Search for H-dibaryon from Lattice QCD

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for HAL QCD Collaboration

HAL (Hadrons to Atomic nuclei from Lattice) QCD Collaboration

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Y. Ikeda (*RCNP*)	**T. Inoue** (*Nihon U.*)	**N. Ishii** (*RCNP*)	**T. Iritani** (*RIKEN*)	**T. Miyamoto** (*YITP*)
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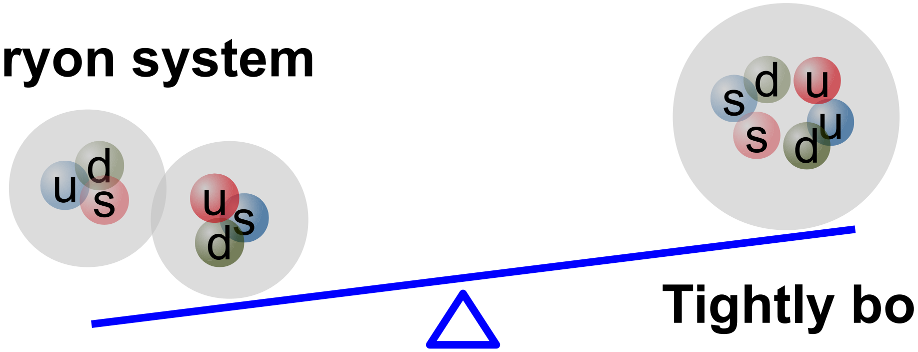
H-dibaryon

- ***What is H-dibaryon?***

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

Free two-baryon system



Tightly bound 6q system

$$V^{CMI}_{OGE} \propto \left\langle \frac{1}{m_{qi} m_{qj}} \lambda_i \cdot \lambda_j \sigma_i \cdot \sigma_j \right\rangle f\left(r_{ij}\right)$$

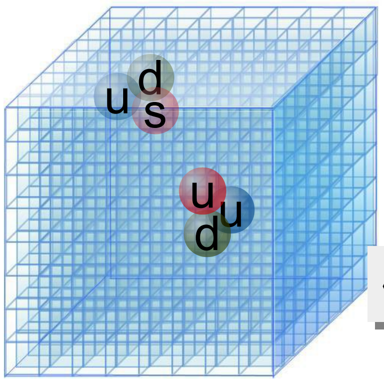
- **Strongly attractive**
  Color Magnetic Interaction.

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

We want to look for H-dibaryon by using LQCD simulation

Hadron interaction from LQCD

Lattice QCD simulation

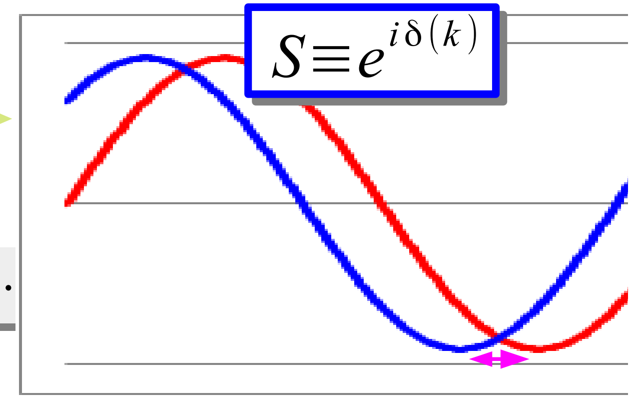


HAL QCD method

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

Scattering S-matrix

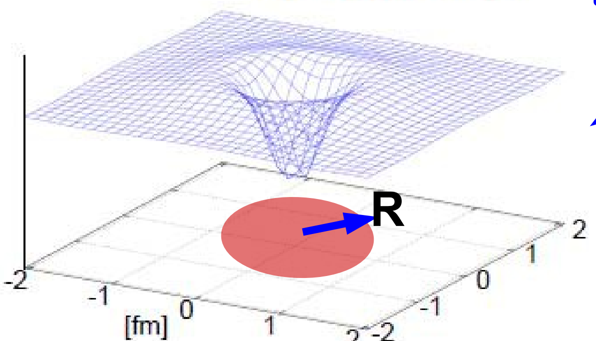
$$S \equiv e^{i\delta(k)}$$



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

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

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.

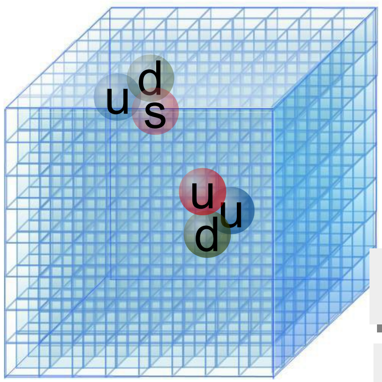
- **Inside of "interacting region"**

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

- **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.**

Hadron interaction from LQCD

Lattice QCD simulation



HAL QCD method

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

Scattering S-matrix

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

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

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

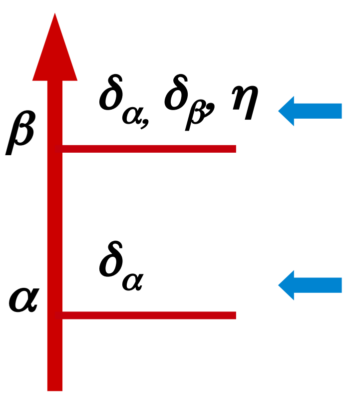
NBS wave function for each channel

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

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

Coupled-channel Schrödinger equation

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



$\Psi^{\alpha}_{sc}(\vec{r}),\ \Psi^{\beta}_{sc}(\vec{r})$

$\Psi^{\alpha}_{sc}(\vec{r})$

- **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.**

Time-dependent HAL QCD method

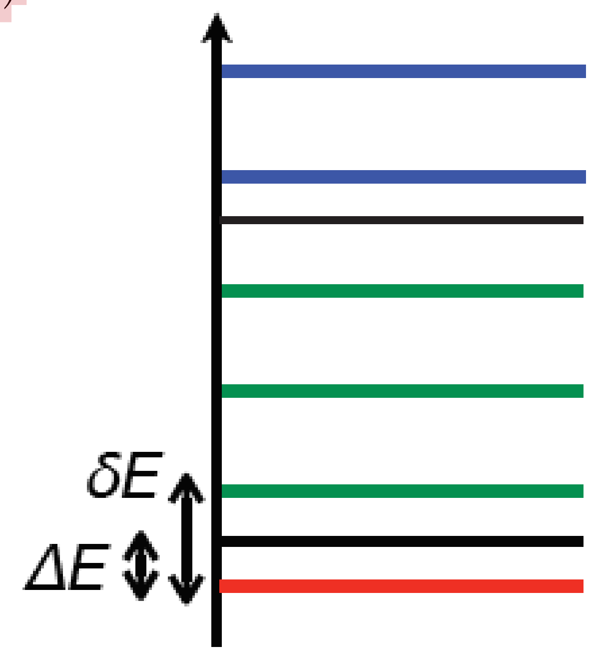
Considering the normalized four-point correlator,

$$R_I^{B_1 B_2}(t,\vec{r}) = F^{B_1 B_2}{}_I(t,\vec{r})\, e^{(m_1+m_2)t}$$
$$= A_0 \Psi(\vec{r},E_0) e^{-(E_0-m_1-m_2)t} + A_1 \Psi(\vec{r},E_1) e^{-(E_1-m_1-m_2)t} + \cdots$$

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

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

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



A single state saturation is not required!!

