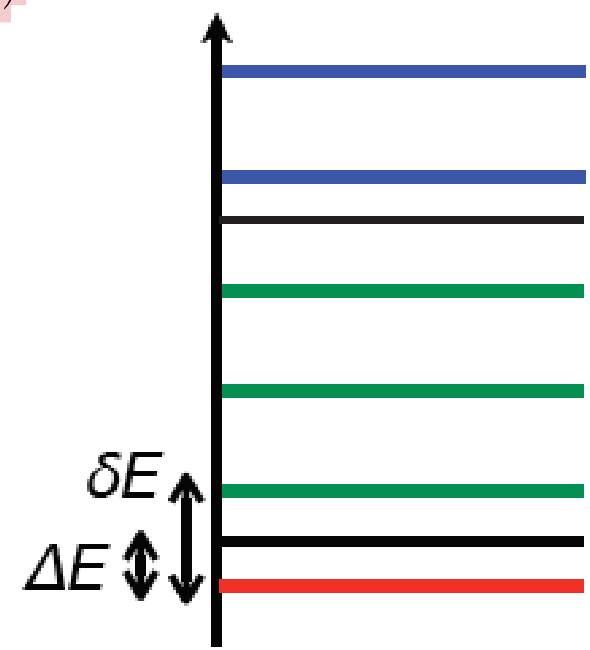
$$R_I^{B_1 B_2}(t,\vec{r}) = F^{B_1 B_2}{}_I(t,\vec{r}) e^{(m_1+m_2)t}$$

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

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

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

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



A single state saturation is not required!!

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

All elastic energies contribute as a signal of energy indep. pot.

Derivative (velocity) expansion of U

$$U(\vec{r}, \vec{r}\,') = V_C^{eff}(r) + O(\nabla^2)$$

Effects of higher order contributions can be seen as the time-slice dependence of the local potential.

Baryon operators and projection

Local composite interpolating operators

$$B_\alpha(x) = \epsilon^{abc}(q_a^T(x) C \gamma_5 q_b(x)) q_{c\alpha}(x)$$
$$D_{\mu\alpha}(x) = \epsilon^{abc}(q_a^T(x) C \gamma_\mu q_b(x)) q_{c\alpha}(x)$$

$p = [ud]u \quad \Xi^0 = [su]s \quad \Lambda = ([sd]u + [us]d - 2[du]s)/\sqrt{6}$

$n = [ud]d \quad \Xi^- = [sd]s$

Flavor structure is put on top of quark operators

Projection of NBS wave function

$$\Psi^\chi_{J=S}(E, \vec{r}) = P^{L=0} P^S_{\alpha\beta} \sum_{\vec{x}} \langle 0 | B^\chi_{1\alpha}(\vec{x}+\vec{r}) B^\chi_{2\beta}(\vec{x}) | E \rangle$$

E : Total energy of the system

Projection operator into the S-wave (L=0 component)

For discrete space:

This corresponds to the projection into A_1 representation in the cubic group, which contains not only L=0 component but also the L>=4 component.

Lattice artifacts from L>=4 partial waves have better to be removed.

Miyamoto et al in prep.

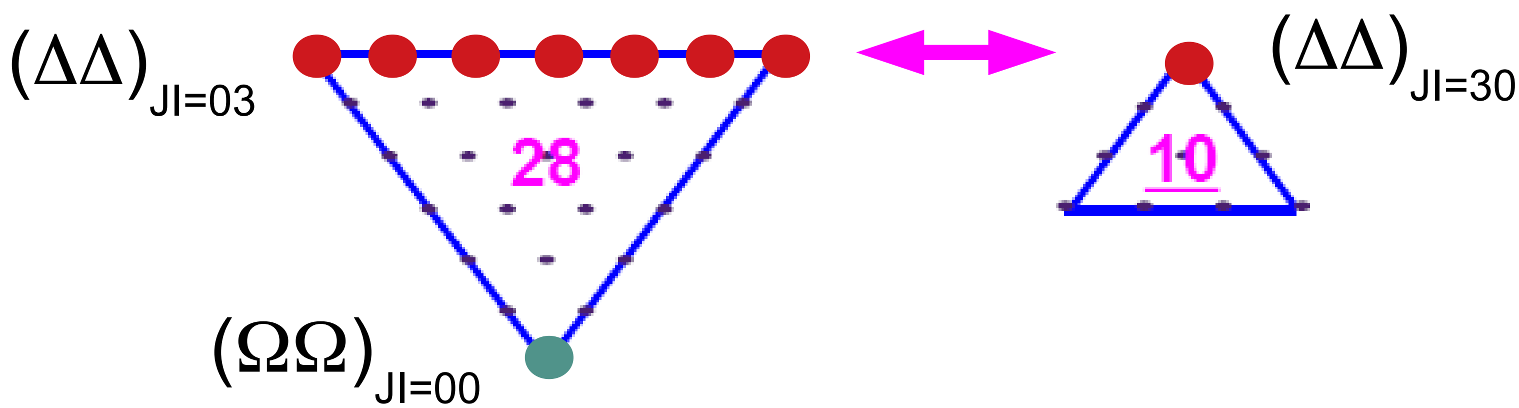
ΔΔ and ΩΩ interaction

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**

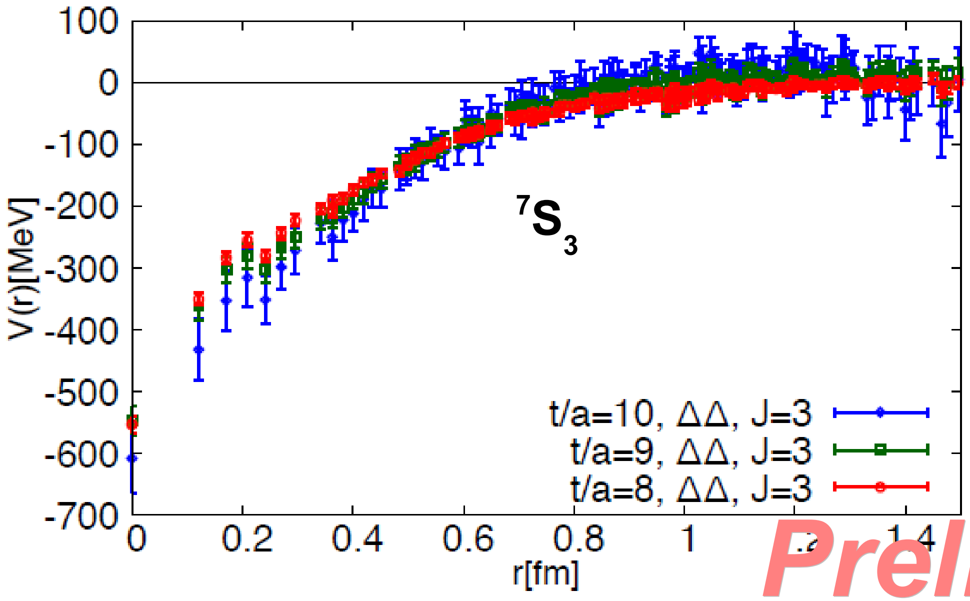
- **Δ–Δ(J=3) : Bound (resonance) state was found in experiment.**

WASA at COSY Coll.

- **Δ–Δ(J=0) [and Ω–Ω(J=0)] : Mirror of Δ–Δ(J=3) state**

Decuplet-Decuplet interaction in SU(3) limit

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



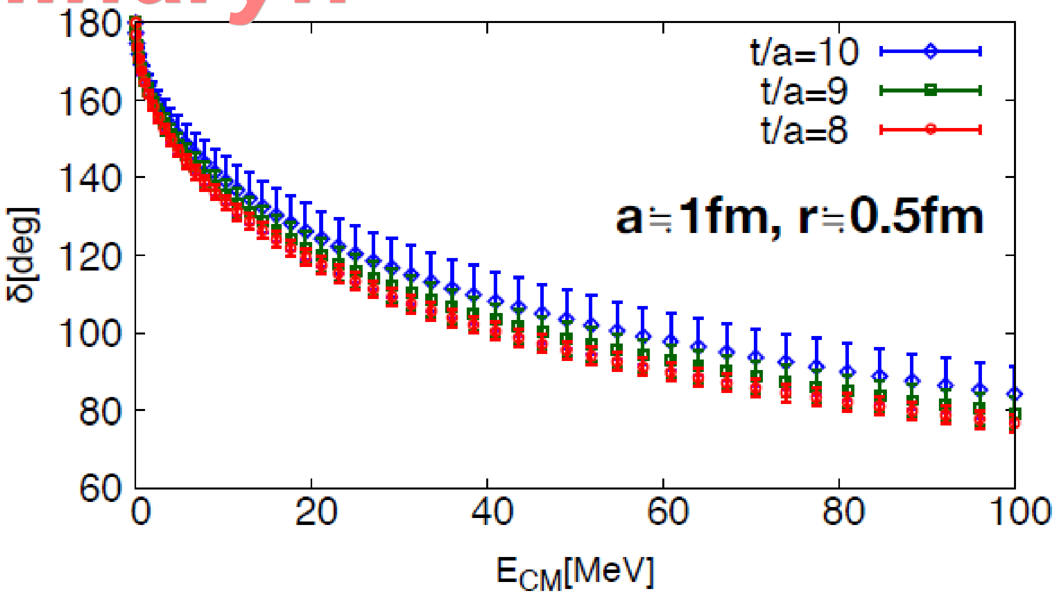
Δ–Δ(J=3) **10*plet**

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

Preliminary!!

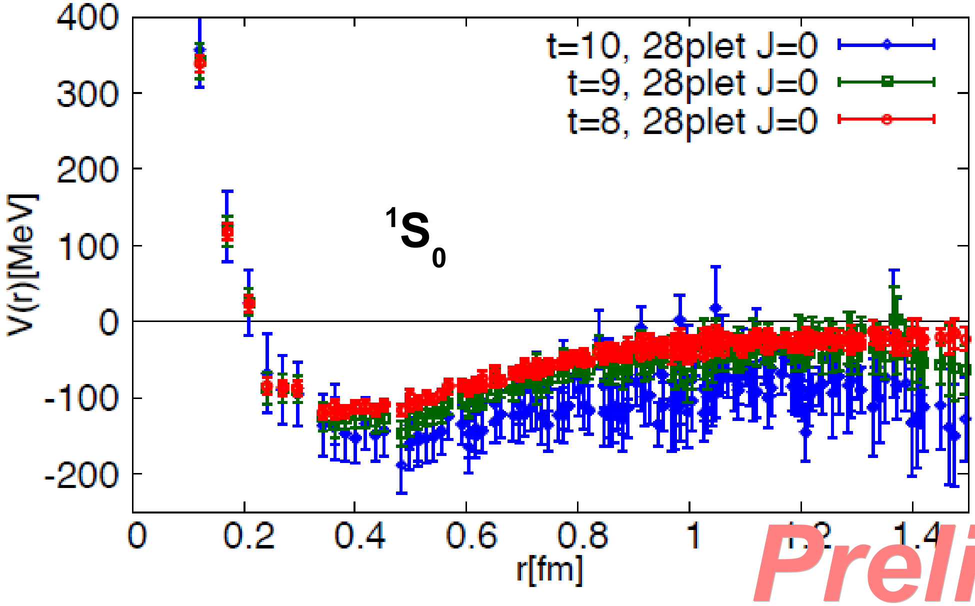
Bound ΔΔ state is found.

