Lattice QCD studies of dibaryon candidates

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for HAL QCD collaboration

HAL(Hadrons to Atomic nuclei from Lattice) QCD Collaboration

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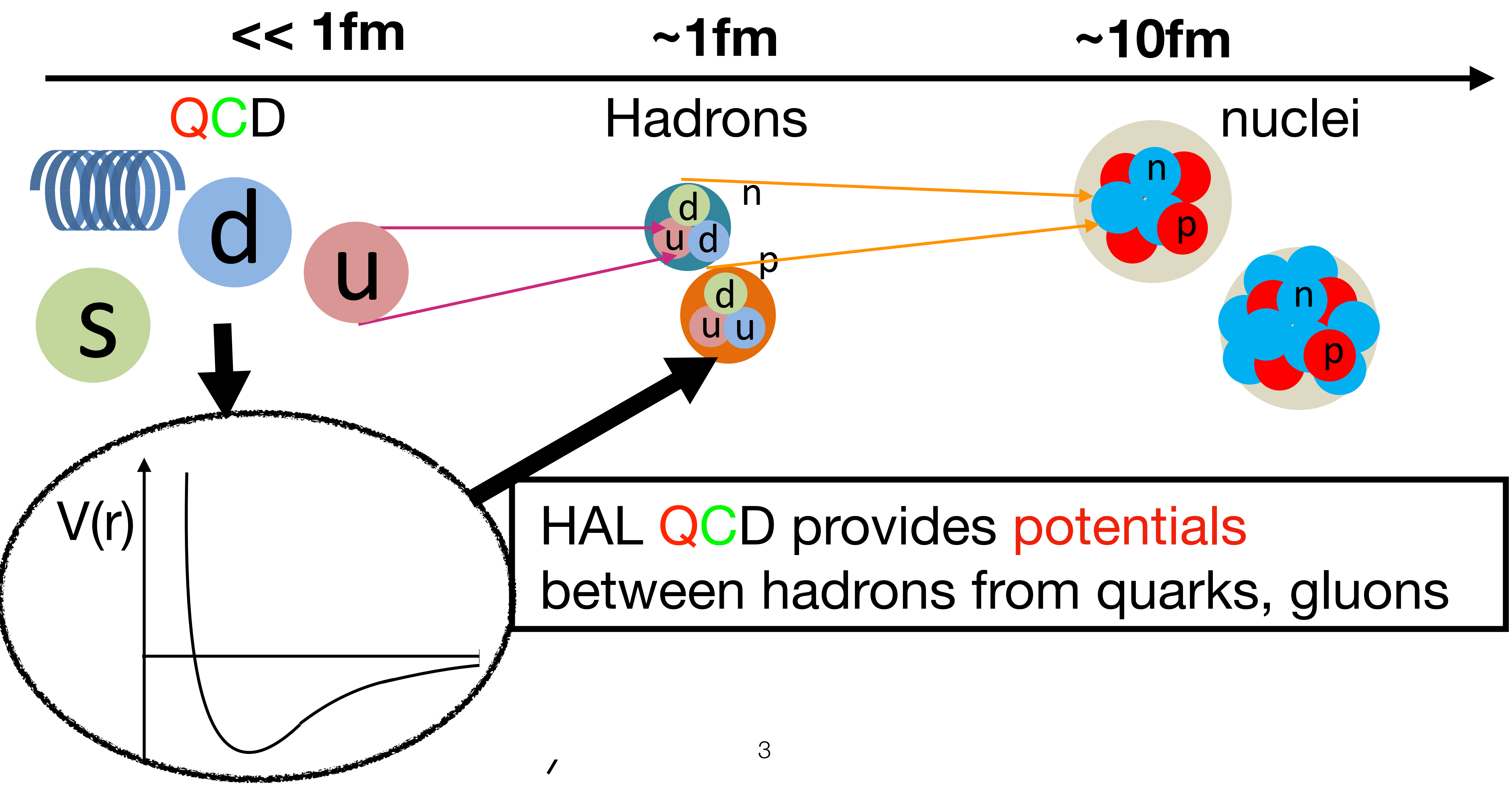
Outline

- Introduction
  - What's HAL QCD method and its role?
  - Dibaryon candidates from model works
- Theoretical framework for HAL QCD method
- results at heavy quark masses
- results at physical quark masses

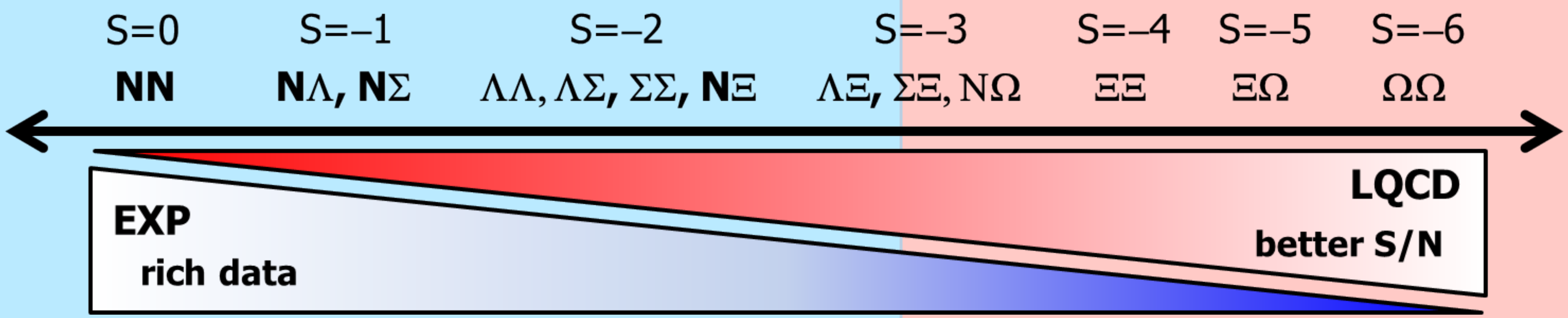
Introduction

- HAL QCD method: we study hadron physics from QCD (quarks and gluons) —first-principles calculation—



role of our work

Experiment ← complementary works → Lattice QCD



- rich data for less strange quarks
- More # of strangeness, more difficult experiment due to short life time

- better S/N for more strange quarks
- Less # of strangeness, more difficult numerical simulation due to increasing statistical noise

provide the data

models & EFTs

Best to collaborate with three fields to understand hadron physics

Dibaryon candidates

model study gives the prediction of dibaryons

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

found in experiment
(CELSIUS/WASA
PRL 102, 052301 (2009))

・B.E. largely depends on the model parameters
・Depending on models, the dibaryon does not exist
Lattice QCD avoids these problems.

- *Some dibaryon candidates include decuplet baryons*
- *We focus on the channels where dibaryon candidates exit*

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- results of ΩΩ interactions at physical quark masses

Aoki, Hatsuda, Ishii, PTP123, 89 (2010)

How to get the potential from QCD

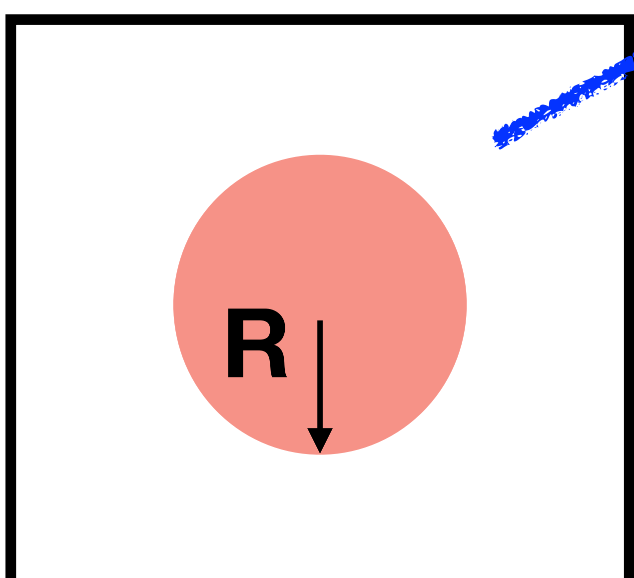
Key quantity: Nambu-Bethe-Salpeter (NBS) wave function

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

Local operators B_1&B_2 for decuplet baryons

$$D_{\mu\alpha} = \epsilon_{abc}\left(q^{aT} C \gamma_\mu q^b\right) q^c_\alpha$$

Outside interactions (asymptotic region)
Helmholtz eq. is satisfied for r>>R



$$\left(\vec{p}_n^{\,2} + \nabla^2\right) \Psi_n(\vec{r}) = 0 \qquad \Psi_n(\vec{r}) \sim A \frac{\sin(kr + \delta_l(k))}{kr}$$

$$S(k) = e^{2i\delta(k)}$$

NBS includes information
on the phase shifts & S matrix

Aoki, Hatsuda, Ishii, PTP123, 89 (2010)

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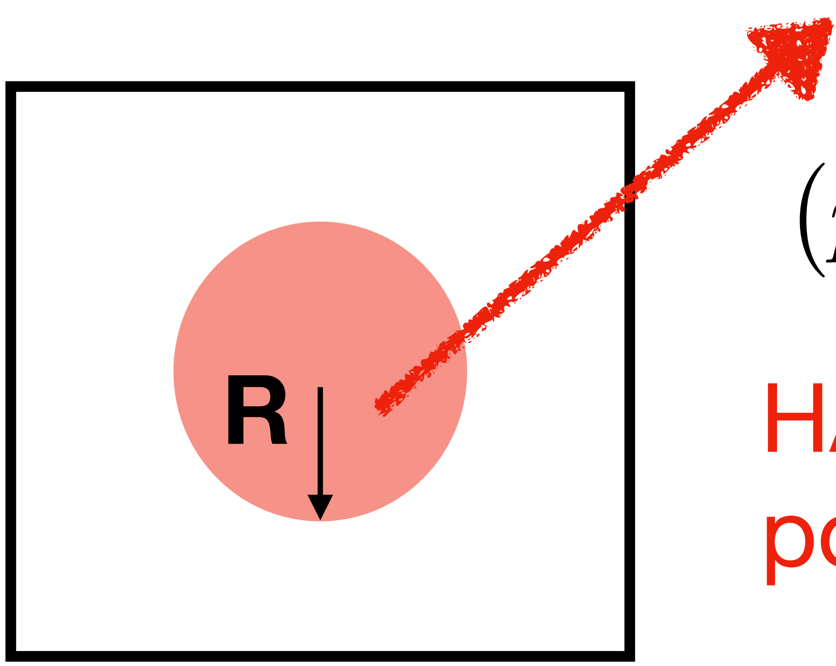


Inside interactions (r < R)

Schroedinger-type eq. is satisfied:

$$\left(\vec{p}_n^{\,2} + \nabla^2 \right) \Psi_n(\vec{r}) = 2\mu \int d\vec{r'}\, U(\vec{r}, \vec{r'}) \Psi_n(\vec{r'})$$

HAL QCD method extracts the nonlocal potential U(r,r’) from NBS w.f.