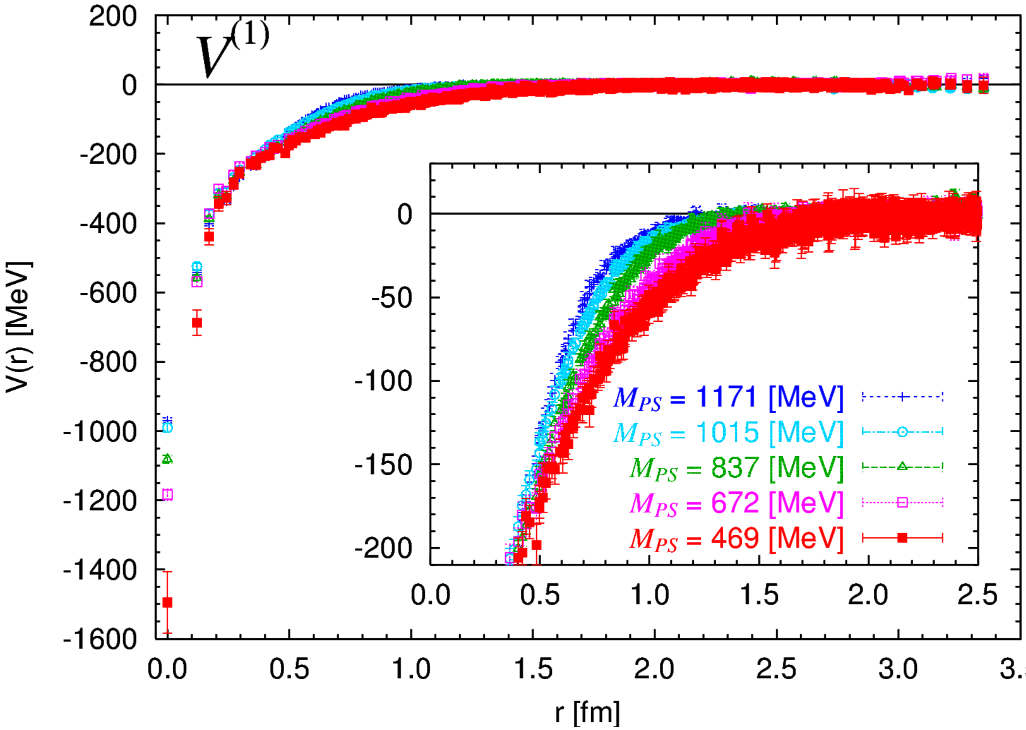
$$\left(-\frac{\partial}{\partial t}+\frac{\nabla^2}{2\mu}\right) R_I^{B_1 B_2}(t,\vec{r}) = \int U(\vec{r},\vec{r}\,') R_I^{B_1 B_2}(t,\vec{r}\,)\,d^3r'$$

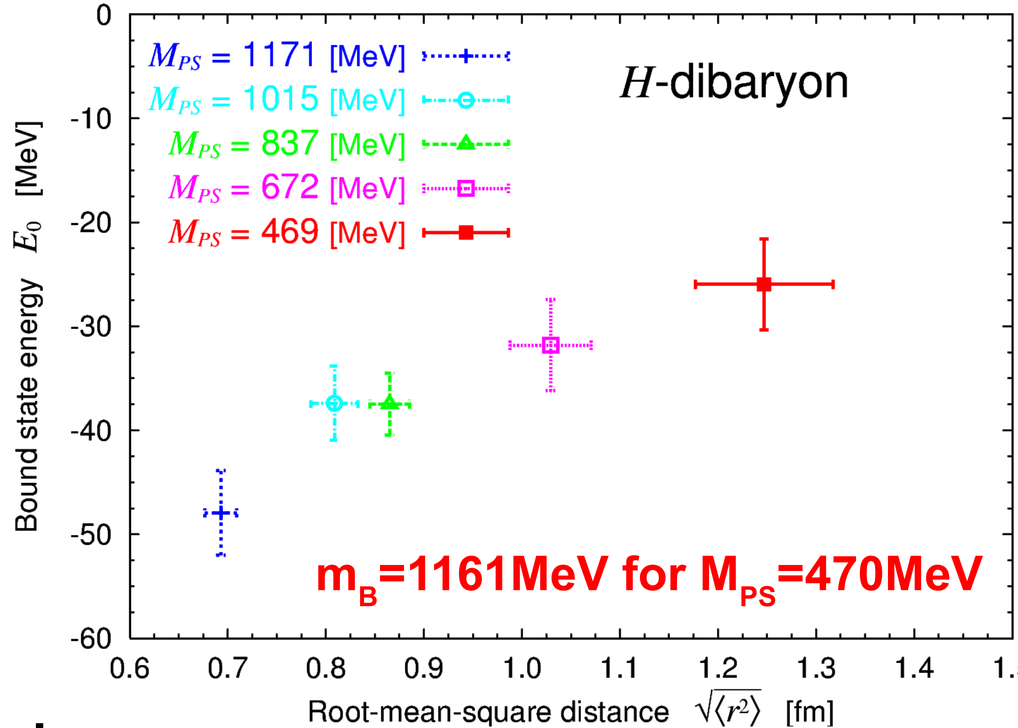
All elastic energies contribute as a signal of energy indep. pot.

Derivative (velocity) expansion of U

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

Searching for H-dibaryon in SU(3) limit





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

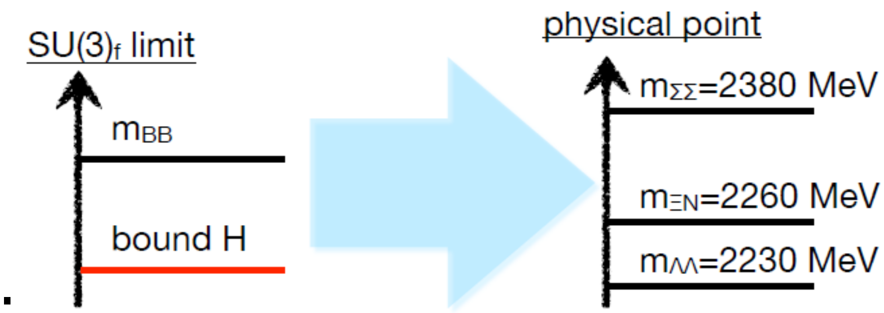
- **Strongly attractive potential was found in the flavor singlet channel.**
- **Short range attraction is consistent with consistent quark model.**

	1
Pauli	allowed
CMI	attractive

M. Oka et al NPA464 (1987)

- **Bound state was found in this mass range.**

What happens at the physical point?



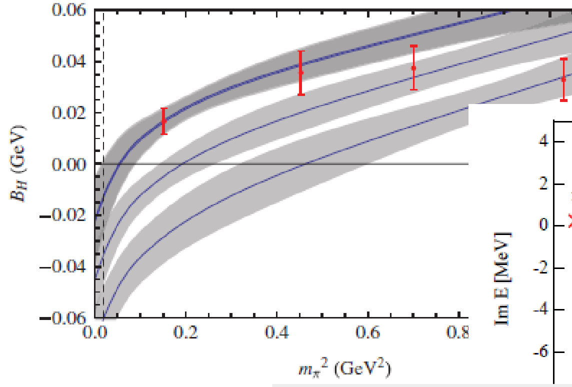
Works on H-dibaryon state

Theoretical status

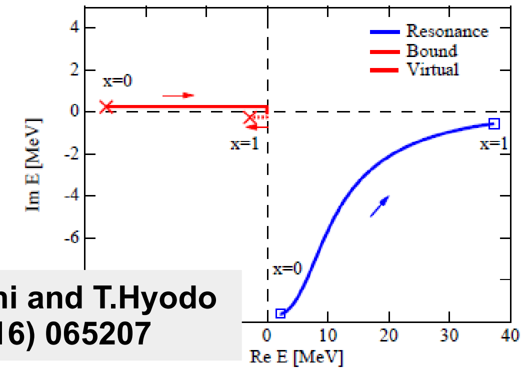
Several sort of calculations and results (bag models, NRQM, Quenched LQCD….)

There were no conclusive result.