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



Decuplet-Decuplet interaction in SU(3) limit

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

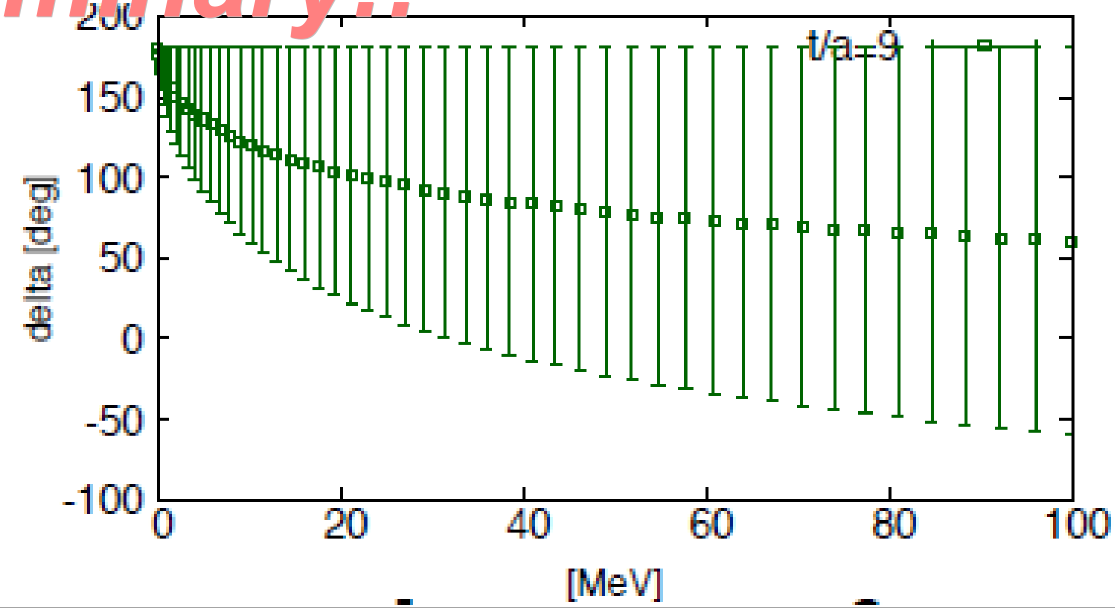


Δ−Δ(J=0) 28plet

- 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.

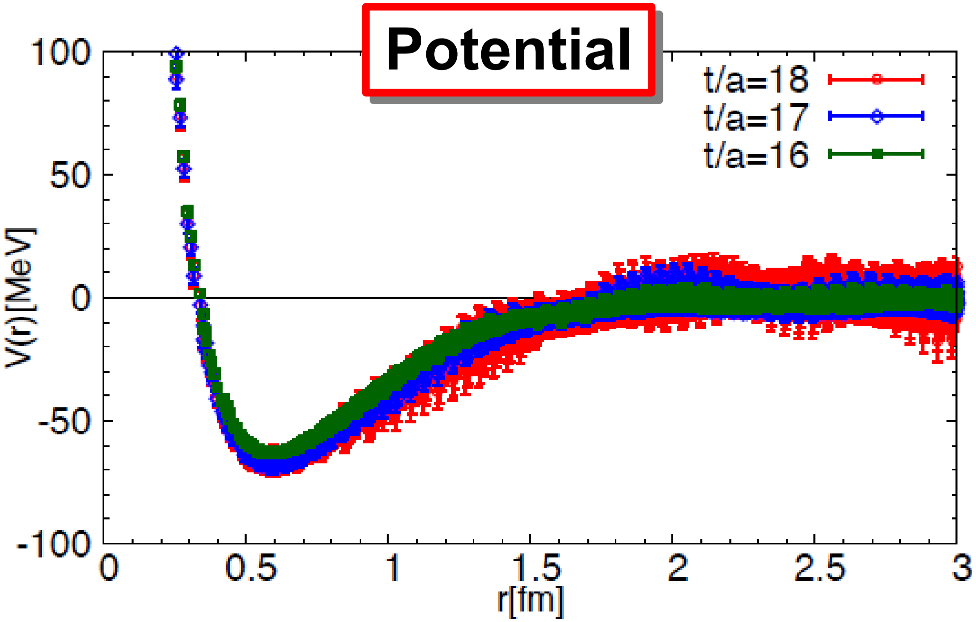


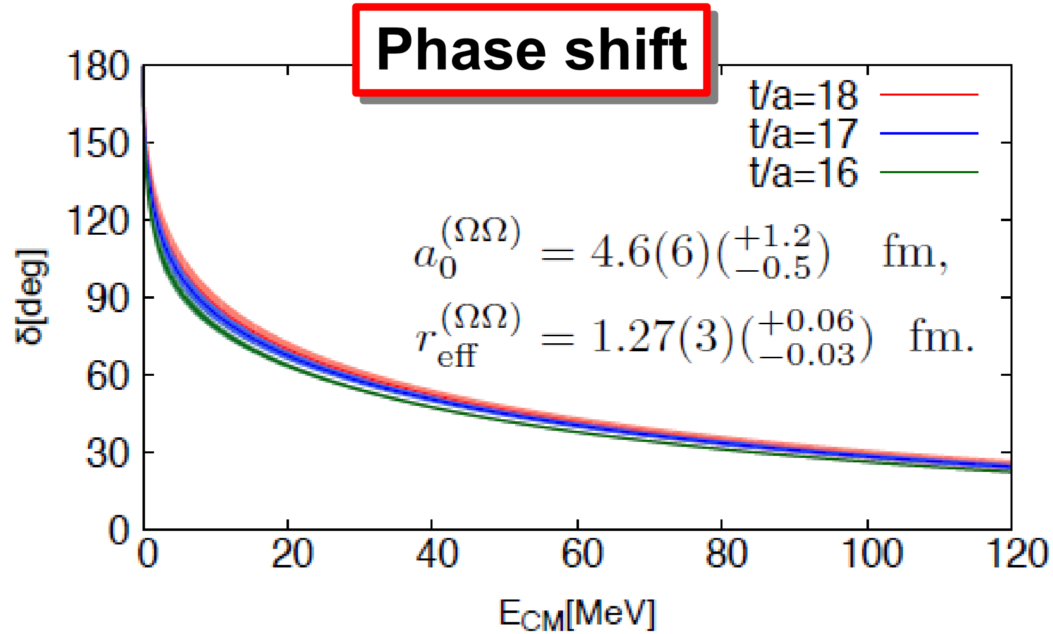
- Δ baryon can not decay into N+π in this lattice setup

Go to the physical point simulation

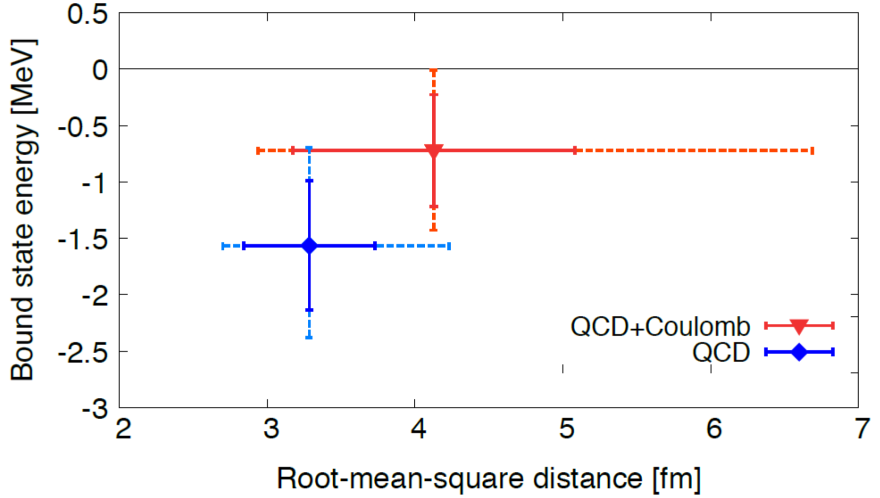
$\Omega\Omega$ $J^p(I) = 0^+(0)$ state near the physical point

▶ N_f = 2+1 full QCD with L = 8.1fm, $m\pi$ = 146 MeV m_Ω = 1712 MeV





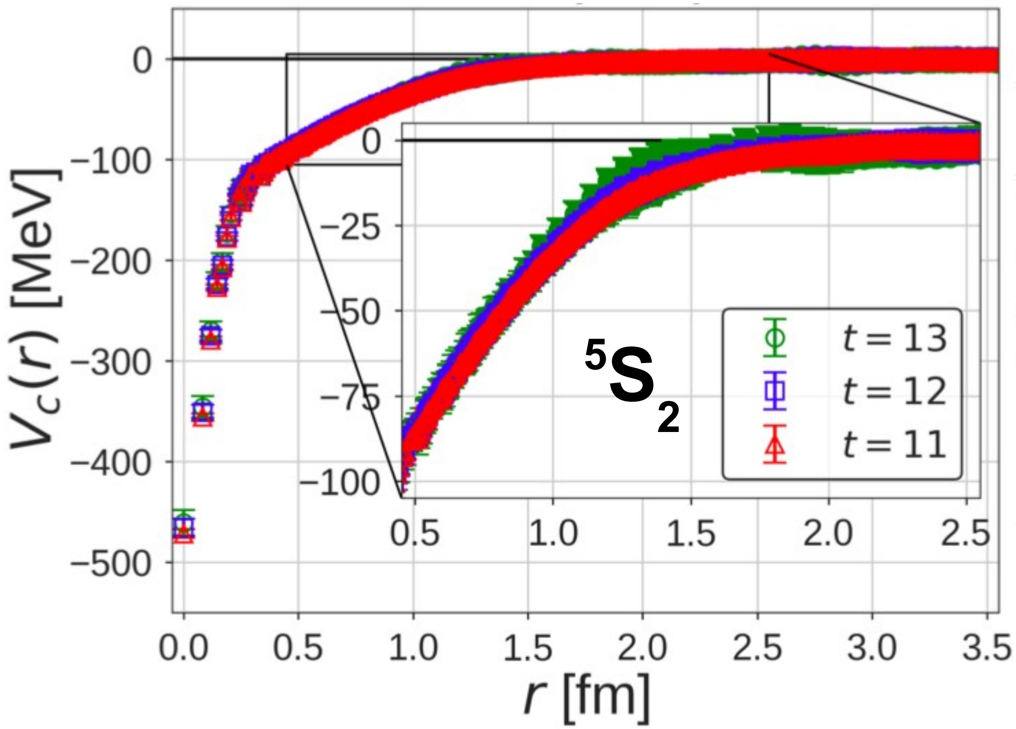
- Short range repulsion and attractive pocket is found.
- Calculated phase shift indicates a bound $\Omega\Omega$ state [Most strange dibaryon].
- Physical $\Omega\Omega$ state in $J^p(I) = 0^+(0)$ is very close to unitary region.