Aoki, Hatsuda, Ishii, PTP123, 89 (2010)

Nonlocal potential U(r,r')

$$\left(\vec{p}_n^2 + \nabla^2\right) \Psi_n\left(\vec{r}\right) = 2\mu \int d\vec{r'} U(\vec{r}, \vec{r'}) \Psi_n(\vec{r'})$$

Remarkable facts for the non-local potential U(r,r')

- The potential is given by energy-independent potential, but non-locality cannot be removed.
- The local potential can be obtained by its derivative expansion:

$$\begin{aligned} U(\vec{r}, \vec{r'}) &= \underline{V_c(r) + V_\sigma(r)(\vec{S}_1 \cdot \vec{S}_2) + S_{12} V_{T_1}(r)} \\ &\quad + O(\nabla^2) \\ &= \underline{V_C^{eff}(r)} + O(\nabla^2) \end{aligned}$$

- The convergence of the expansion can be checked
- The potential includes the tensor parts

Aoki, Hatsuda, Ishii, PTP123, 89 (2010)

How to extract the NBS w.f. on lattice

4pt correlation function

$$\mathcal{G}(\vec{x},\vec{y},t-t_0;J^P) = \langle 0|\, B_1(\vec{y},t)B_2(\vec{x},t)\bar{\mathcal{J}}(t_0;J^P)\,|0\rangle$$

$$1 = \sum_n |E_n\rangle\langle E_n|$$

$$= \sum_{n=0}^{\infty} A_n \Psi_n(\vec{r}) e^{-E_n(t-t_0)}$$

$$\xrightarrow{t \gg t_0} A_0 \Psi_0(\vec{r}) e^{-E_0(t-t_0)}$$

- NBS w.f. can be extracted from 4pt correlation function
- Elastic saturation & ground state saturation are required.

$$E_1 = \sqrt{E_0^2 + (2\pi/L)^2} \sim E_0 \quad (L \gg 1)$$

This becomes more serious as lattice size becomes larger
In HAL method, this is avoided by time-dependent extension.
[c.f. serious problem for Luscher's method, **see Iritani 2016&2017]**

N. Ishii et al, PLB712, 437 (2010)

Technical development: Time-dependent method

normalized 4pt correlation function:

$$m_{B_1} = m_{B_2}$$

$$\mathcal{R}(\vec{x}, \vec{y}, t - t_0; J^P) = e^{(m_{B_1}+m_{B_2})t} \langle 0 | B_1(\vec{y}, t) B_2(\vec{x}, t) \bar{\mathcal{J}}(t_0; J^P) | 0 \rangle$$

$$\simeq \sum_n A_n \Psi_n(\vec{r}) e^{-\Delta E_n t}$$

$$\Delta E_n = 2\sqrt{m_B^2 + k_n^2} - 2m_B$$

elastic saturation

1. ∂/∂t
2. $\Delta E_n = \dfrac{k_n^2}{m_B} - \dfrac{\Delta E_n^2}{4m_N}$

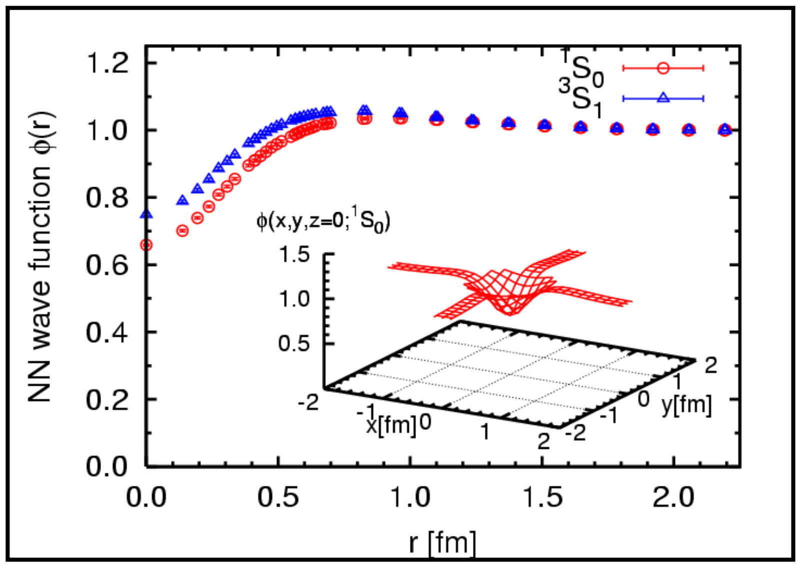
$$\left(\frac{1}{4m_B} \frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{m_B} \right) \mathcal{R} = \int U(\vec{r}, \vec{r'}) \mathcal{R} d^3 r'$$

- Potential can be extracted directly from the correlator
- No need for ground state extraction

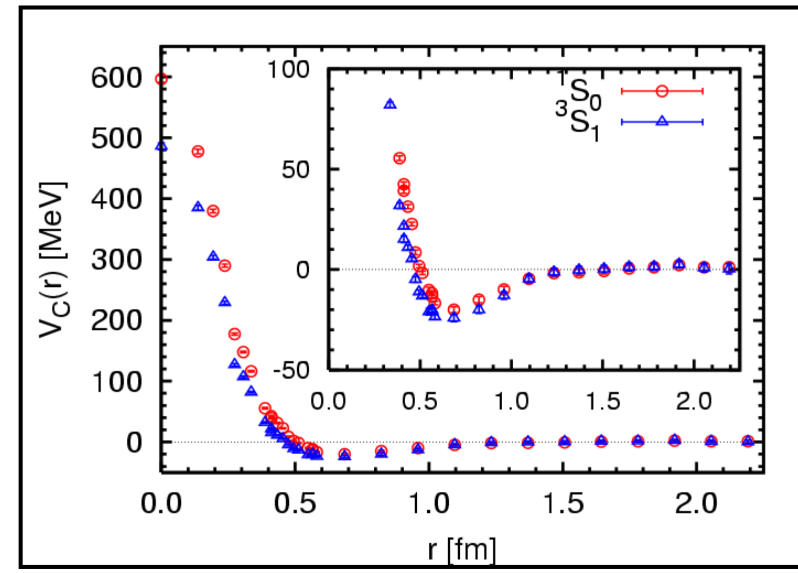
Strategy for HAL method

Lattice QCD

NBS wave func.



Lat Hadron Force



Time-dependent HAL method

observables
phase shift, binding energy, ….

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interaction of decuplet baryons