Chiral extrapolations of recent LQCD data



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



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

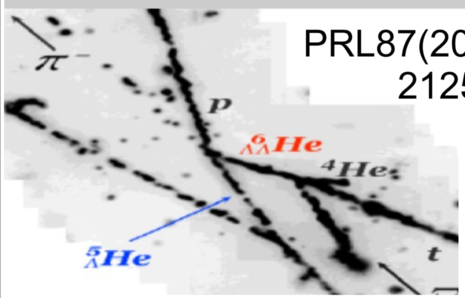
Unbound or resonance

Experimental status

"NAGARA Event"

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

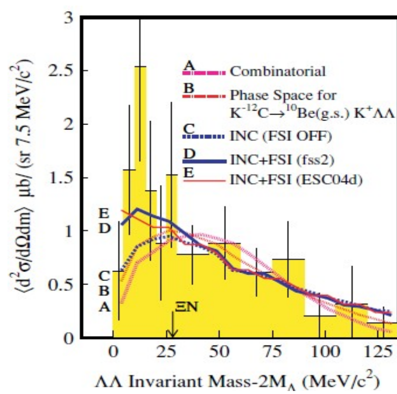
PRL87(2001) 212502



- Deeply bound dibaryon state is ruled out

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

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



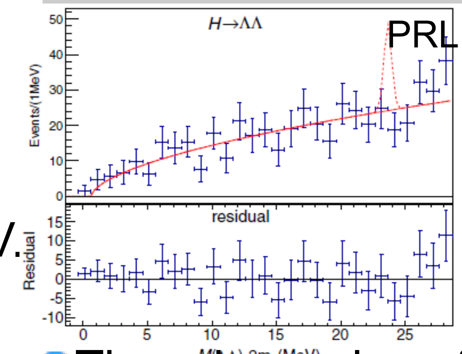
PRC75(2007) 022201(R)

- 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

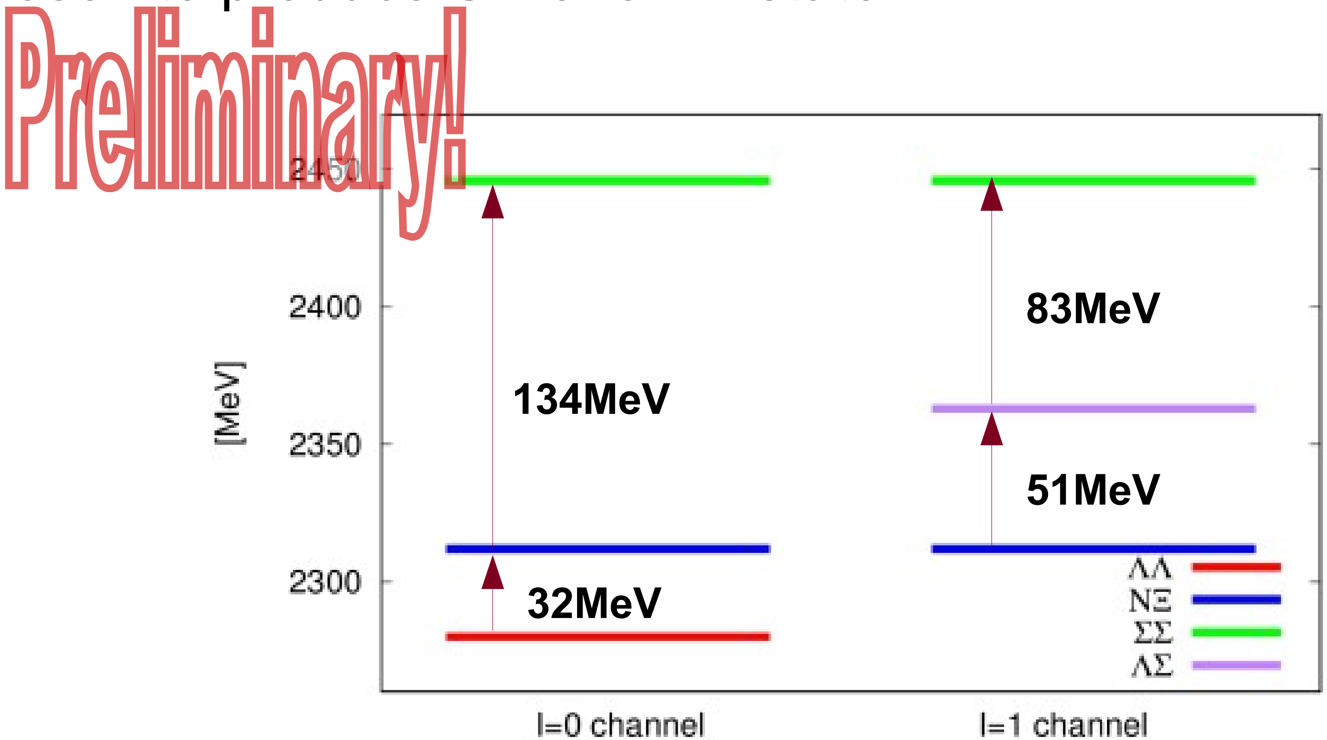
- There is no sign of near threshold enhancement.

Numerical setup

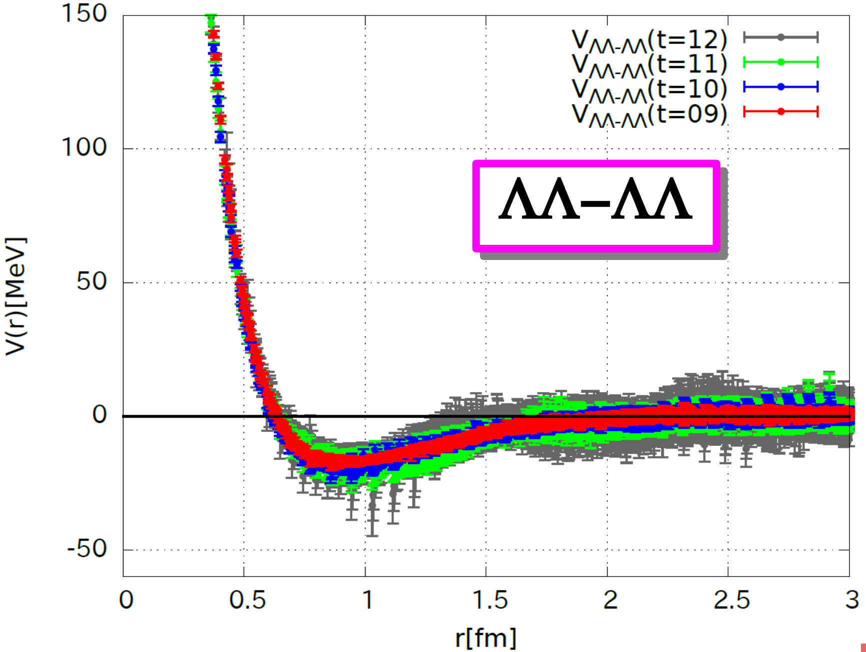
- 2+1 flavor gauge configurations.
  - Iwasaki gauge action & O(a) improved Wilson quark action
  - a = 0.084 [fm], a^{-1} = 2.333 GeV.
  - 96^3x96 lattice, L = 8.12 [fm].
  - 414 confs x 96 sources x 4 rotations.

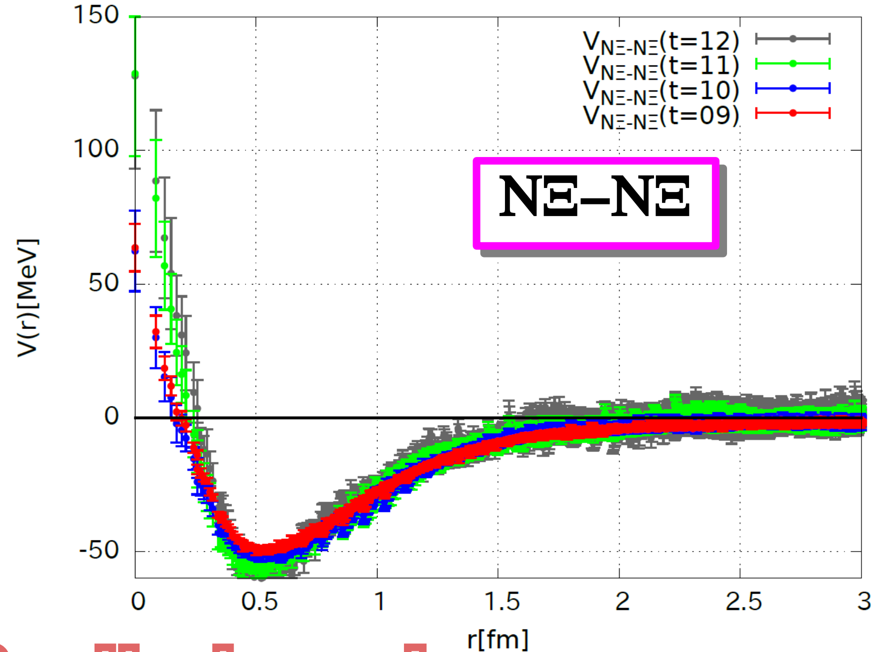
- Wall source is chosen to produce S-wave BB state.