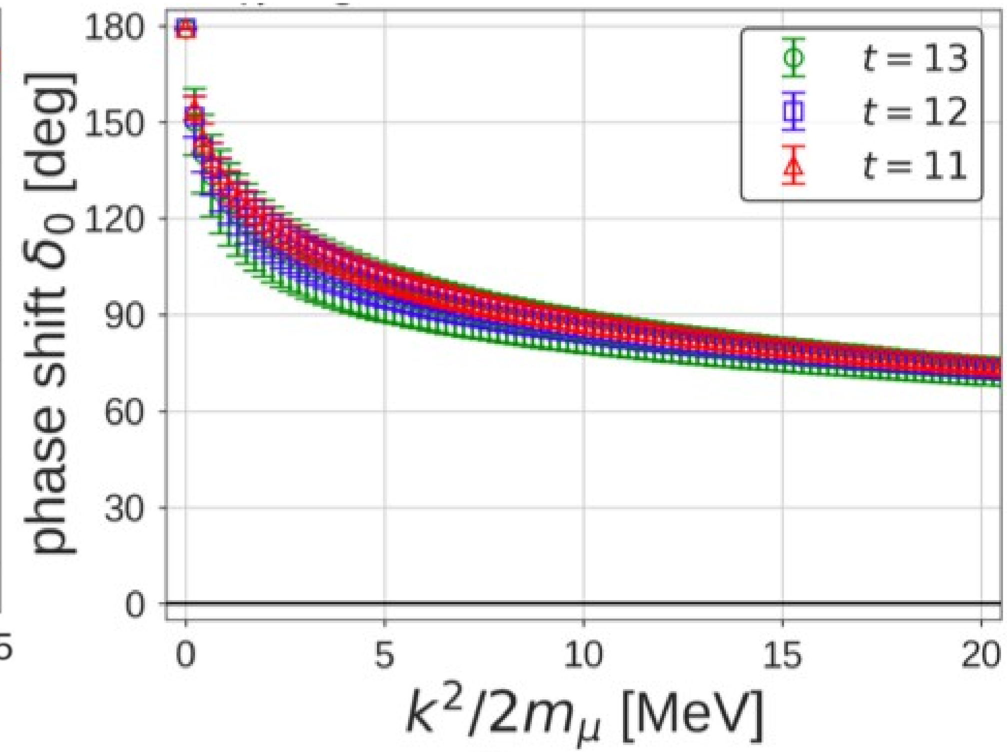


NΩ interaction

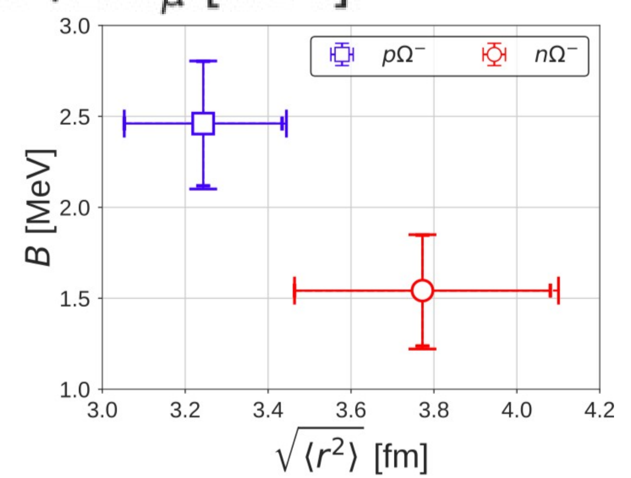
NΩ system $J^p=2^+$ near the physical point

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





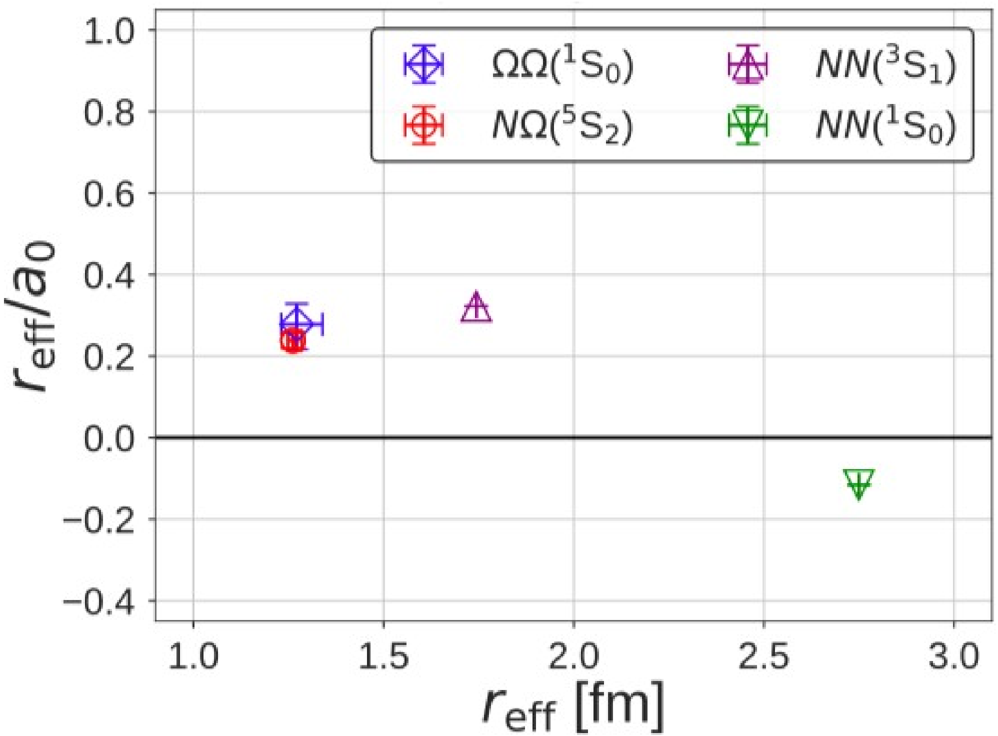
NΩ state decay into ΛΞ (D-wave) state is suppressed.



- **The system is bound (compared to the NΩ threshold) within the errors because of the strongly attractive int.**
  → The doorway to the S=-3 nuclear system.

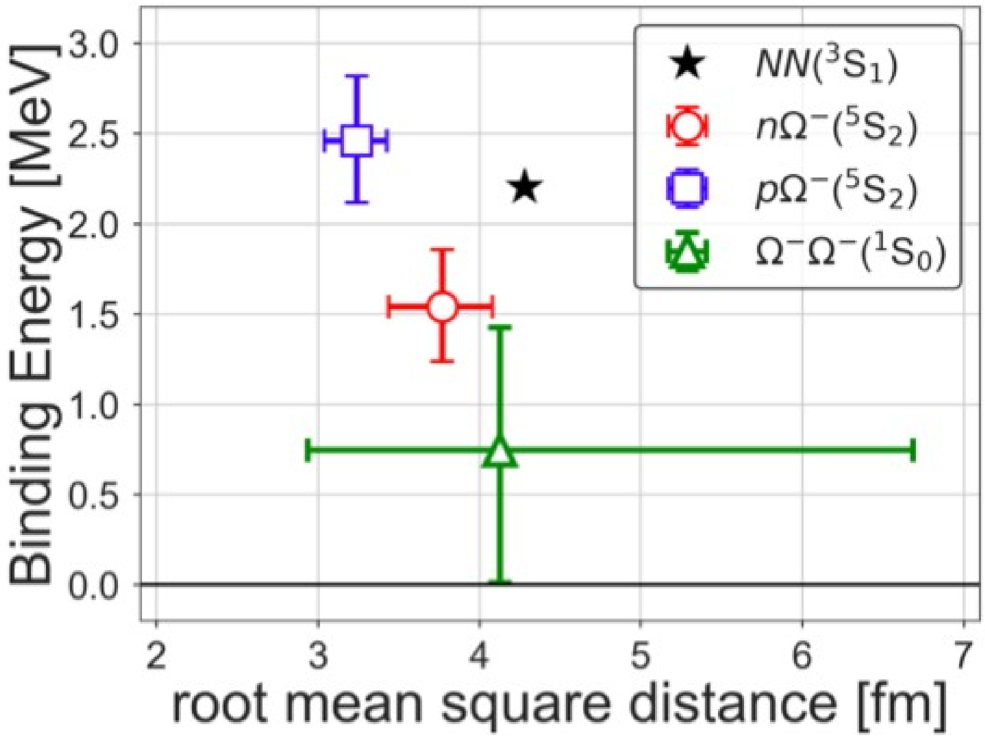
Comparisons of ΩΩ and NΩ system

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



$|r_{eff}/a_0|<<1$

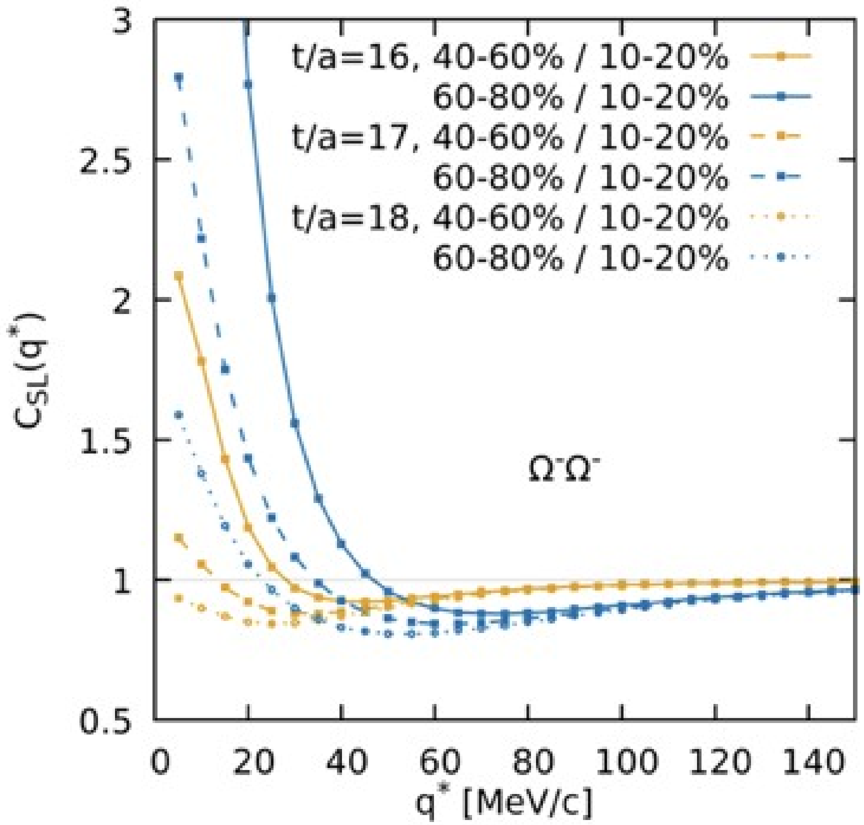
The system is close to the unitary region.

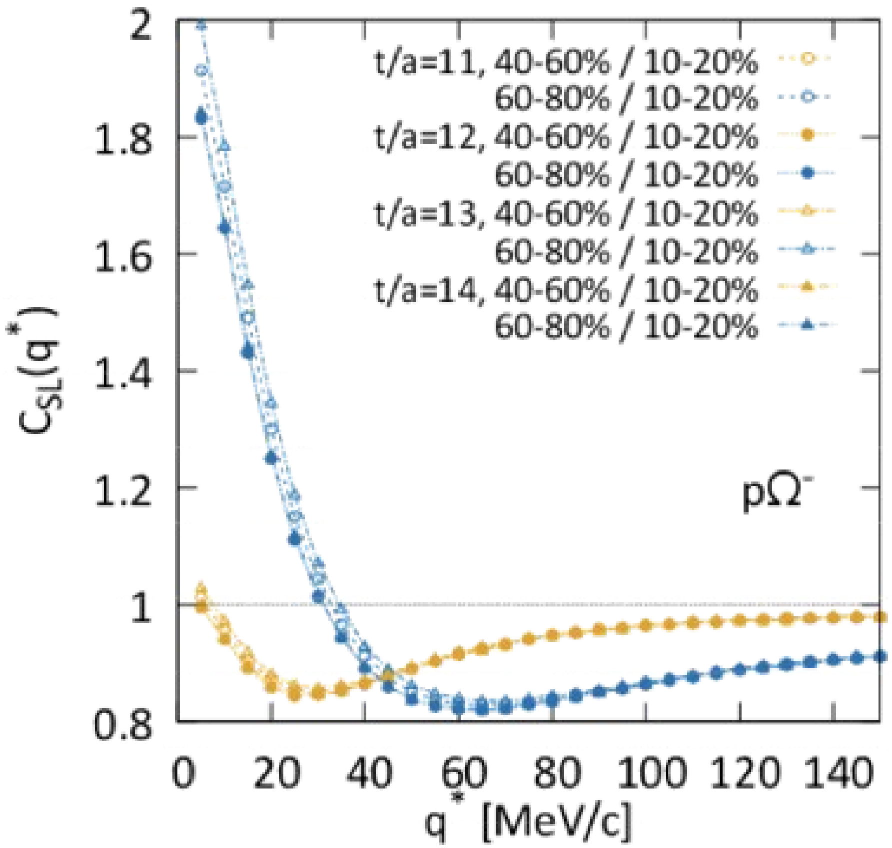


All these systems are similar size and small binding energies

Correlations of ΩΩ and NΩ from HIC

▶ Predicted correlation functions (K. Morita et al. in prep.)