Irreducible representation involving with decuplet baryons

I. decuplet-octet system

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

M. Oka PRD38 -298

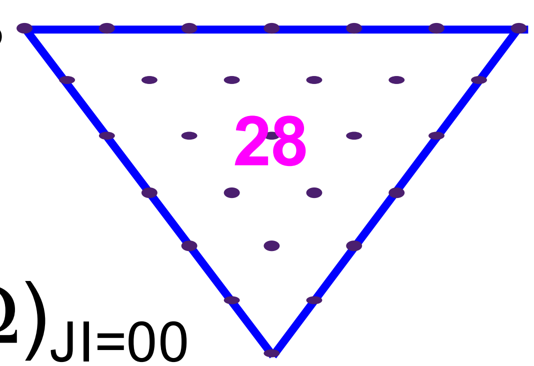
strong attractive CMI is expected

dibaryon (ΩN in $J^p(I) = 2^+(1/2)$) is expected

II. decuplet-decuplet system

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

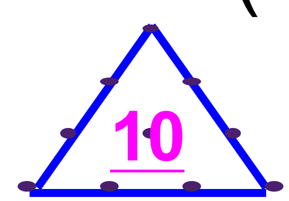
$(\Delta\Delta)_{JI=03}$



$(\Omega\Omega)_{JI=00}$

Flavor symmetric

$(\Delta\Delta)_{JI=30}$



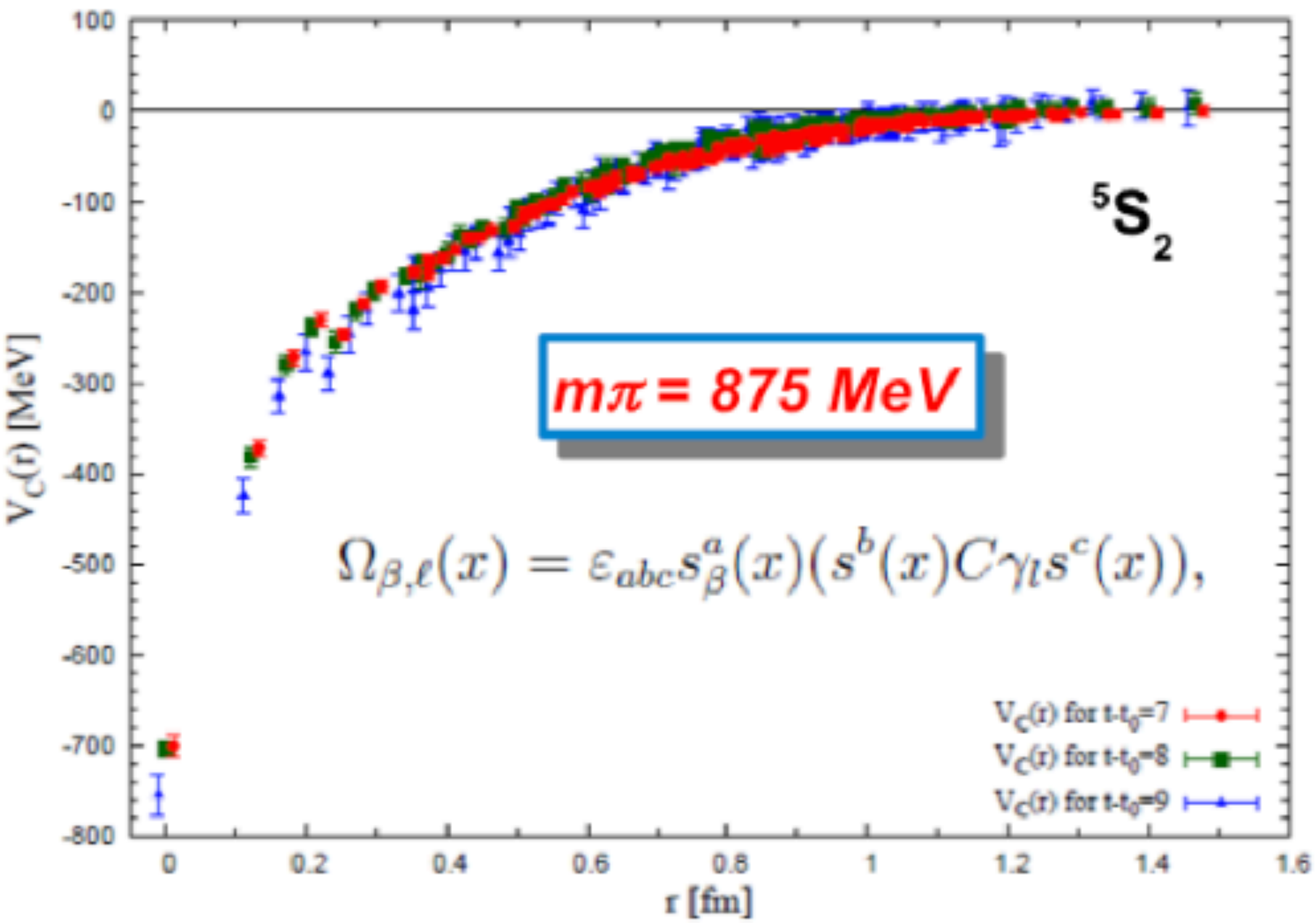
Flavor anti-symmetric

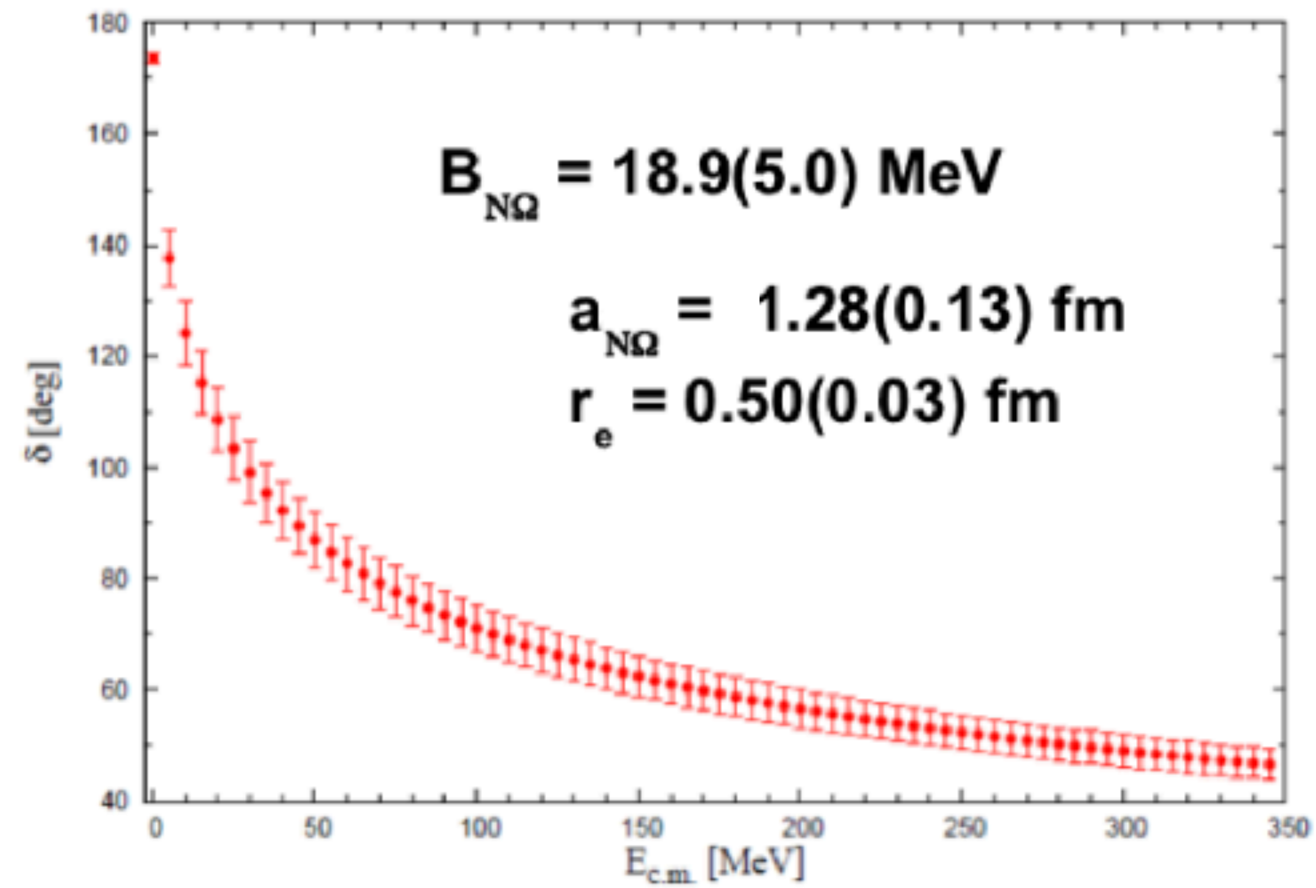
I. decuplet-octet system
NΩ system

NΩ system $J^p(I) = 2^+(1/2)$

Nf = 2+1 full QCD with L= 1.9fm, m_π=875MeV

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





- In short range, there is no repulsive core
- strong attraction leads to deep bound state

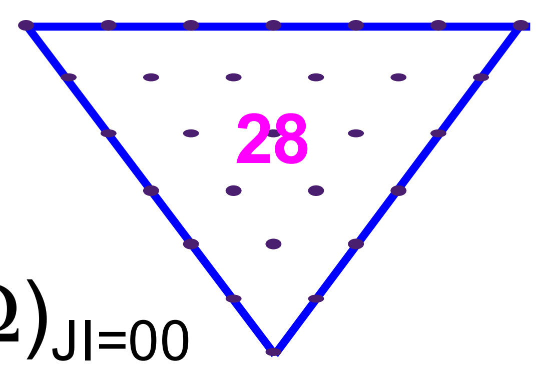
<= *the signal is expected to be found in HIC*

Physical point result will be open. (Iritani et al.)