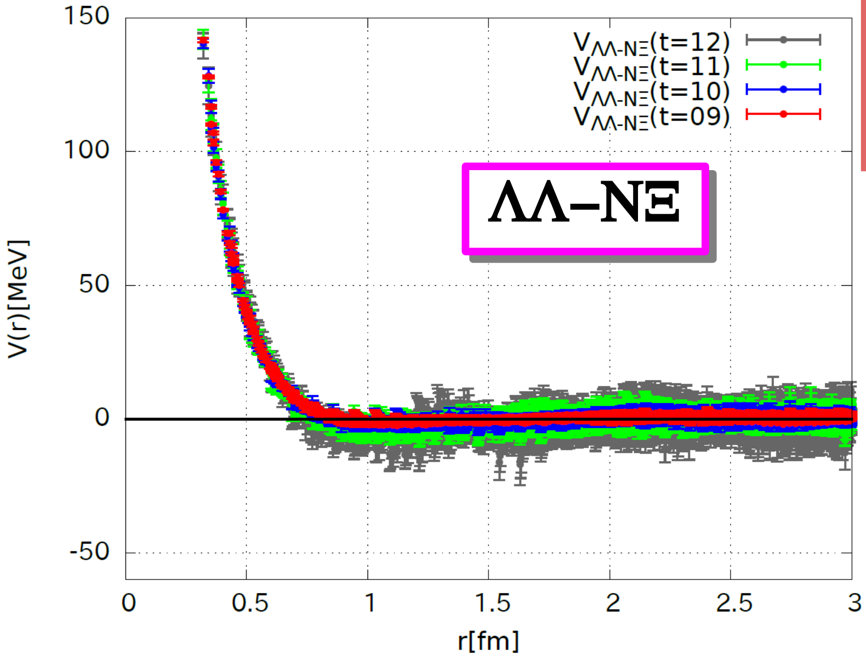
	Mass [MeV]
π	146
K	525
m_p/m_K	0.28
N	958±3
Λ	1140±2
Σ	1223±2
Ξ	1354±1



ΛΛ, NΞ (I=0) $^1S_0$ potential







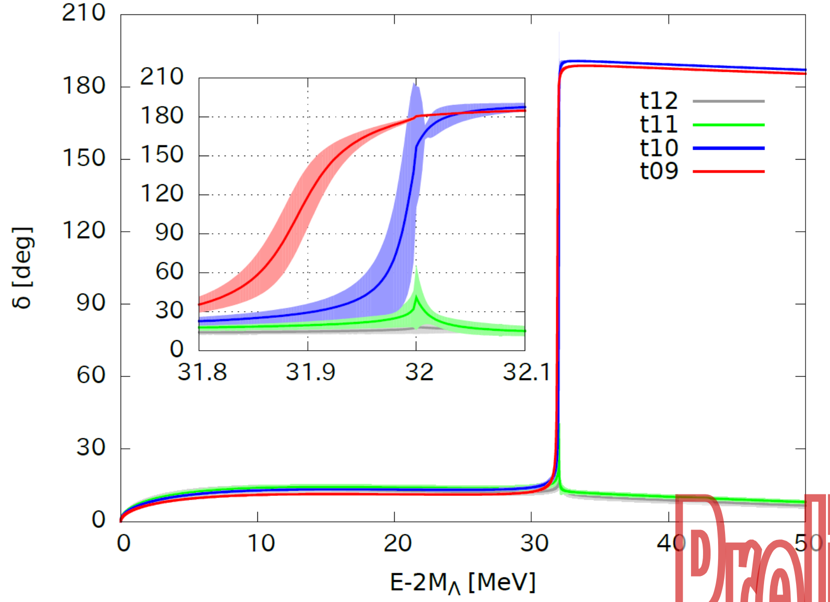
Preliminary!

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

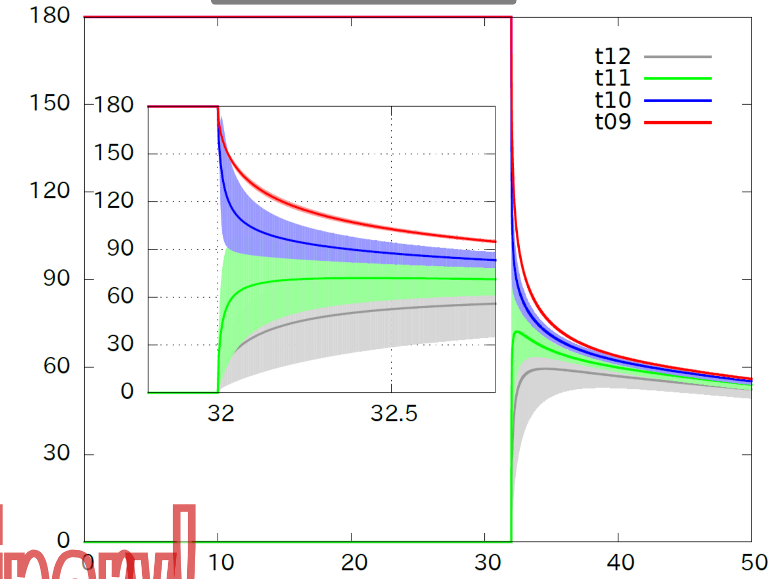
ΛΛ and NΞ phase shift and inelasticity

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

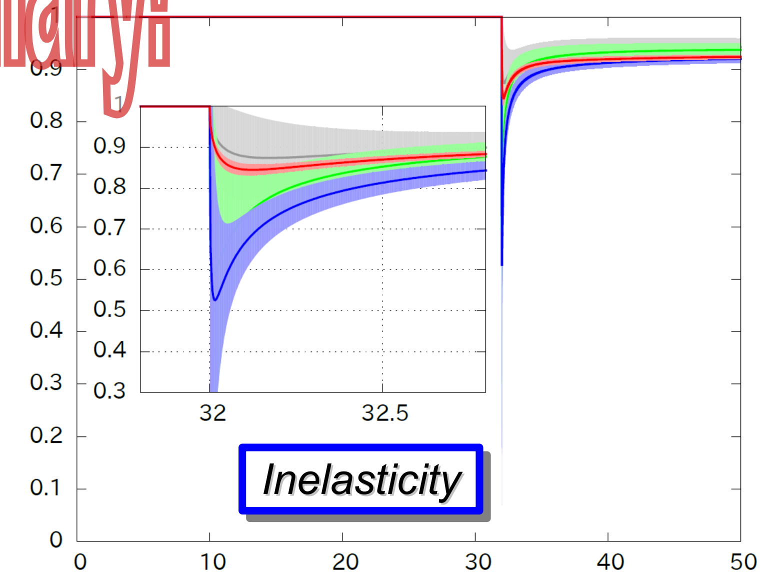
ΛΛ phase shift



NΞ phase shift



Preliminary!