- **Measurements of NΩ and ΩΩ correlations at RHIC and LHC are expected.**

→ **The proton–Ω correlation function in Au+Au collisions**

STAR Collaboration PLB 790 (2019) 490

H-dibaryon channel

Works on H-dibaryon state

Theoretical status

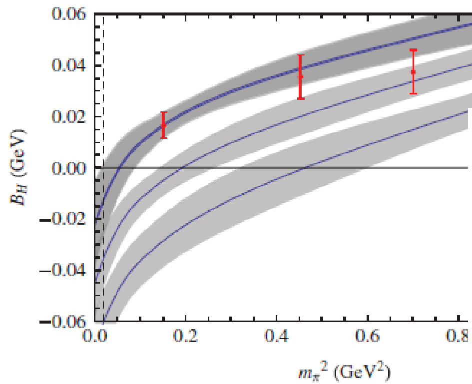
Several sort of calculations and results
(bag models, NRQM, Quenched LQCD….)

There were no conclusive result.

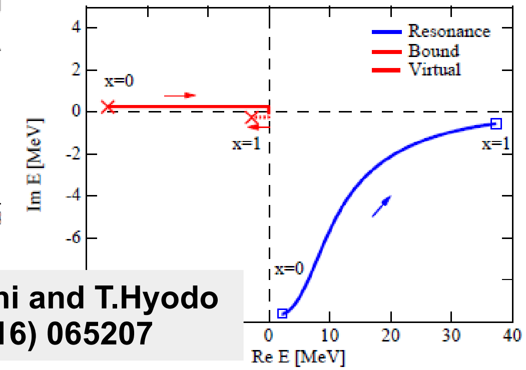
Bound H was found by LQCD with heavy mass

Chiral extrapolations of recent LQCD data

Unbound or resonance



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



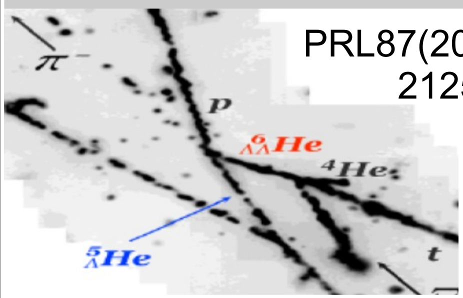
Y.Yamaguchi and T.Hyodo
PRC 94 (2016) 065207

Experimental status

"NAGARA Event"

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

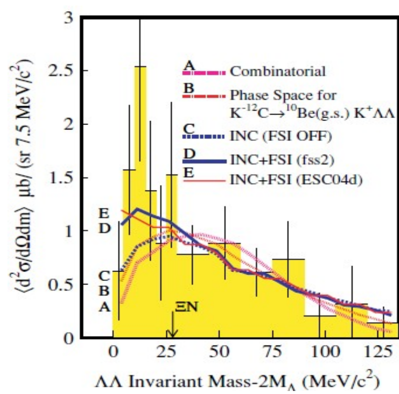
PRL87(2001) 212502



- Deeply bound dibaryon state is ruled out

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

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



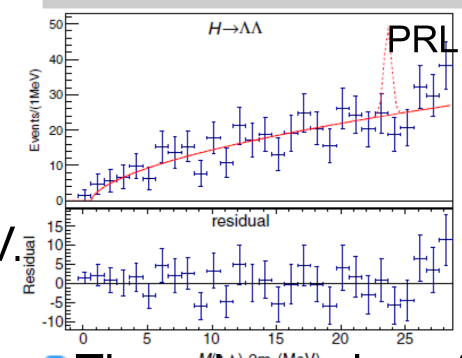
PRC75(2007) 022201(R)

- Significance of enhancements below 30 MeV.

Larger statistics
J-PARC E42

"Υ(1S) and Υ(2S) decays"

B.H. Kim et al Belle Coll.



PRL110(2013) 222002

- There is no sign of near threshold enhancement.

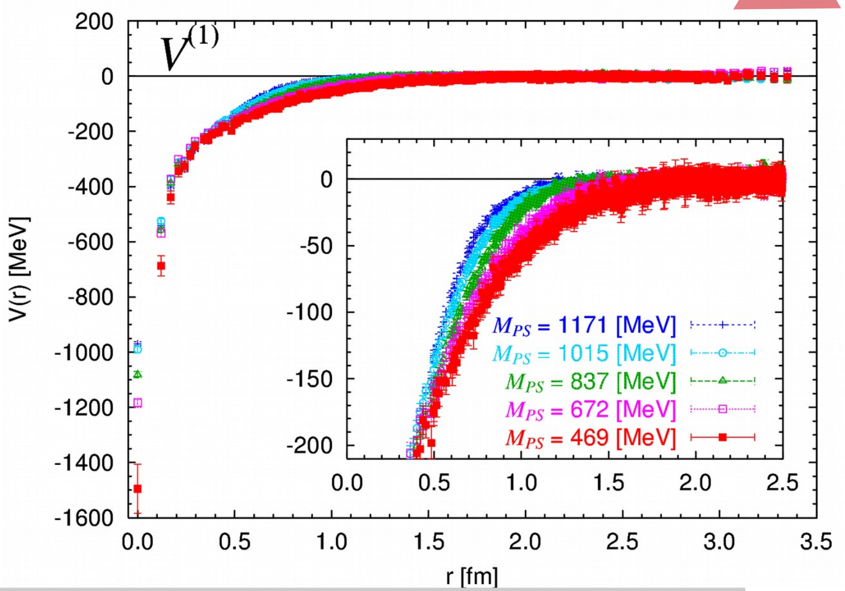
B-B potentials in SU(3) limit

SU(3) classification 8 x 8 = 27 + 8_S + 1 + $\overline{10}$ + 10 + 8_A

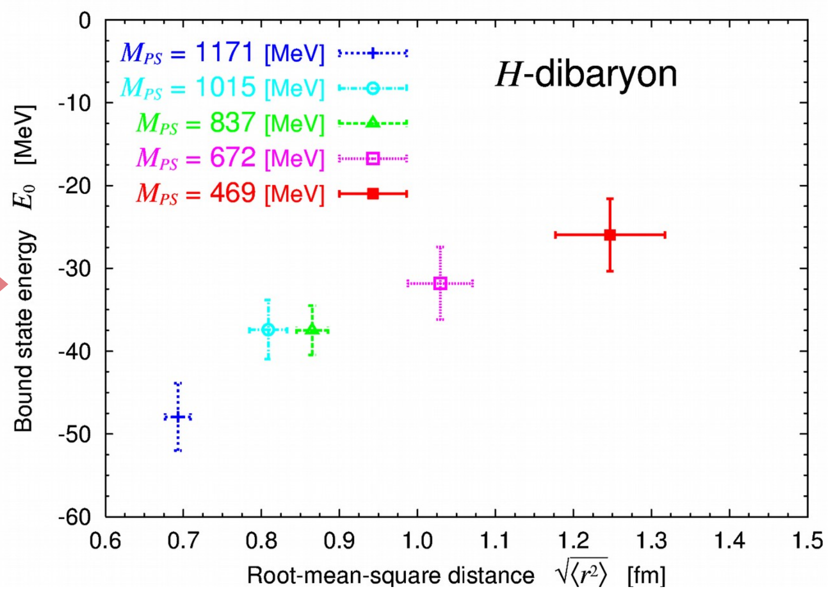
▶ Summary of Pauli blocking effect and Color Magnetic Interaction

	27	8	1	$\overline{10}$	10	8
Pauli	Mixed	forbidden	allowed	Mixed	forbidden	Mixed
CMI	repulsive	repulsive	attractive	repulsive	repulsive	repulsive

M. Oka et al NPA464 (1987)



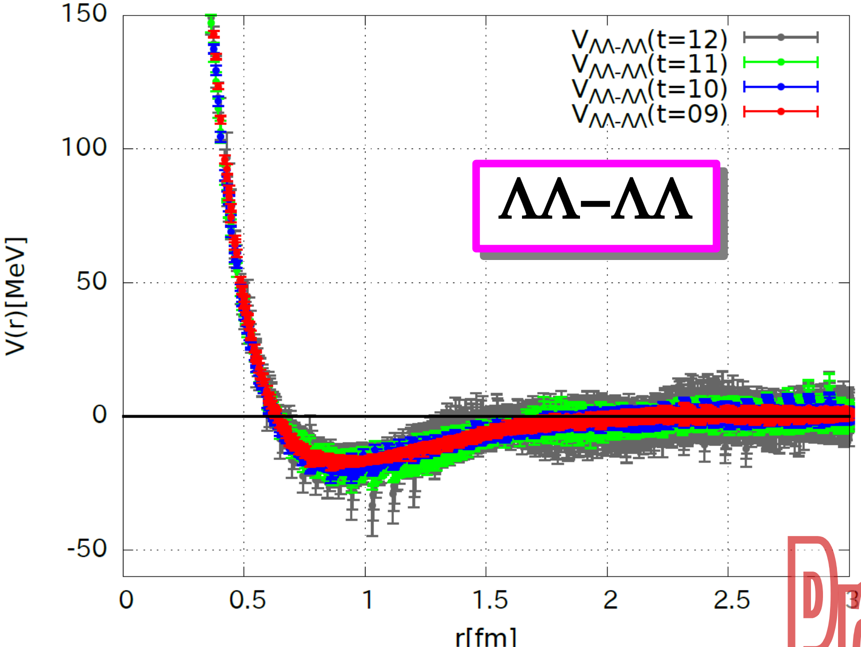
T.Inoue et al[HAL QCD Coll.] NPA881(2012) 28