II. decuplet-decuplet system

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

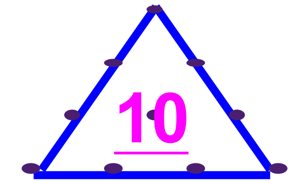
$(\Delta\Delta)_{\mathrm{JI=03}}$



$(\Omega\Omega)_{\mathrm{JI=00}}$

Flavor symmetric

$(\Delta\Delta)_{\mathrm{JI=30}}$



Flavor anti-symmetric

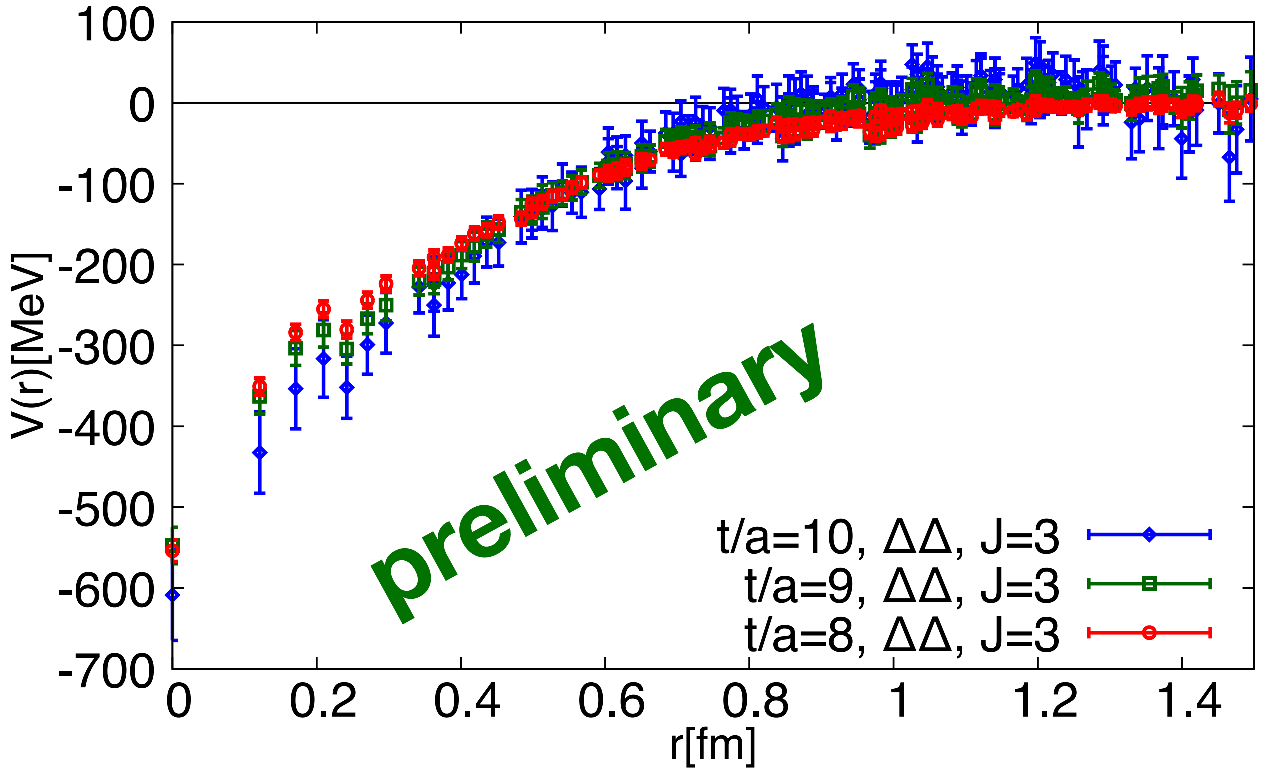
SG and K. Sasaki

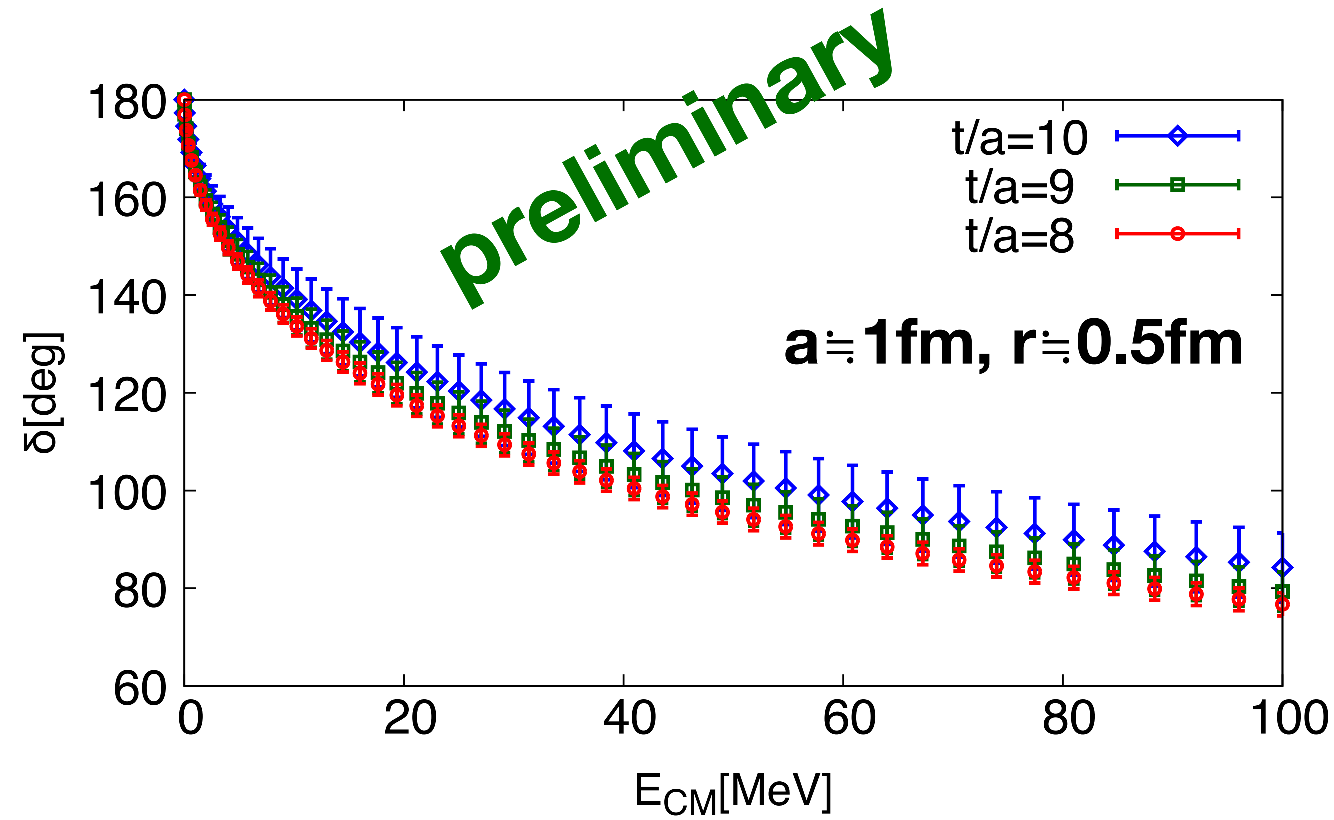
$\overline{10}$ plet in decuplet-decuplet system

Nf = 2+1 full QCD with L = 1.93fm, m_π=1015MeV, SU(3) limit

ΔΔ in $J^p(I) = 3^+(0)$

$m_\Delta \simeq 2225\text{MeV}$





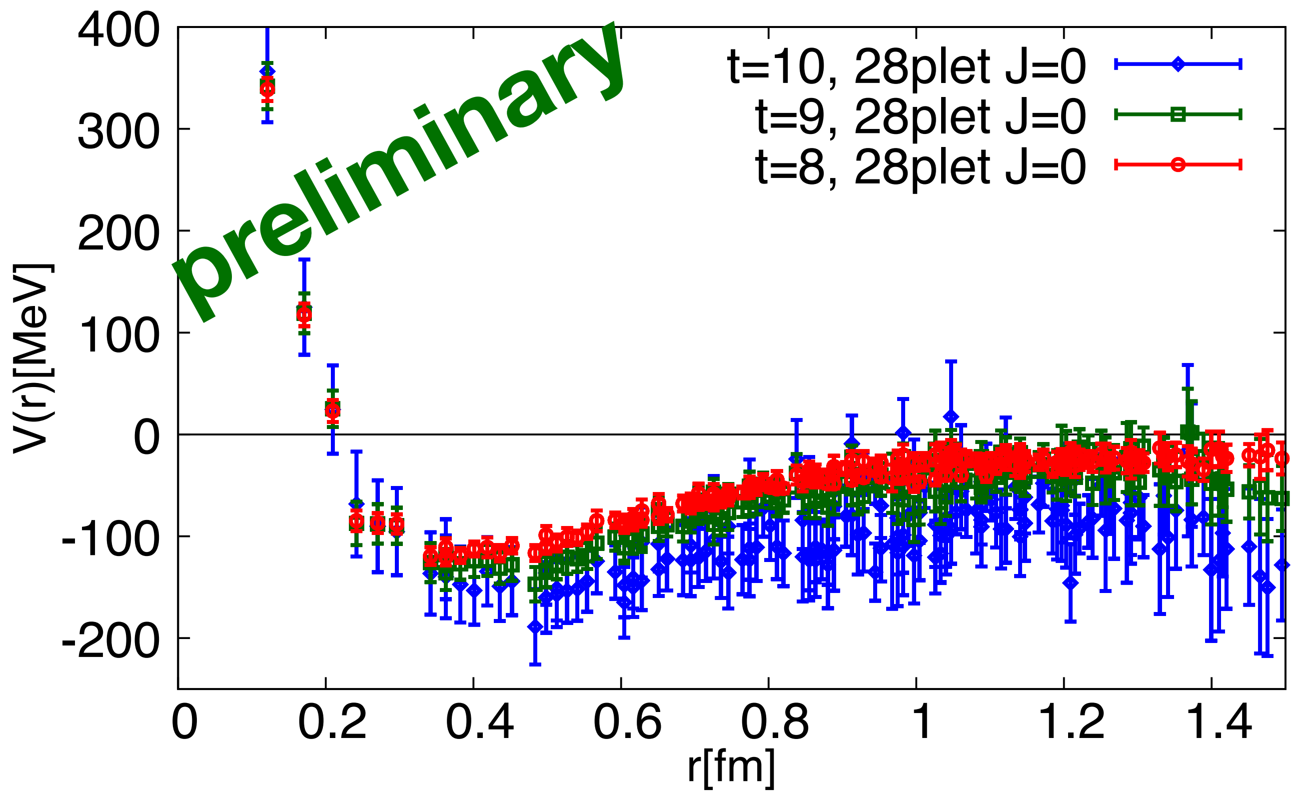
- In short range, there is no repulsive core
- strong attraction leads to deep bound state (ABC effect)