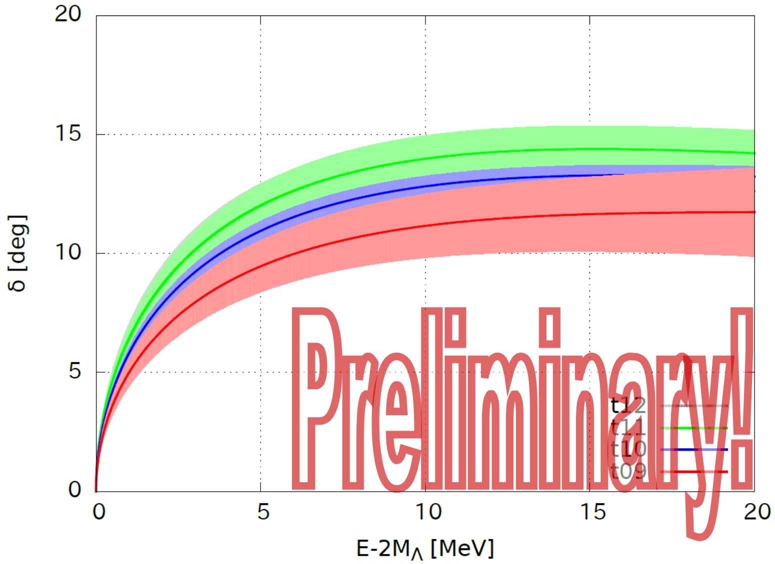
Inelasticity

- **Shape of ΛΛ and NΞ phase shifts drastically change as lattice time "t".**
- **A sharp resonance is found below the NΞ threshold for t=9 - 10.**

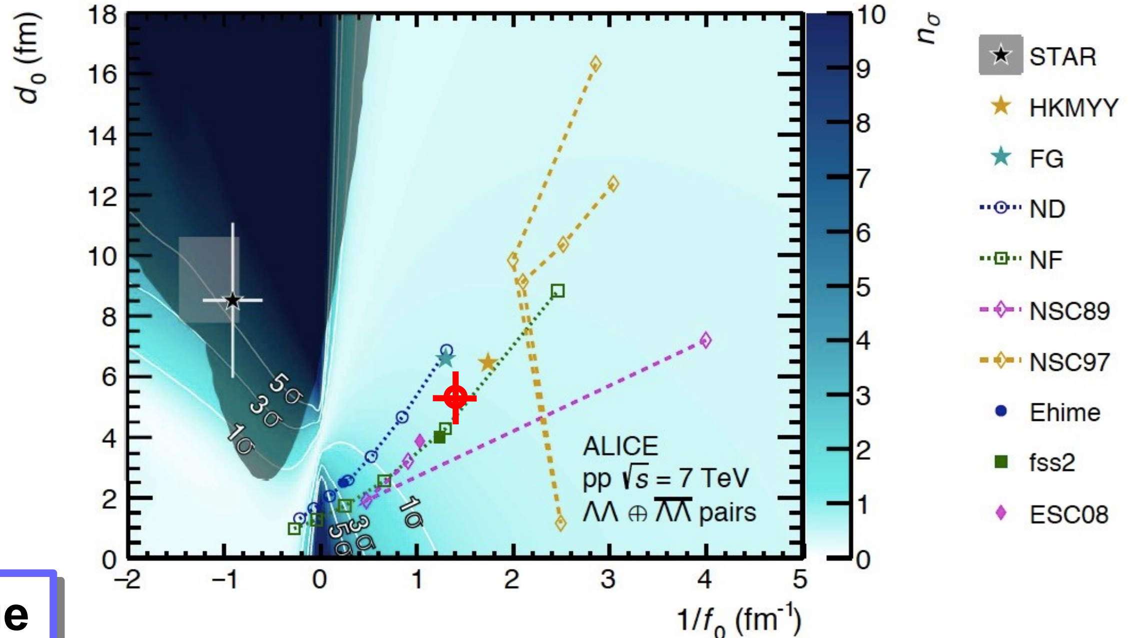
ΛΛ scattering length

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

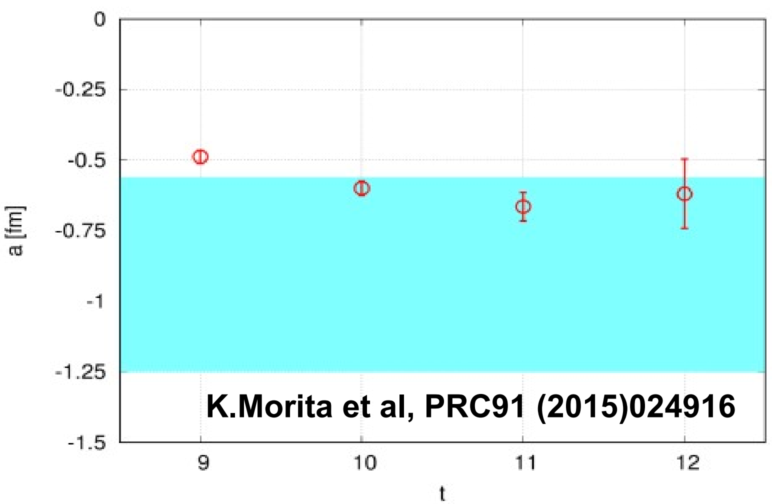
Phase shift

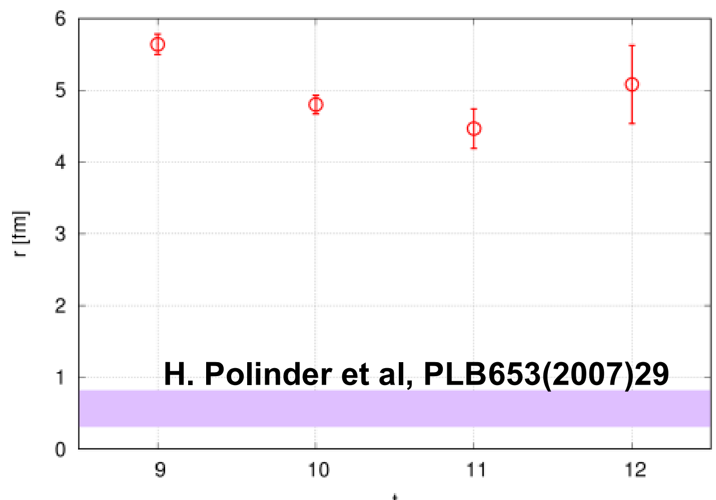


ALICE Coll., arXiv:1805.12455
http://alice-publications.web.cern.ch/node/4445



Scattering length and effective range





$a_{\Lambda\Lambda}$=−0.821fm

Y.Fujiwara et al, PPNP58(2007)

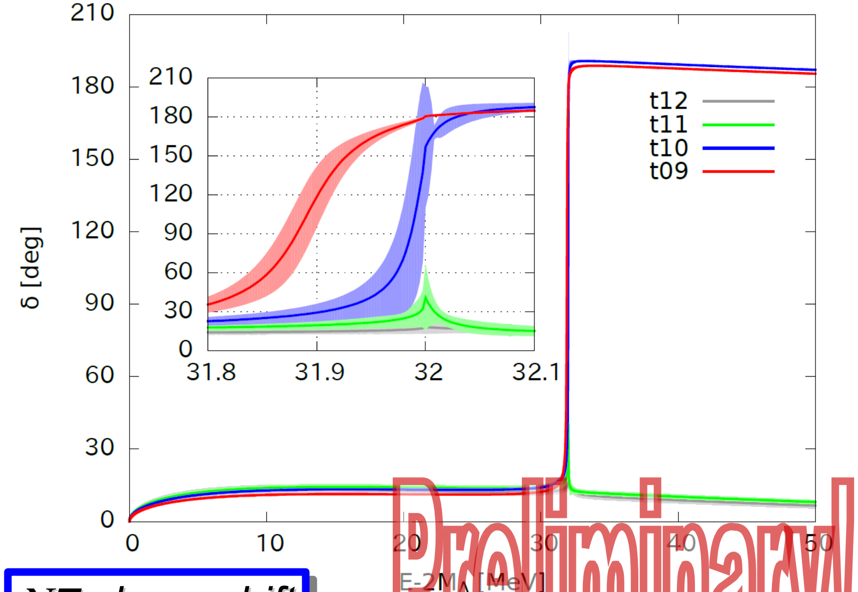
$a_{\Lambda\Lambda}$=−0.97fm

Th.A.Rijken et al, FB Syst 54(2013)