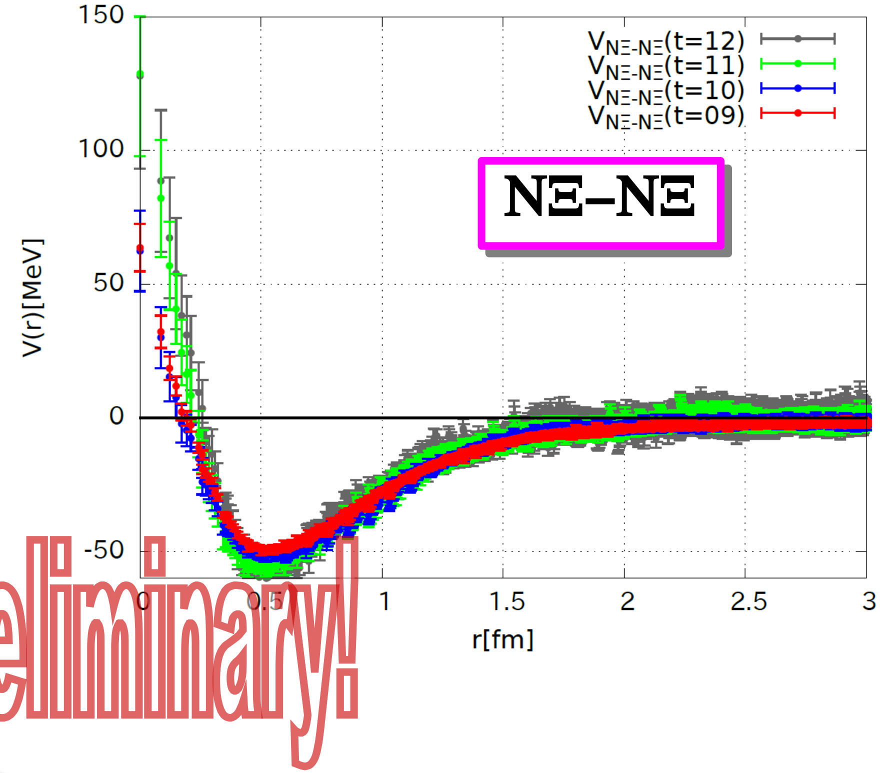


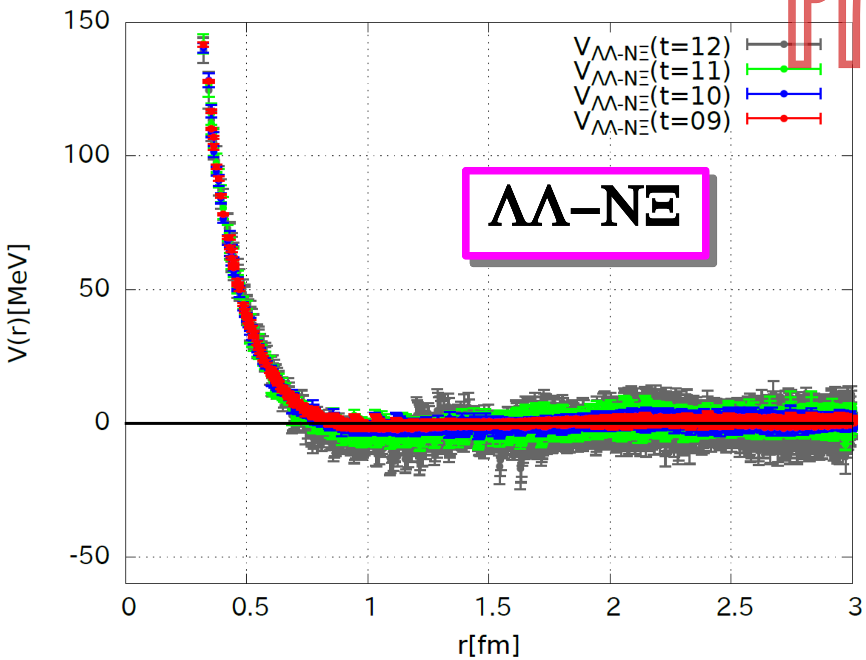
- **Bound state was found in SU(3) environment.**

Go to the physical point simulation!

ΛΛ, NΞ (I=0) $^1S_0$ potential







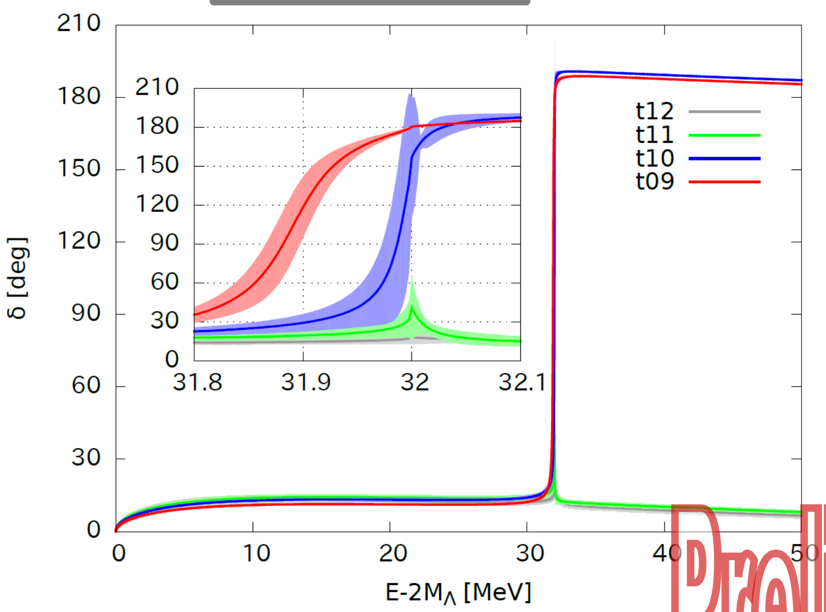
▶ ***Nf = 2+1 full QCD with L = 8.1fm, m_π = 146 MeV***

- **Coupled-channel ΛΛ and NΞ potentials are plotted.**
- **Long range part of potential is almost stable against the time slice.**

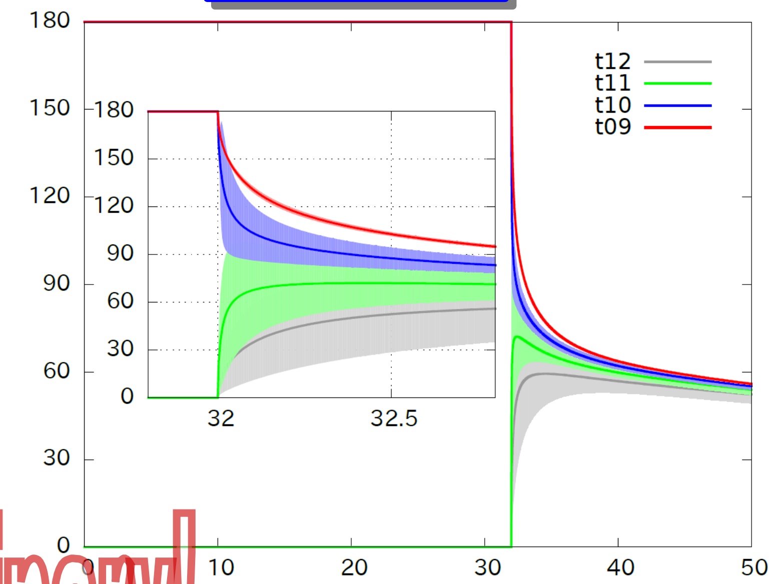
ΛΛ and NΞ phase shift and inelasticity

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

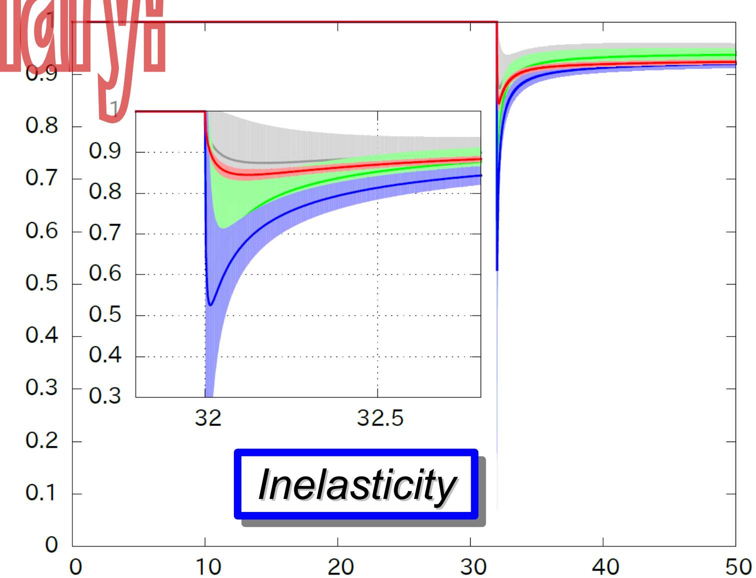
ΛΛ phase shift



NΞ phase shift



Preliminary!



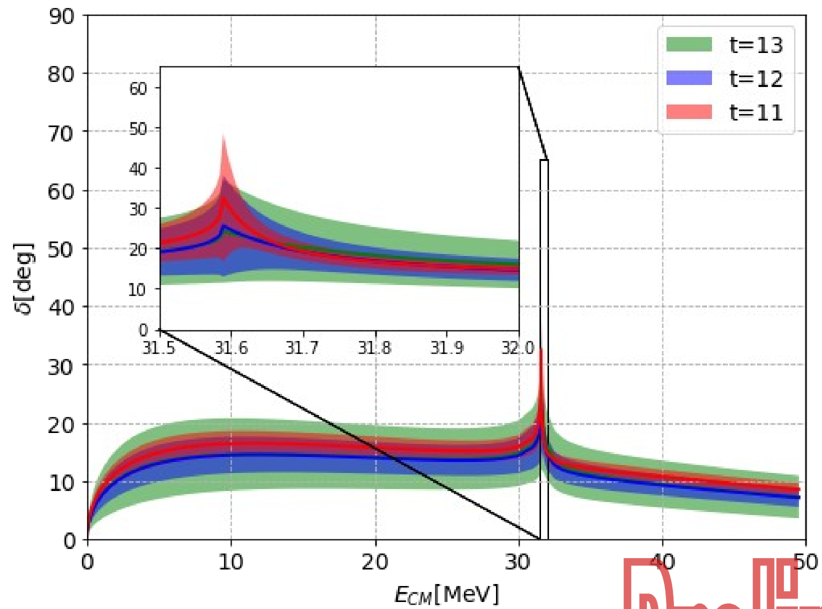
Inelasticity

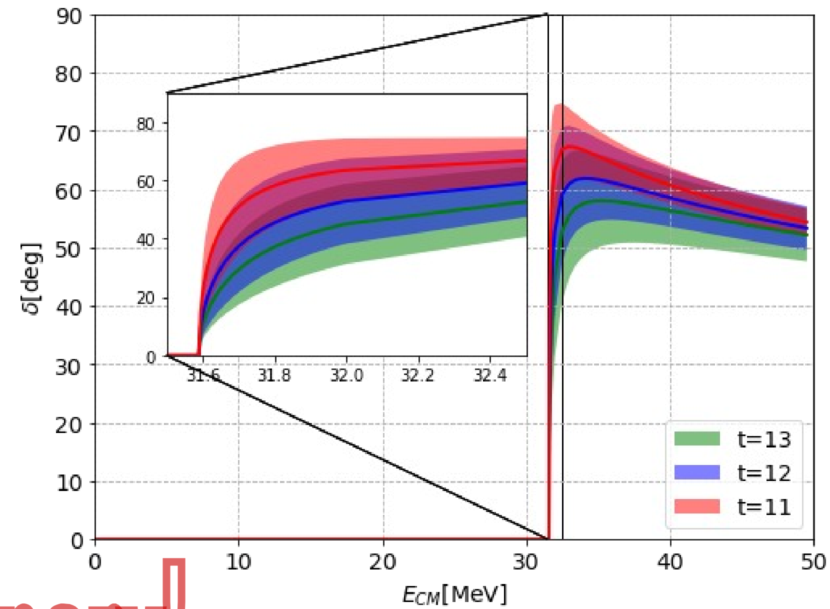
- A sharp resonance is found below the NΞ threshold for t=9 and 10.