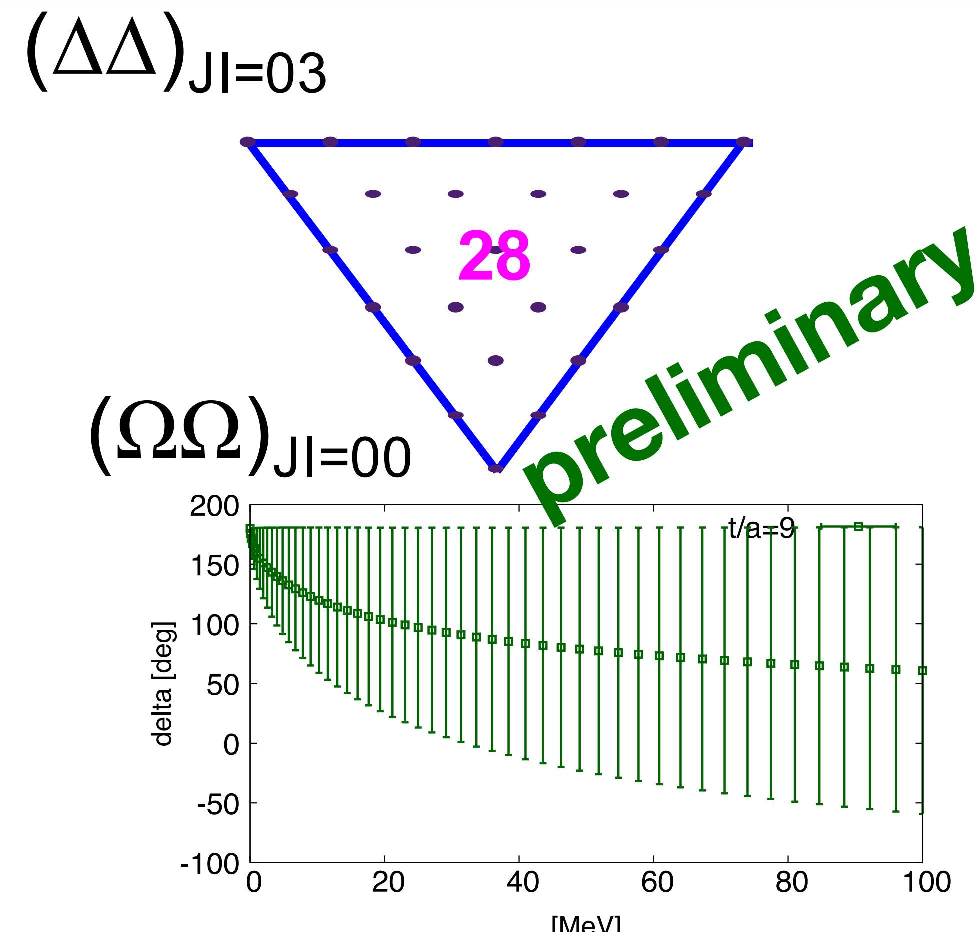
SG and K. Sasaki

28 plet in decuplet-decuplet system

Nf=2+1 full QCD with L = 1.93fm, m_π= 1015MeV, SU(3) limit

ΩΩ in *J* =0 *is identical with* **ΔΔ in *J* =0** *due to SU(3) symmetry*





- Short range repulsive core and attractive pocket are found
- Phase shift shows the system is in the unitary limit
- *Is it the same situation in other conditions? (lighter pion mass & SU(3) breaking case)?*

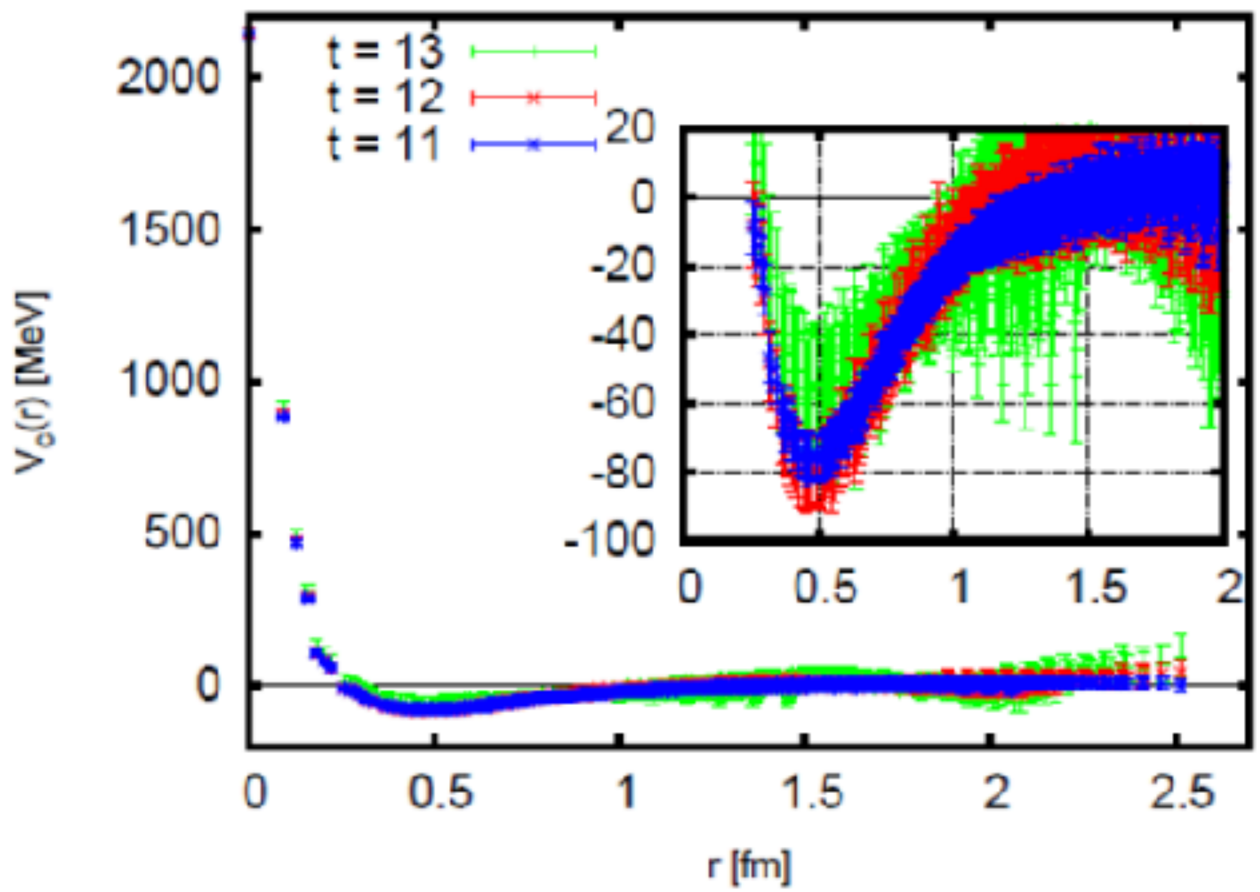
M. Yamada et. al.(HAL QCD), PTEP2015

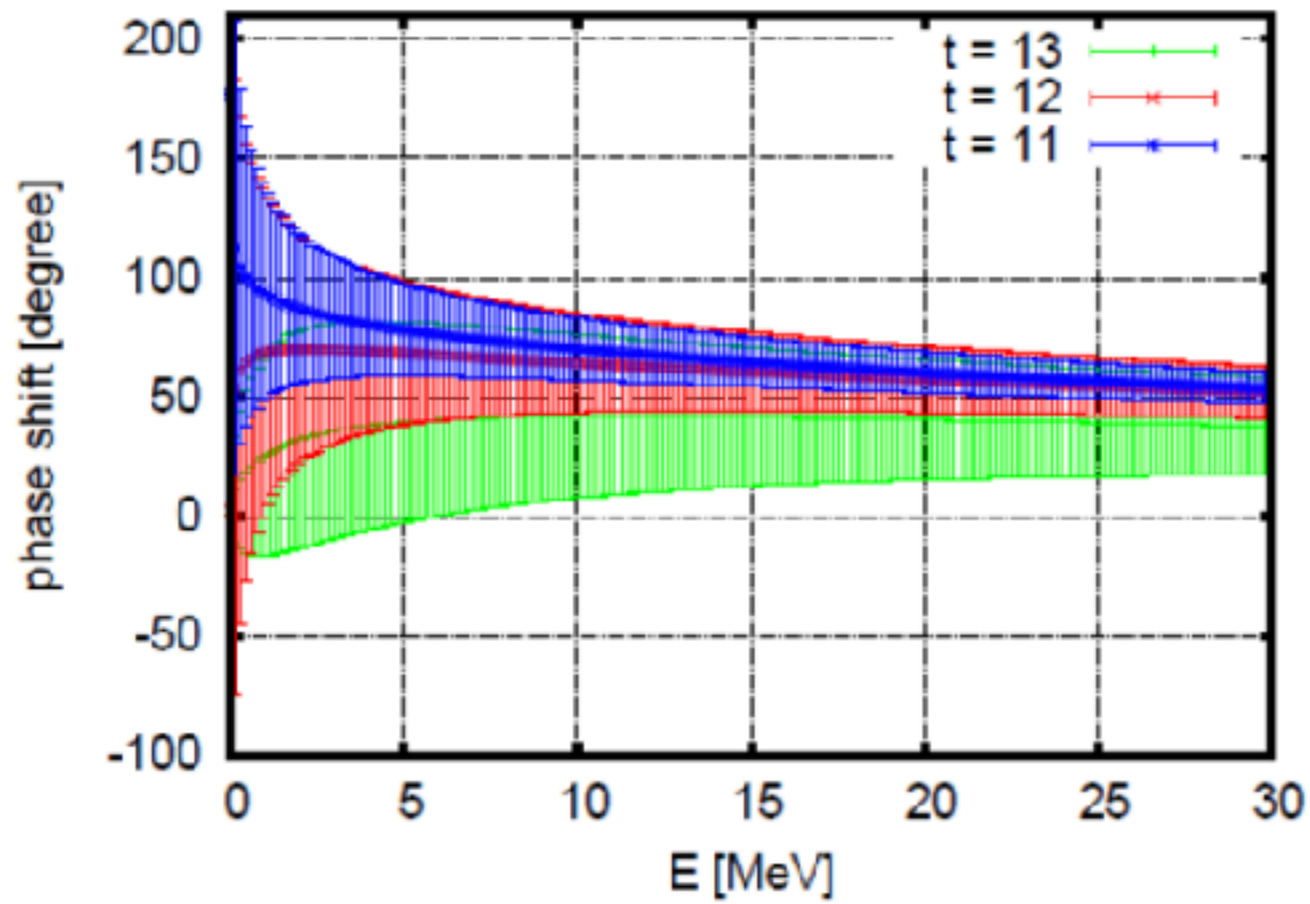
28 plet in decuplet-decuplet system

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

ΩΩ in *J* =*0*

m_Ω= 1970MeV





- Short range repulsive core and attractive pocket are found
- Phase shift shows the system is in the unitary limit
- *Is it the same situation even in physical pion mass?*

Decuplet-Decuplet interaction at physical point

Difficulties of Dec-Dec interaction at physical point

- decuplet baryons except for Ω-baryon decays into other hadrons via the strong interaction at physical point
- There are many coupled channels except for Omega-Omega interaction at physical point