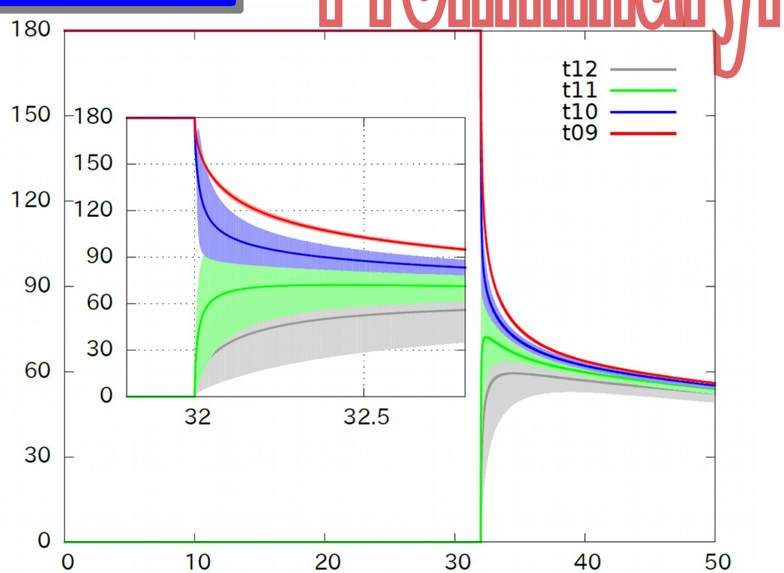
ΛΛ and NΞ phase shift –comparison–

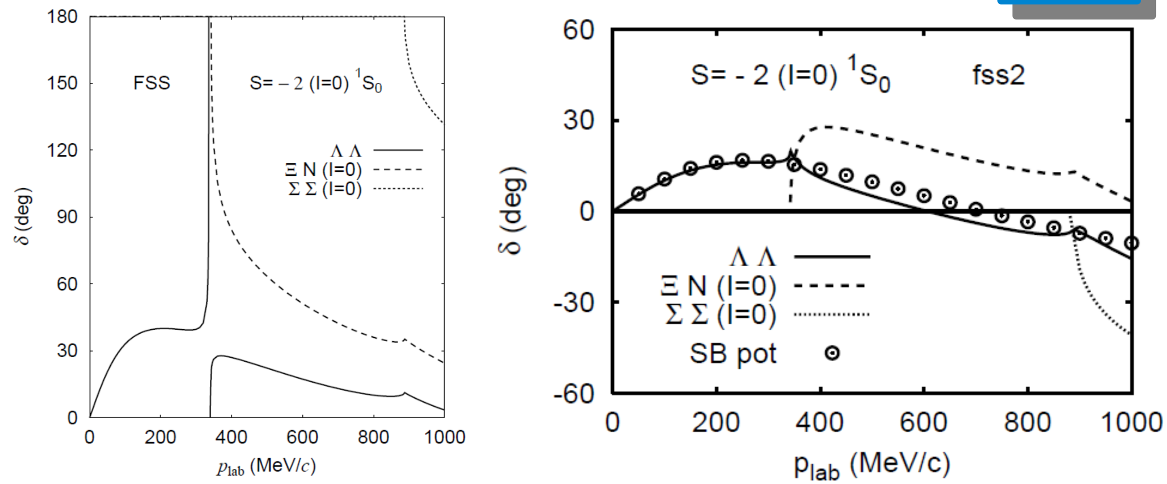
t=09
t=10
t=11
t=12

ΛΛ phase shift

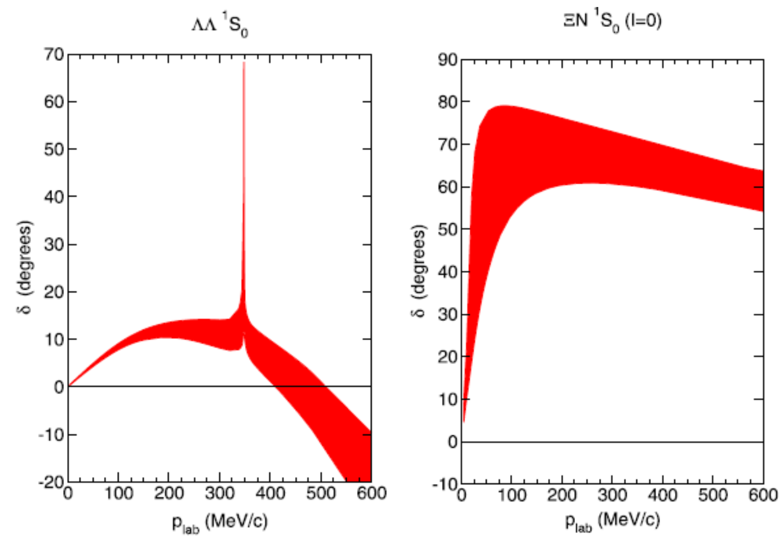


NΞ phase shift





Y.Fujiwara et al, PPNP58(2007)439

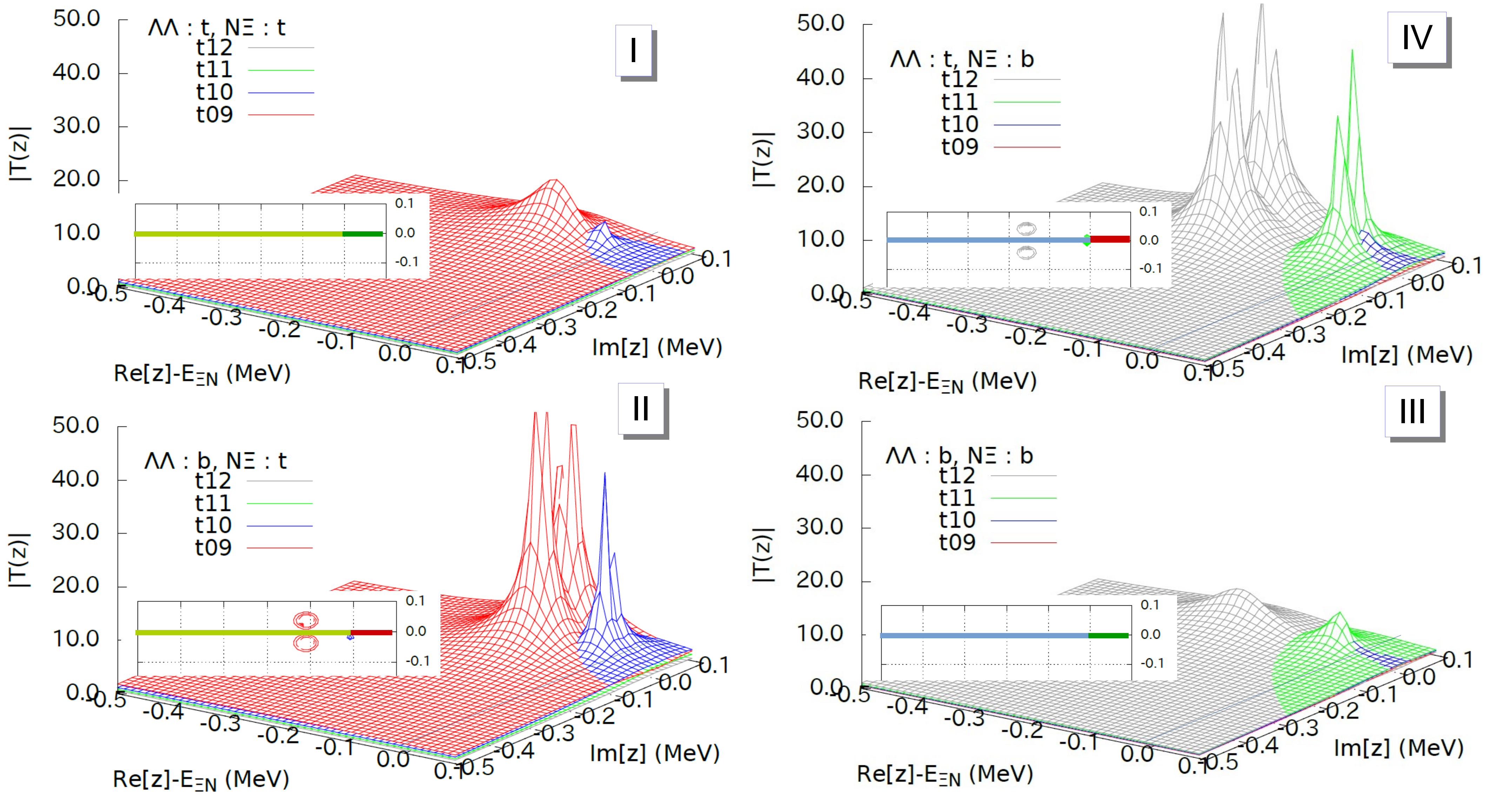


J. Haidenbauer et al, NPA954(2016)273

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

Pole position