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

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

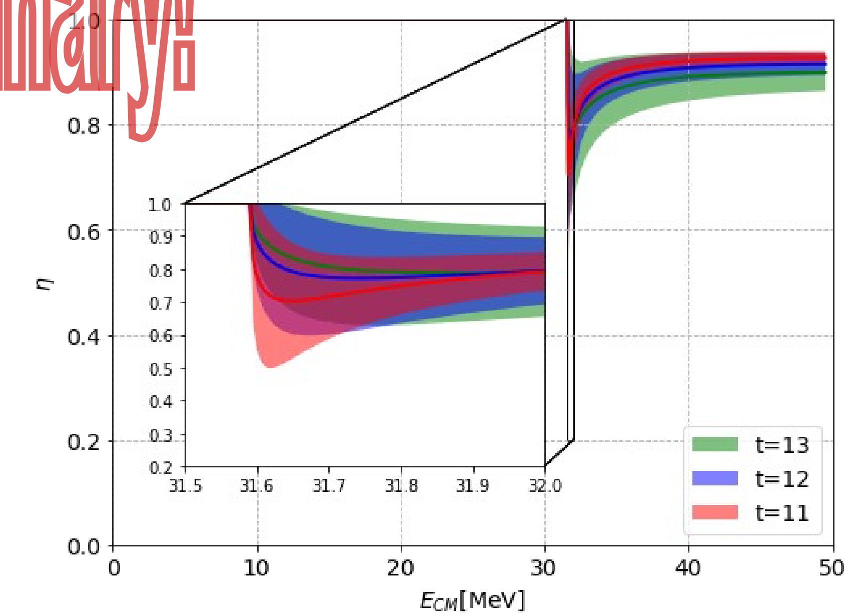
t=11
t=12
t=13





Preliminary!

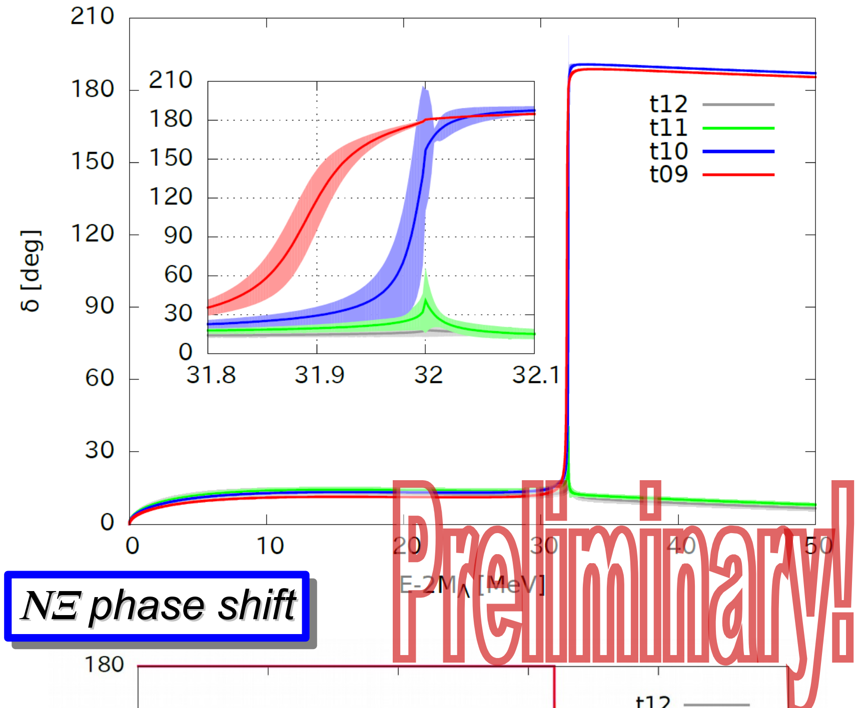
Even at the results at t=13,
we could not find a clear signal
of H-dibaryon resonance.