We focus on Omg-Omg at physical point in decuplet-decuplet interactions

Numerical Setup at (almost) physical mass

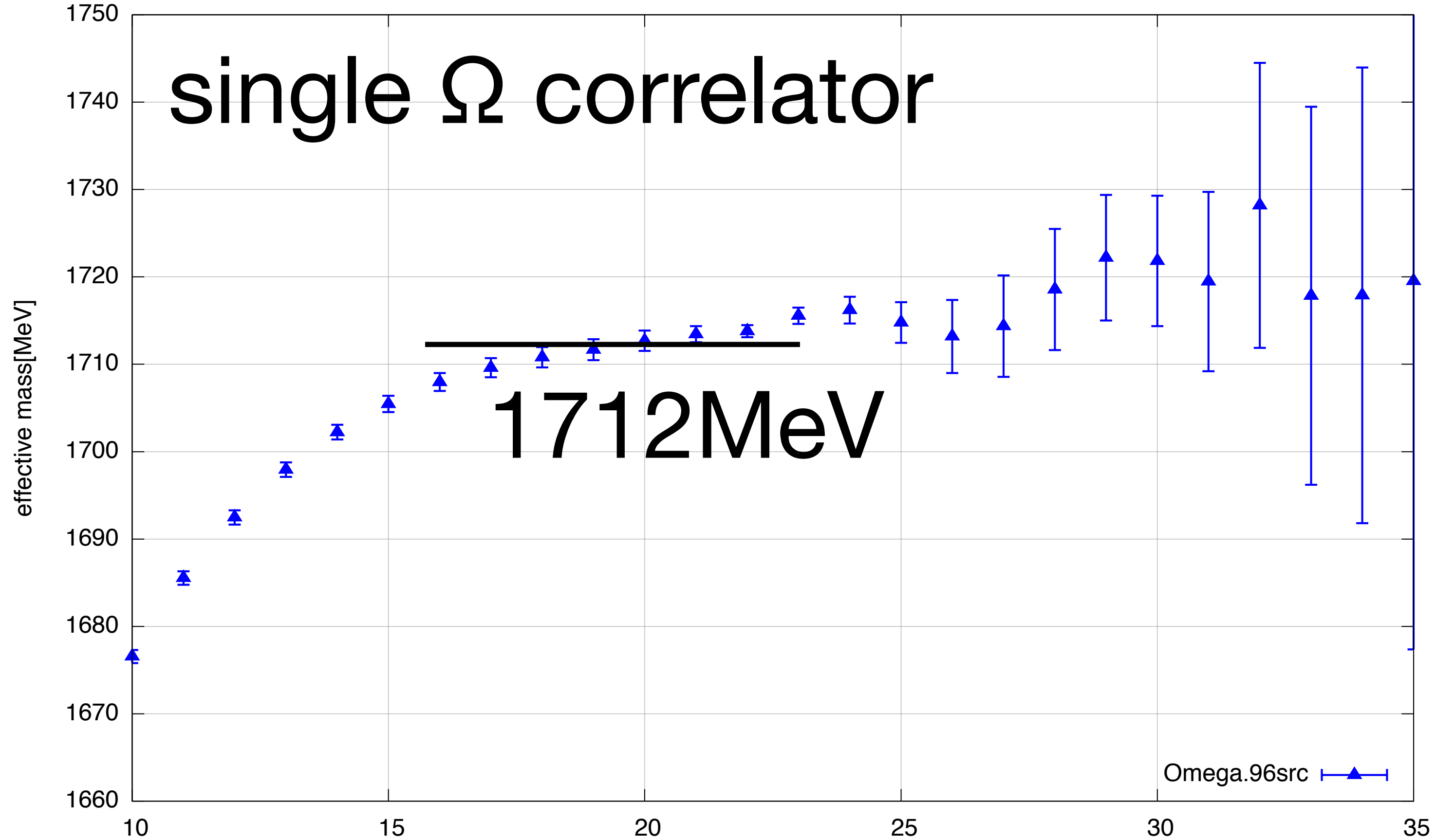
2+1 flavor gauge configurations

- Iwasaki gauge action & O(a) improved Wilson quark action
- a= 0.0846 [fm], a^{-1} = 2333 [MeV]
- 96^3x96 lattice, L = 8.1[fm]
- 400 confs x 48 source positions x 4 rotations

K-computer [10PFlops]

Wall source is employed. only Swave state is produced.

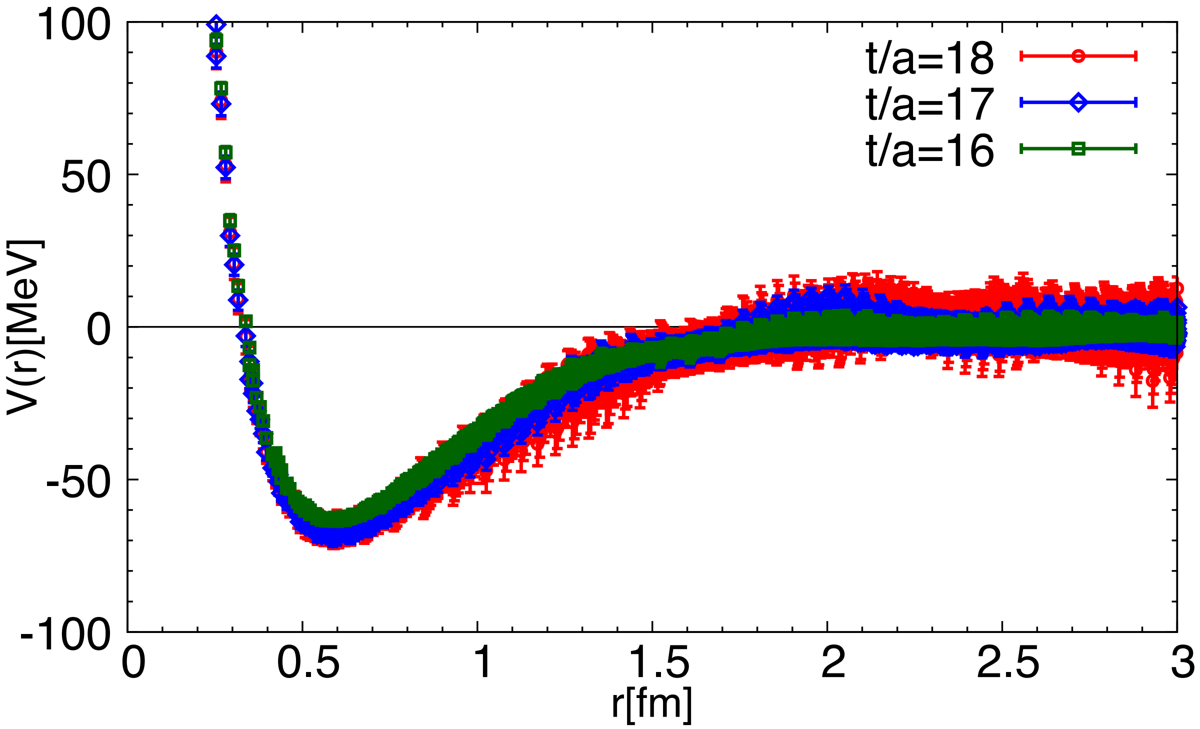
	[MeV]	phys.
π	146	8%
K	525	6%
N	964	3%
Ω	1712	2%