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



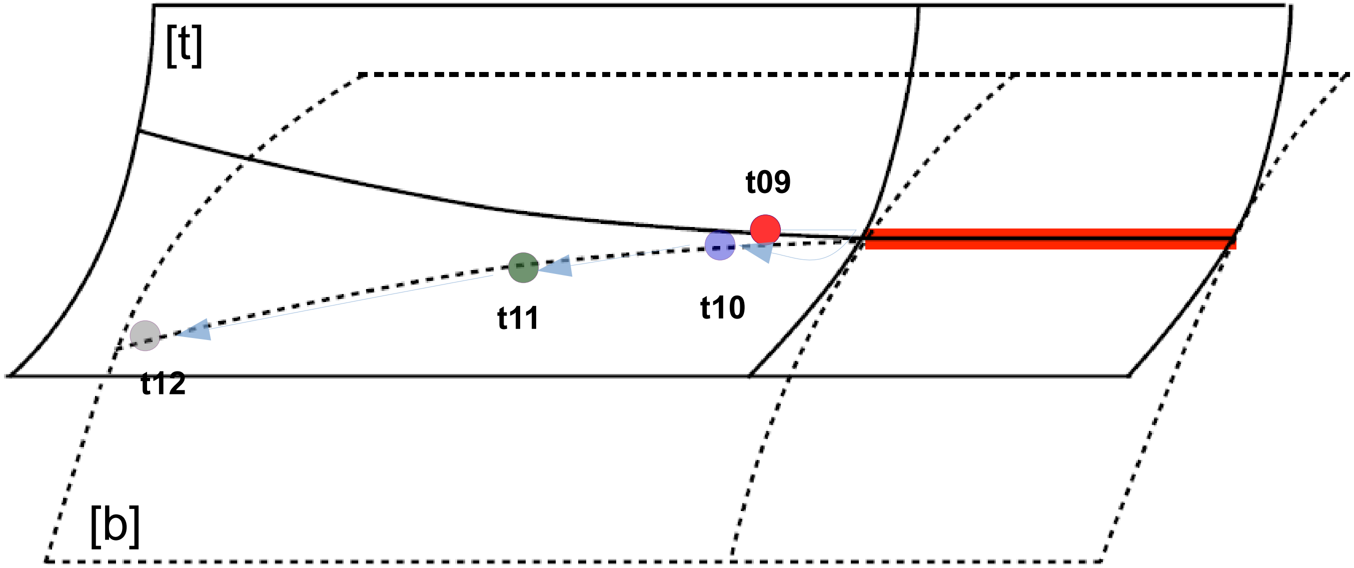
Pole search (from t=09 to t=12) single channel

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

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

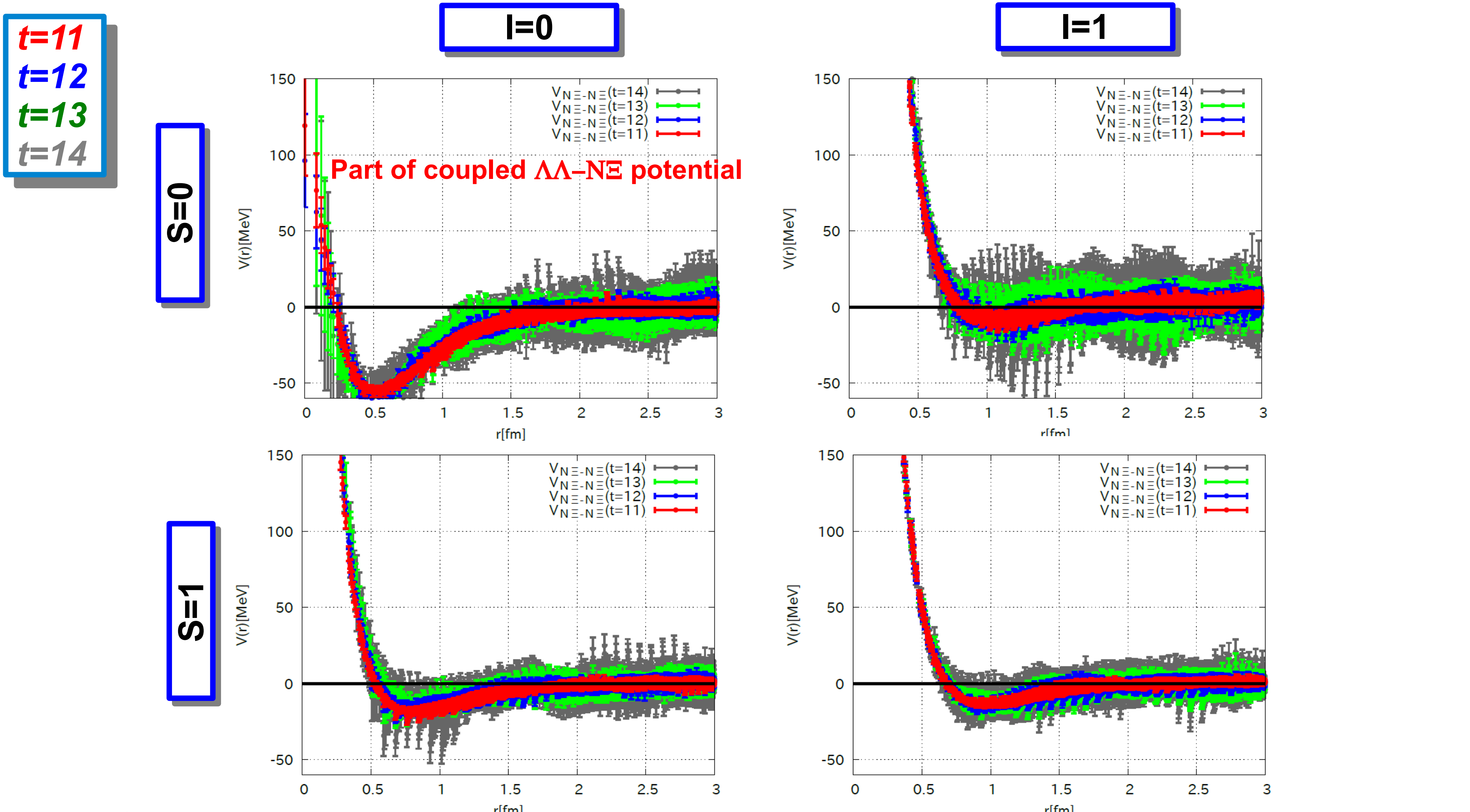
	ΛΛ	NΞ	Re[z] keV	Im[z] keV
t09	---	[t]	-19.21	0.00
t10	---	[b]	-21.34	0.00
t11	---	[b]	-131.87	0.00
t12	---	[b]	-548.40	0.00

Bound state!