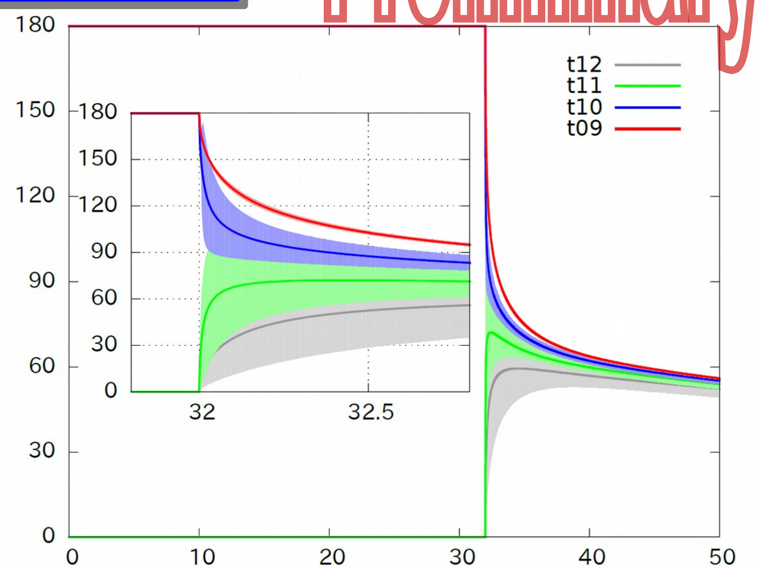
ΛΛ and NΞ phase shift –comparison–

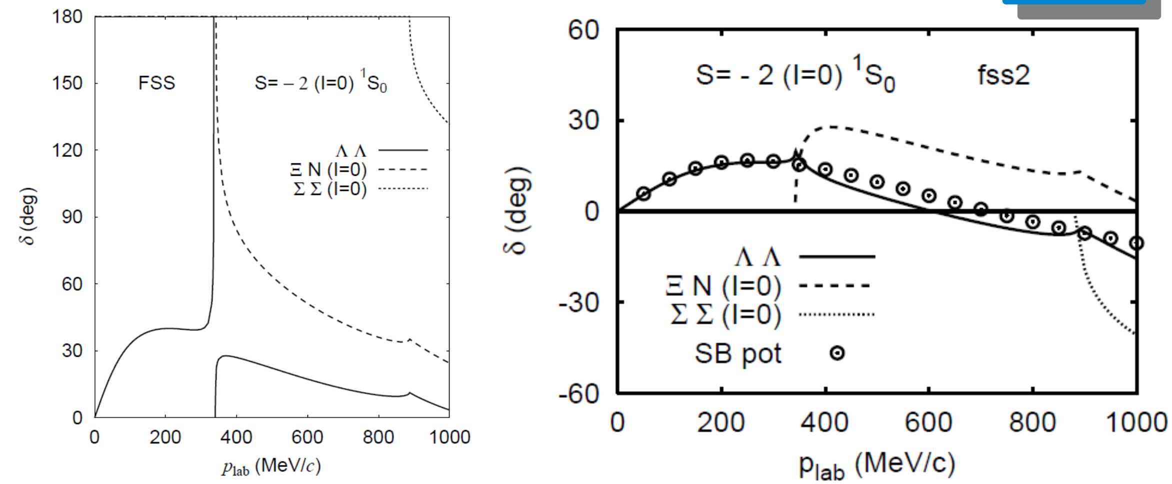
t=09
t=10
t=11
t=12

ΛΛ phase shift

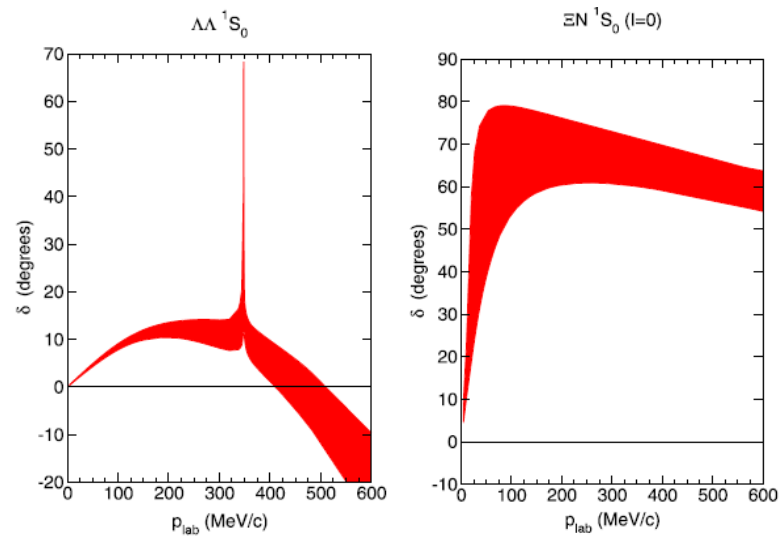


NΞ phase shift





Y.Fujiwara et al, PPNP58(2007)439

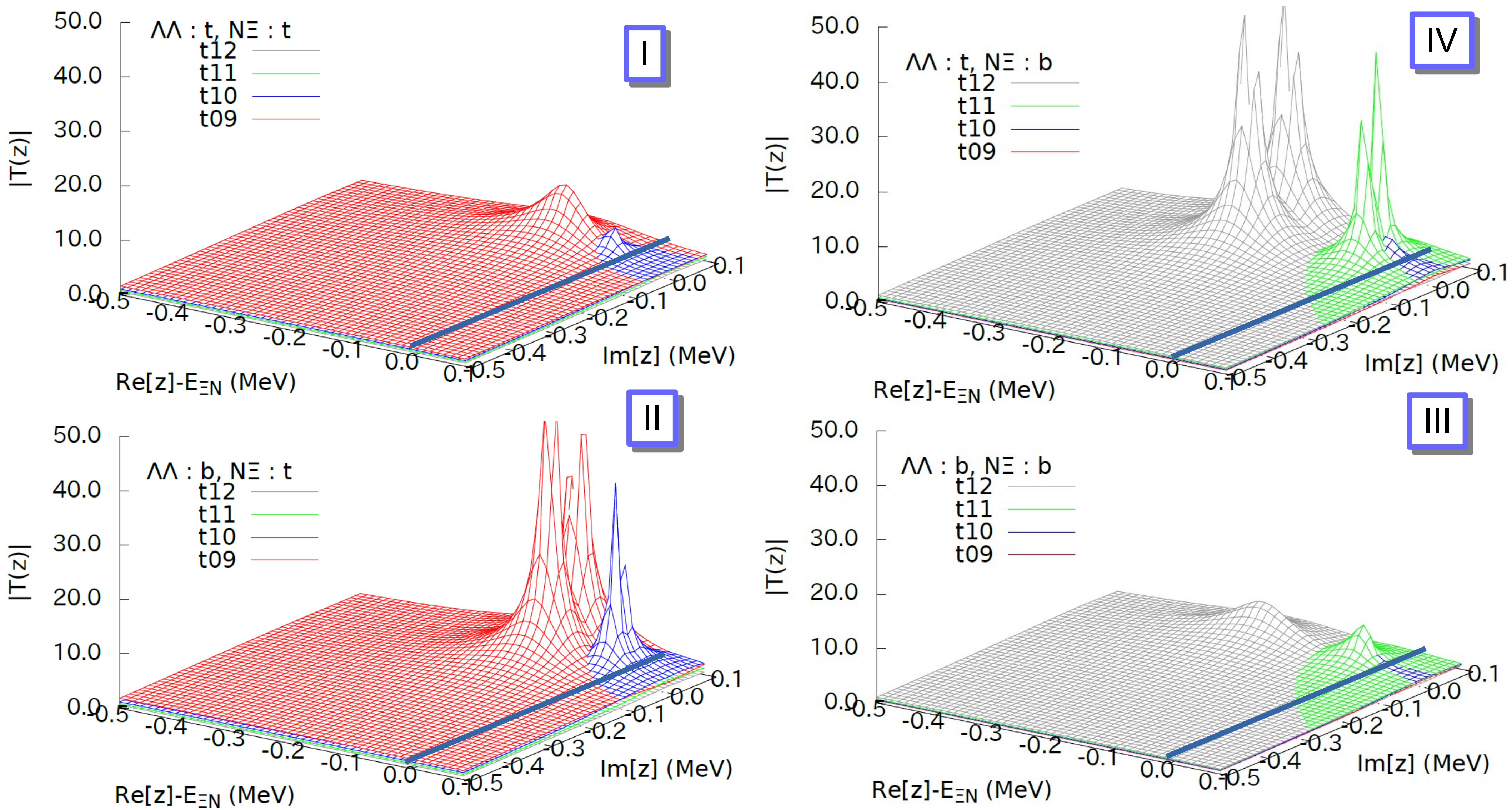


J. Haidenbauer et al, NPA954(2016)273

- **Our results are compatible with the phenomenological ones.**

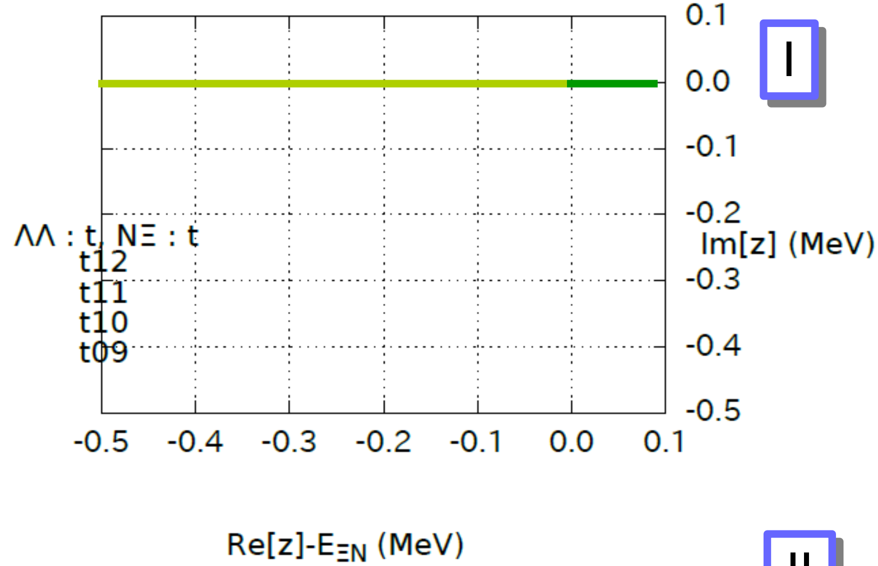
Pole position

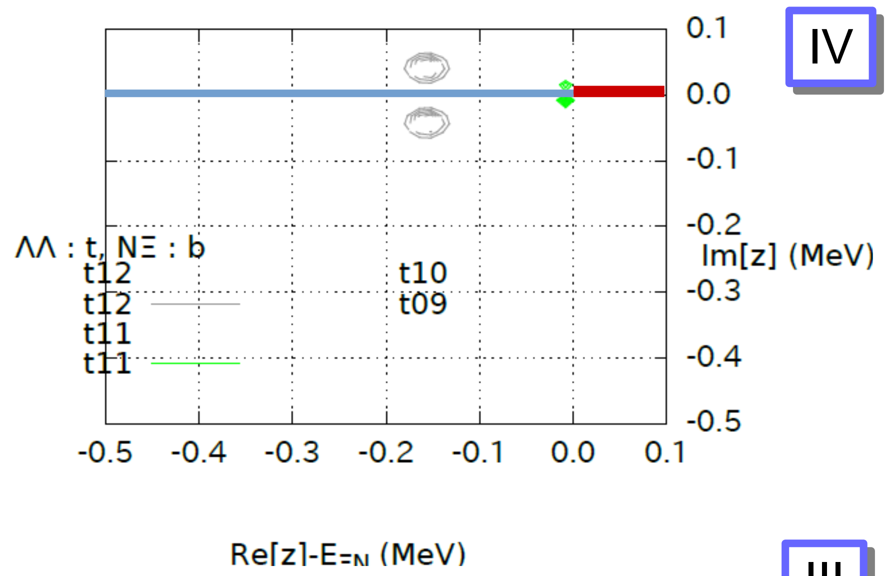
- N_f = 2+1 full QCD with L = 8.1fm, m_π = 146 MeV

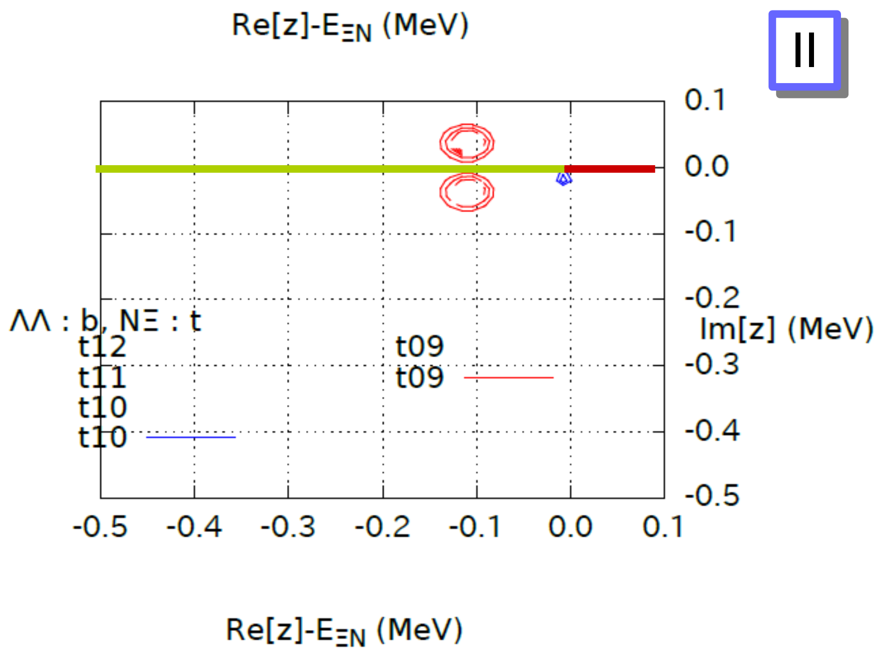


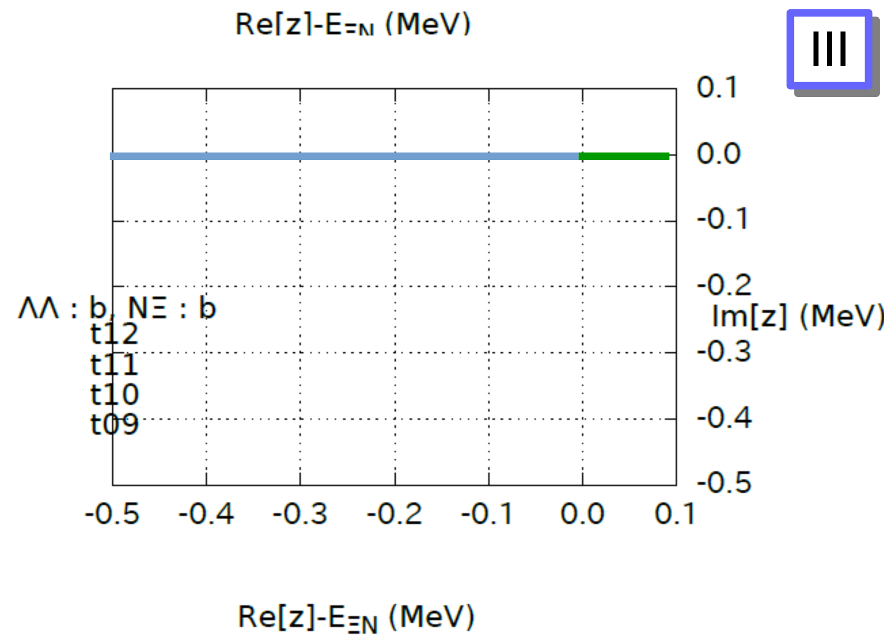
Pole position: contour map

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









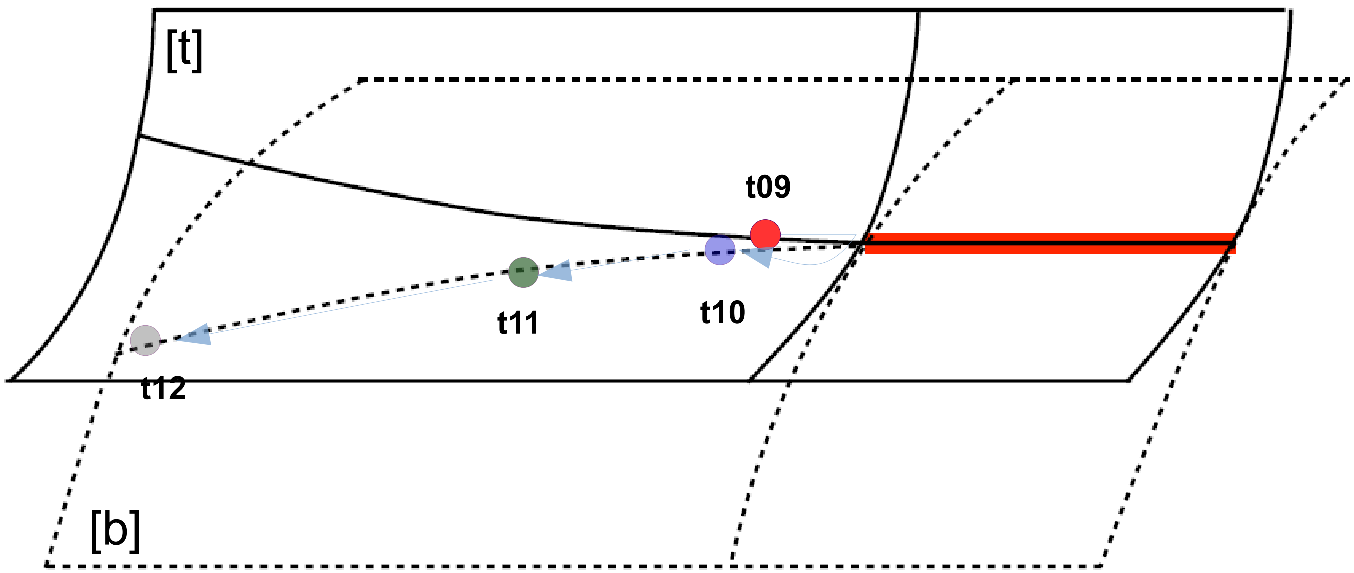
Pole search (from t=09 to t=12) single channel

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

Pole position $Z = E - m_N - m_\Xi$

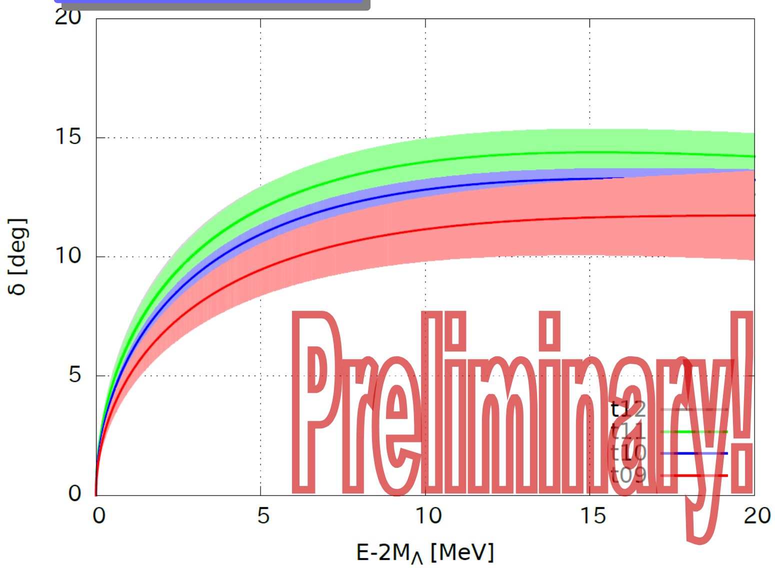
	ΛΛ	NΞ	Re[z] keV	Im[z] keV
t09	---	[t]	-19.21	0.00
t10	---	[b]	-21.34	0.00
t11	---	[b]	-131.87	0.00
t12	---	[b]	-548.40	0.00

Bound state!