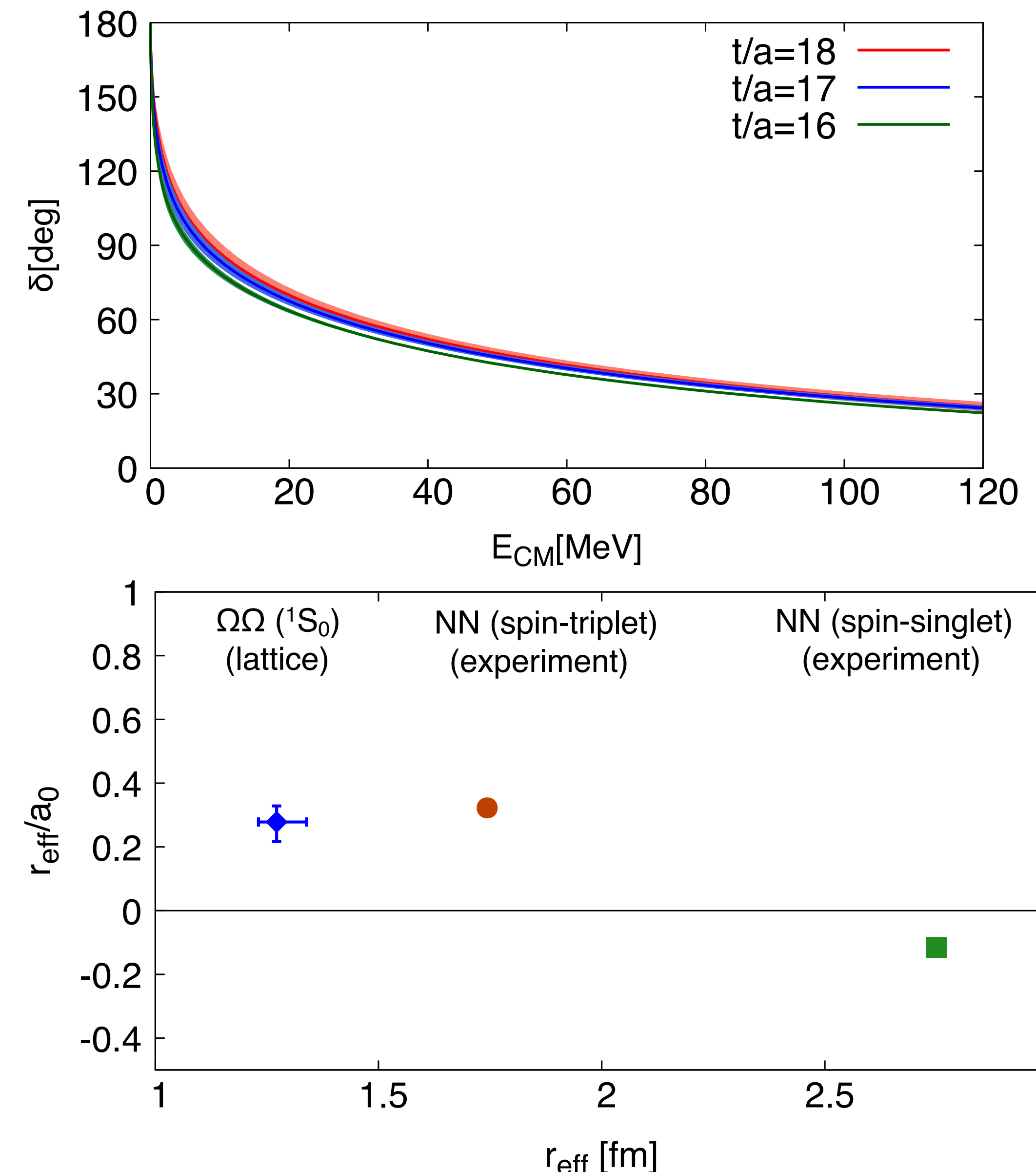


SG and K. Sasaki et.al.(HAL), arXiv:1709.00654

ΩΩ in *J* =*0*

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





$$a_0^{(\Omega\Omega)} = 4.6(6)(^{+1.2}_{-0.5}) \quad \mathrm{fm},$$
$$r_{\mathrm{eff}}^{(\Omega\Omega)} = 1.27(3)(^{+0.06}_{-0.03}) \quad \mathrm{fm}.$$

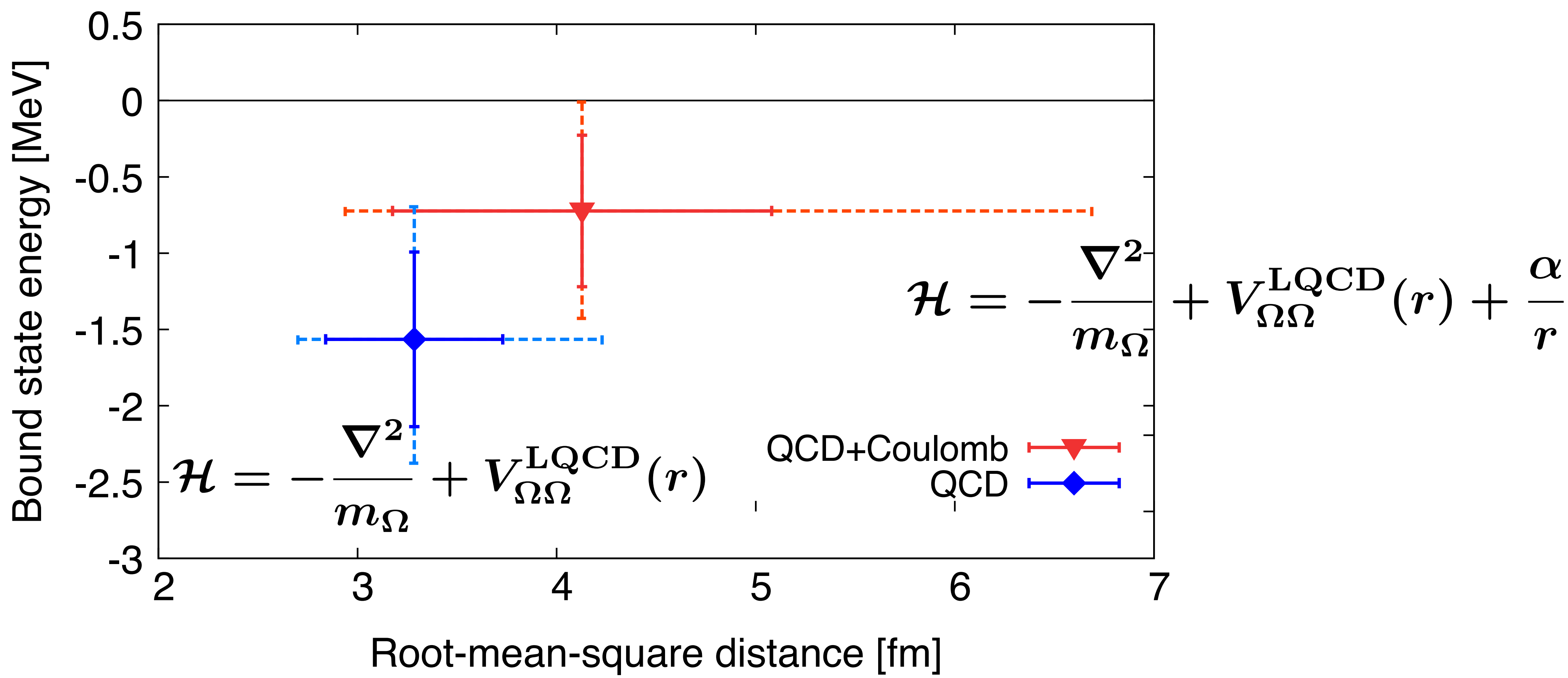
- Short range repulsive core and attractive pocket are found
- Phase shift shows the presence of a bound state
- It is very close to the unitary region (r/a<1)

SG and K. Sasaki et.al.(HAL), arXiv:1709.00654

$\Omega\Omega$ in $J=0$

Binding energy and the Coulomb effect

"most strange dibaryon"



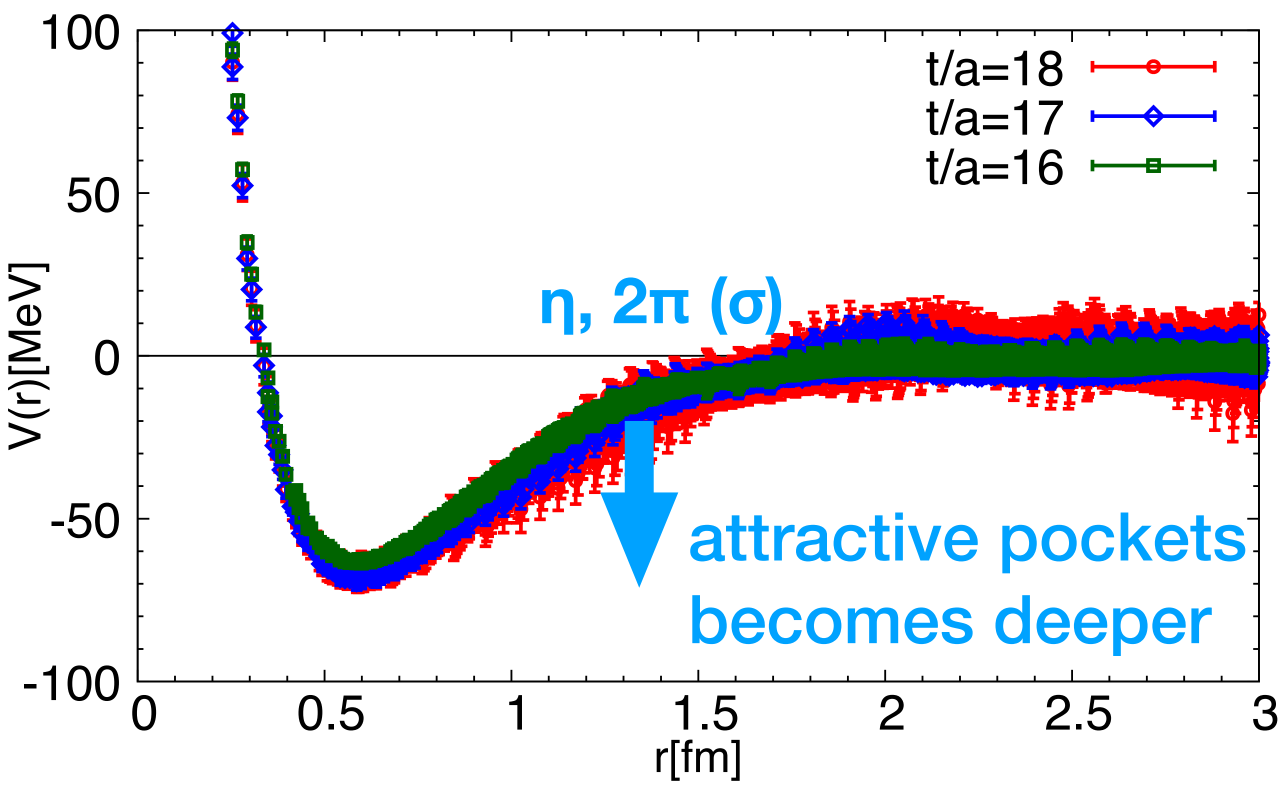
- **Most strange dibaryon appears (within 1σ) even if Coulomb effect is considered.**

$$(B_{\Omega\Omega}^{(\mathrm{QCD})}, B_{\Omega\Omega}^{(\mathrm{QCD+Coulomb})}) = (1.6(6)\mathrm{MeV}, 0.7(5)\mathrm{MeV})$$

Conservative estimate at exact phys. pt.

m_π=146 MeV -> 135 MeV, m_Ω= 1712MeV -> 1672 MeV

B.E. ↑



V.S.