Spin and Isospin dependence of NΞ potentials

- Effective NΞ potentials are plotted. (tensor potential is involved)



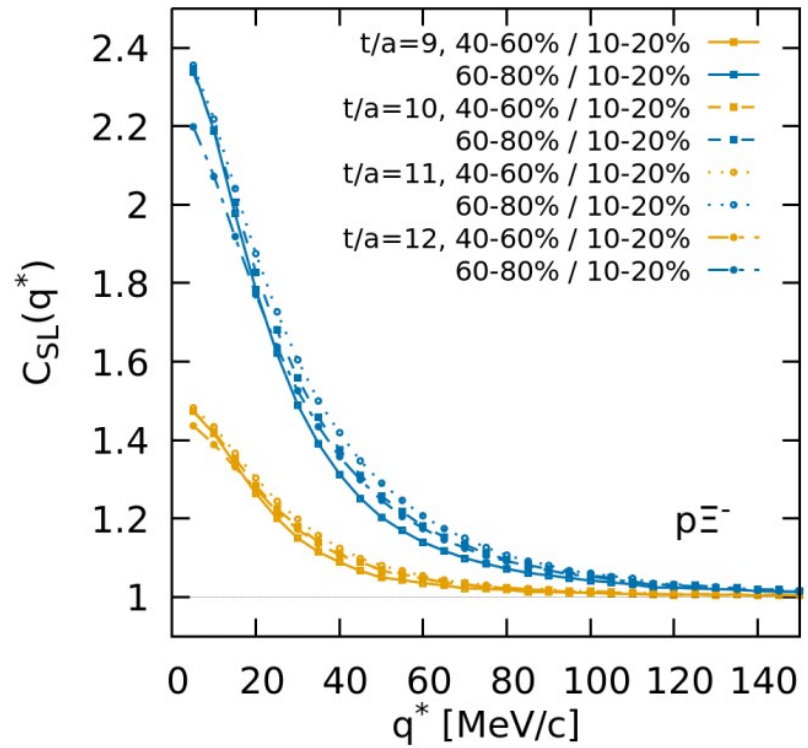
- Strong attraction can be seen in S=0 I=0 state

pΞ⁻ correlation in HIC

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

pΞ⁻ Correlation

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



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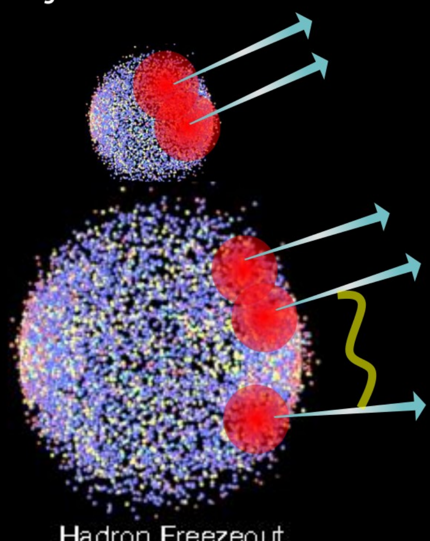
System Size?



Small System:

Most of observed pairs with small Q correlated

Large System:

Less pairs coming from close distance

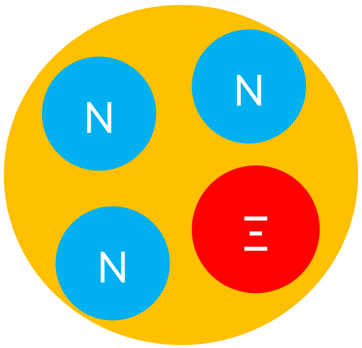
Important Remark:

Coulomb FSI for charged pairs!

Conclusion : measure small Q pairs coming from small region!

NFQCD2018@YITP

NNNΞ system



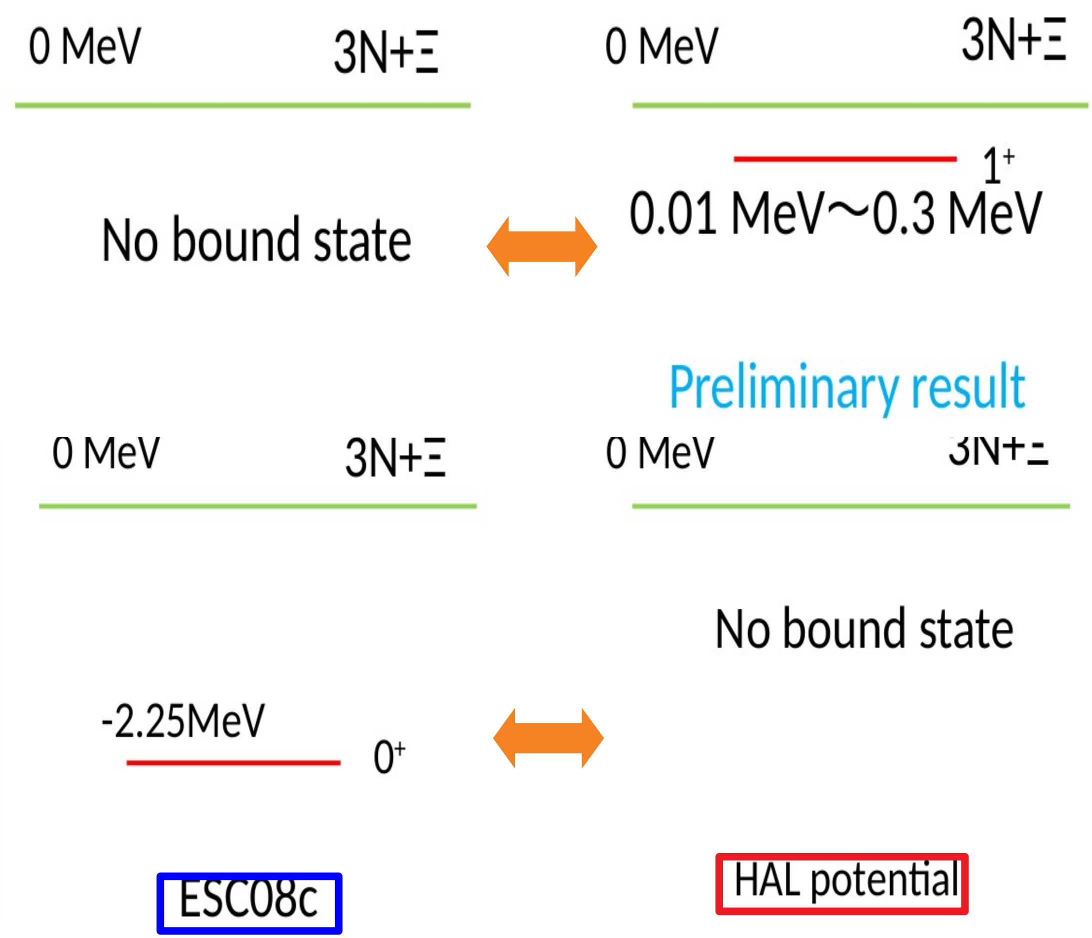
The s-shell Ξ hypernuclei (NNNΞ systems) are studied by Hiyama et al.

They compare the spin-isospin dependence of NΞ potential from ESC08c model and HAL QCD method.

NN interaction: AV8 potential
ΞN interaction :
Nijimegen soft core potential (ESC08c)
Realistic potential (only ΞN channel)

ΞN interaction by HAL collaboration

V(T,S)	ESC08c	HAL
T=0, S=1	strongly attractive	Weakly attractive
T=0, S=0	weakly repulsive	Strongly attractive
T=1, S=1	strong attractive	Weakly attractive
T=1, S=0	weakly repulsive	Weakly repulsive



Experimental search for light Ξ hypernuclei is important.

Summary

- We have investigated H-dibaryon state through S=-2 baryonic interactions from lattice QCD.

- We find that
  - $\Lambda\Lambda$ potential in $^1S_0$ channel is weakly attractive.
  - $N\Xi$ potential in $^1S_0$ channel is strongly attractive.
- It is difficult to conclude that whether H-dibaryon state survives as a resonance state or not at this moment...

- $N\Xi$ interaction plays a key role not only for the formation of Ξ nucleus but also for the fate of H-dibaryon.