ΛΛ scattering length

Phase shift



Λ	550	600	650	700
$a^{\Lambda\Lambda}_{1S0}$	−1.52	−1.52	−1.54	−1.67
$r^{\Lambda\Lambda}_{1S0}$	0.82	0.59	0.31	0.34

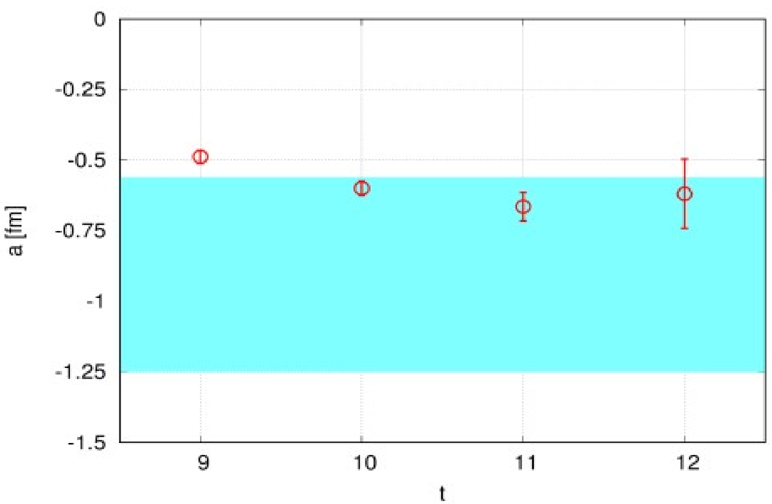
H. Polinder et al, PLB653(2007)29

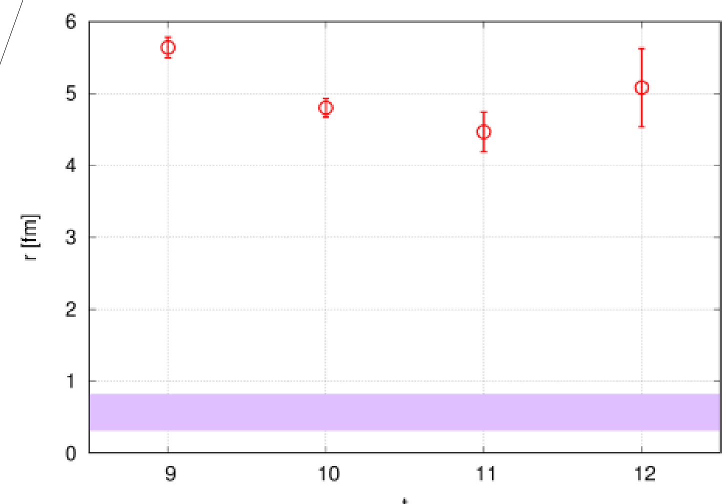
$a_{\Lambda\Lambda}=-0.821$fm — Y.Fujiwara et al, PPNP58(2007)439

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

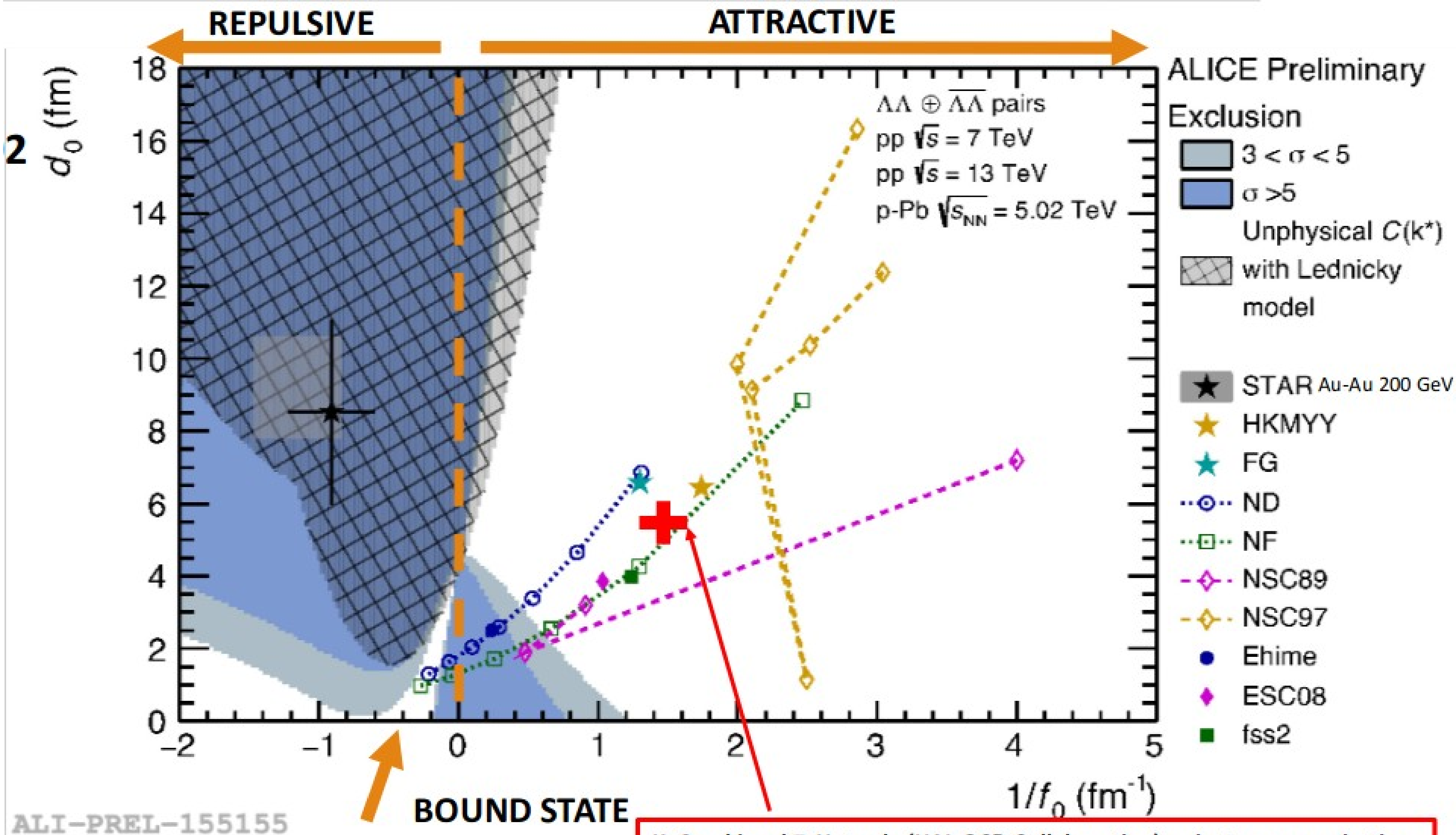
$-1.25 < a_{\Lambda\Lambda} < -0.56$fm — K.Morita et al, PRC91 (2015)024916

Scattering length





ΛΛ scattering length



K. Sasaki and T. Hatsuda (HAL QCD Collaboration), private communication

(STAR data: STAR coll. Phys.Rev.Lett. 114 (2015) no.2,022301)

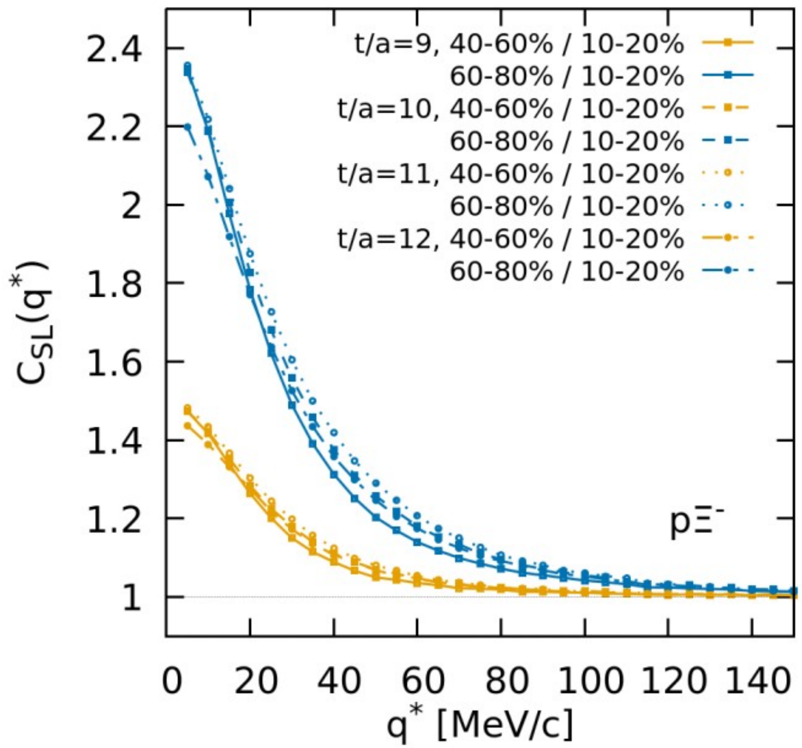
Slide was taken from ALICE COLLABORATION in QNP18 Satellite Workshop (Tokai)

$p\Xi^-$ correlation in HIC

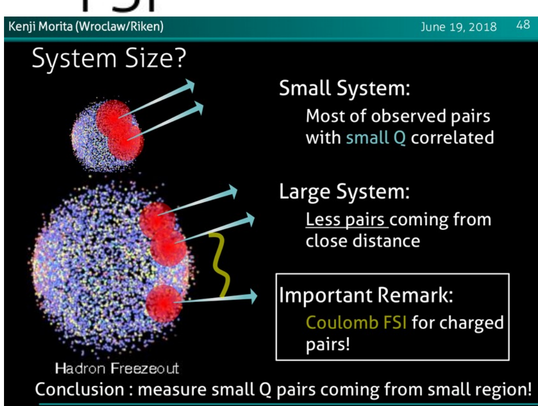
Kenji Morita (Wroclaw/Riken) June 19, 2018 42

$p\Xi^-$ Correlation

$$|\varphi_{p\Xi^-}^{\text{spin-averaged}}|^2 = \sum_{I=0}^{1} \frac{1}{8}|\varphi^I(^1S_0)|^2 + \frac{3}{8}|\varphi^I(^3S_1)|^2$$



Unitary regime: Notable enhancement by FSI



NFQCD2018@YITP

Summary

- We have investigated dibaryon candidate states from LQCD

  - ΔΔ and ΩΩ states
    - 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.
    - Physical point result for ΩN channel shows that interaction is attractive enough to form the bound state.

  - 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.