B.E. ↓

$$\mathcal{H} = -\frac{\nabla^2}{m_\Omega} + V_{\Omega\Omega}^{\mathrm{LQCD}}(r)$$

kinetic term becomes more dominant
-> B.E. is reduced

conservative estimate:
only change the mass of schroedinger eq.

$$(B_{\Omega\Omega}^{(\mathrm{QCD})}, B_{\Omega\Omega}^{(\mathrm{QCD+Coulomb})}) = (1.6(6)\mathrm{MeV}, 0.7(5)\mathrm{MeV})$$
$$\to (1.3(5)\mathrm{MeV}, 0.5(5)\mathrm{MeV})$$

These changes are well within errors

Conclusion and future work

- We have investigated dibaryon candidates involving with decuplet baryon from lattice QCD

- heavy pion masses:
  (i) ΩN interaction in ($^5S_2$)
  - no repulsion core and only attractive region
  - a bound state (is expected to be found in HIC)
  (ii) ΔΔ interaction in ($^5S_2$)
  - bound state in ΔΔ interaction ($^7S_0$)
  - a bound state (ABC effect)

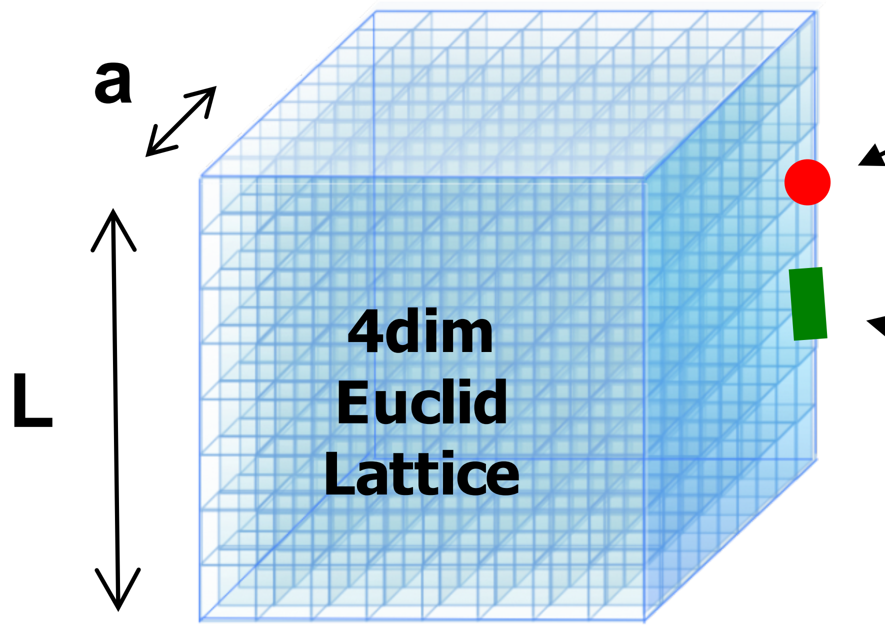
- physical pion masses:
  ΩΩ interaction in ($^1S_0$)
  - short range repulsive and attractive pocket
  - a very shallow bound state [Most strange dibaryon] (or unitary region?)

statistics will be increased by two times!

Back Slides

First-principles calculation (Lattice QCD)

$$Z = \int dU\, dq d\bar{q}\ e^{-S_E}$$



quarks on sites

$q(x)$

gluons on links

$U_\mu(x, x+\mu) = \exp[-iaA_\mu]$

- **Well-defined reguralized system (finite a and L)**
- **Gauge-invariance manifest**
- **Fully-Nonperturbative**
- **DoF ~ 10^9 ➔ Monte-Carlo w/ Euclid time**

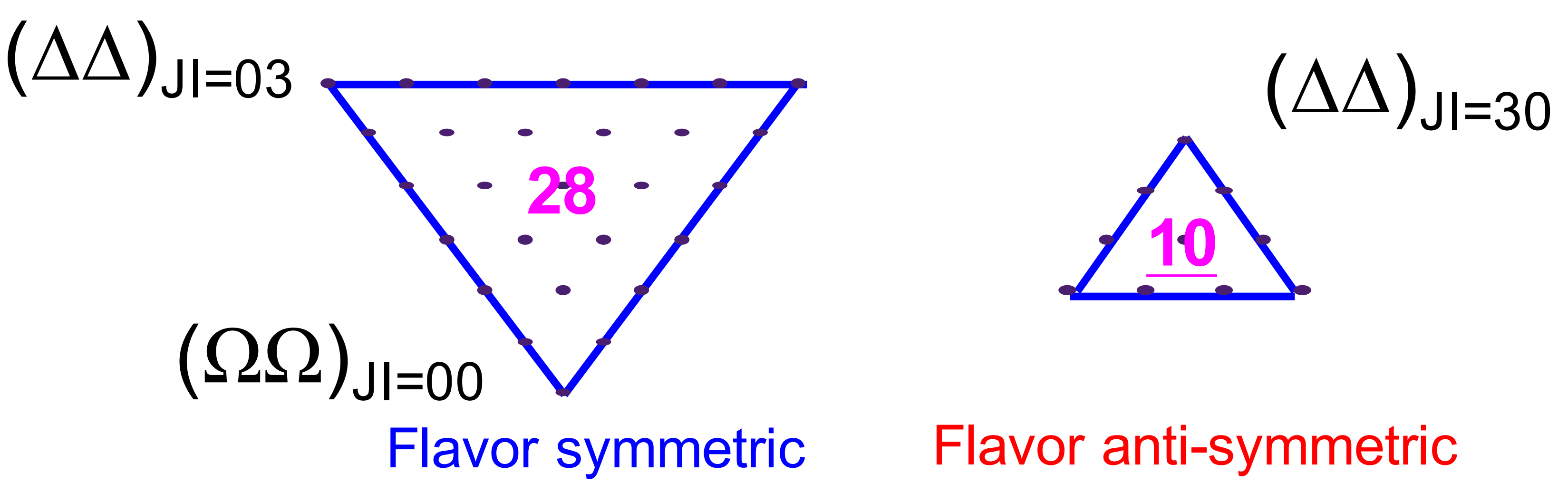
Significant theoretical and hardware advances

classification from CMI & quak pauli

Oka, Shimizu, and Yazaki NPA464 (1987)

- repulsive core is a result of Pauli principle and color-magnetic interaction for the quarks

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



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

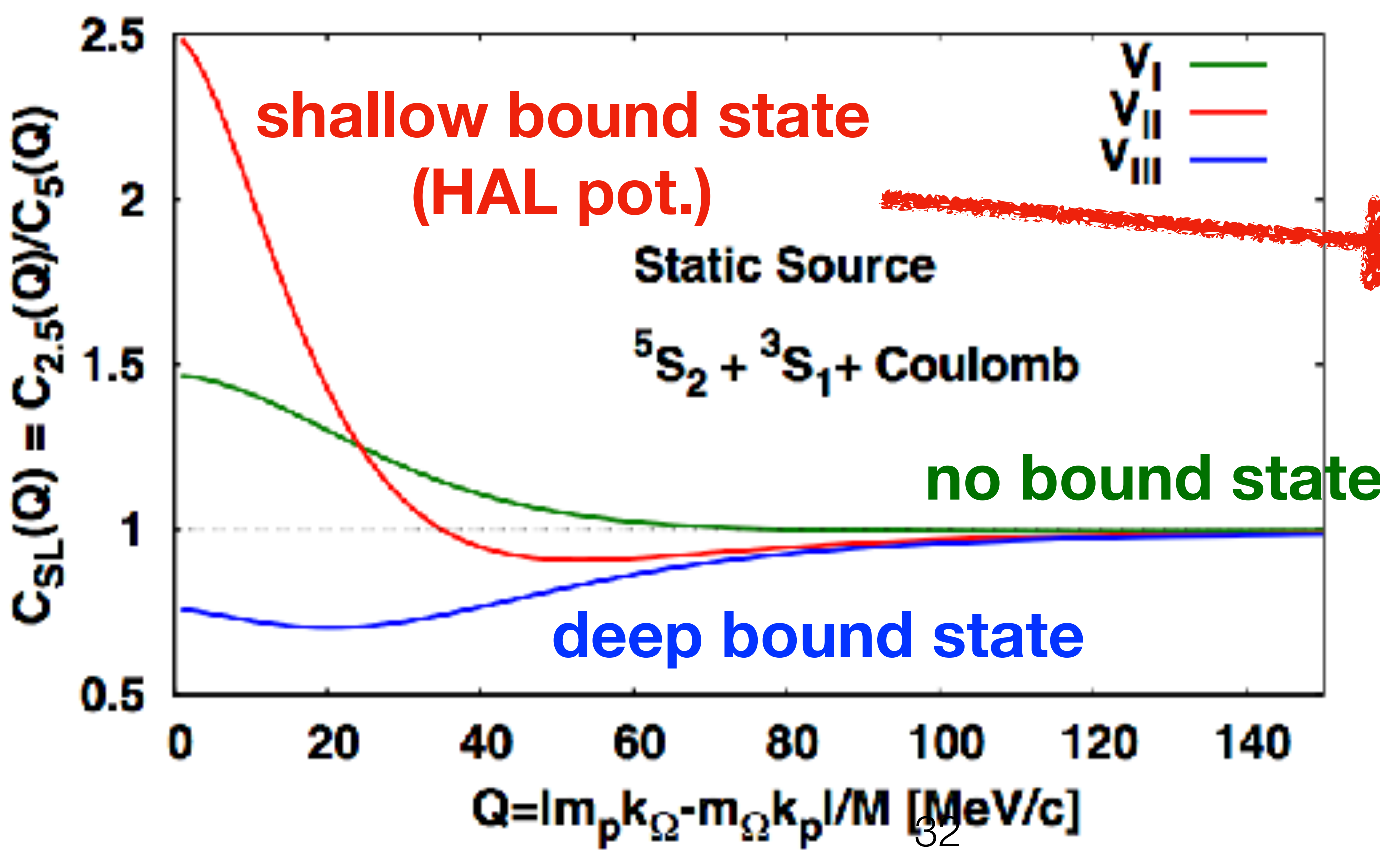
How to find a ΩN bound state in HIC

Morita, Ohnishi, Etminan, Hatsuda, 2016

$$\boxed{C_{\rm SL}(Q) \equiv \frac{C_{R_{p,\Omega}=2.5{\rm fm}}(Q)}{C_{R_{p,\Omega}=5{\rm fm}}(Q)},}$$

$C_{R_{p,\Omega}}(Q)$: pΩ correlation function with effective size R

(i) Comparison of the peripheral and central collisions for the same nuclear system
(ii)Comparison of the central collisions with different system sizes
,e.g. central Cu+Cu & central Au+Au collisions at RHIC.



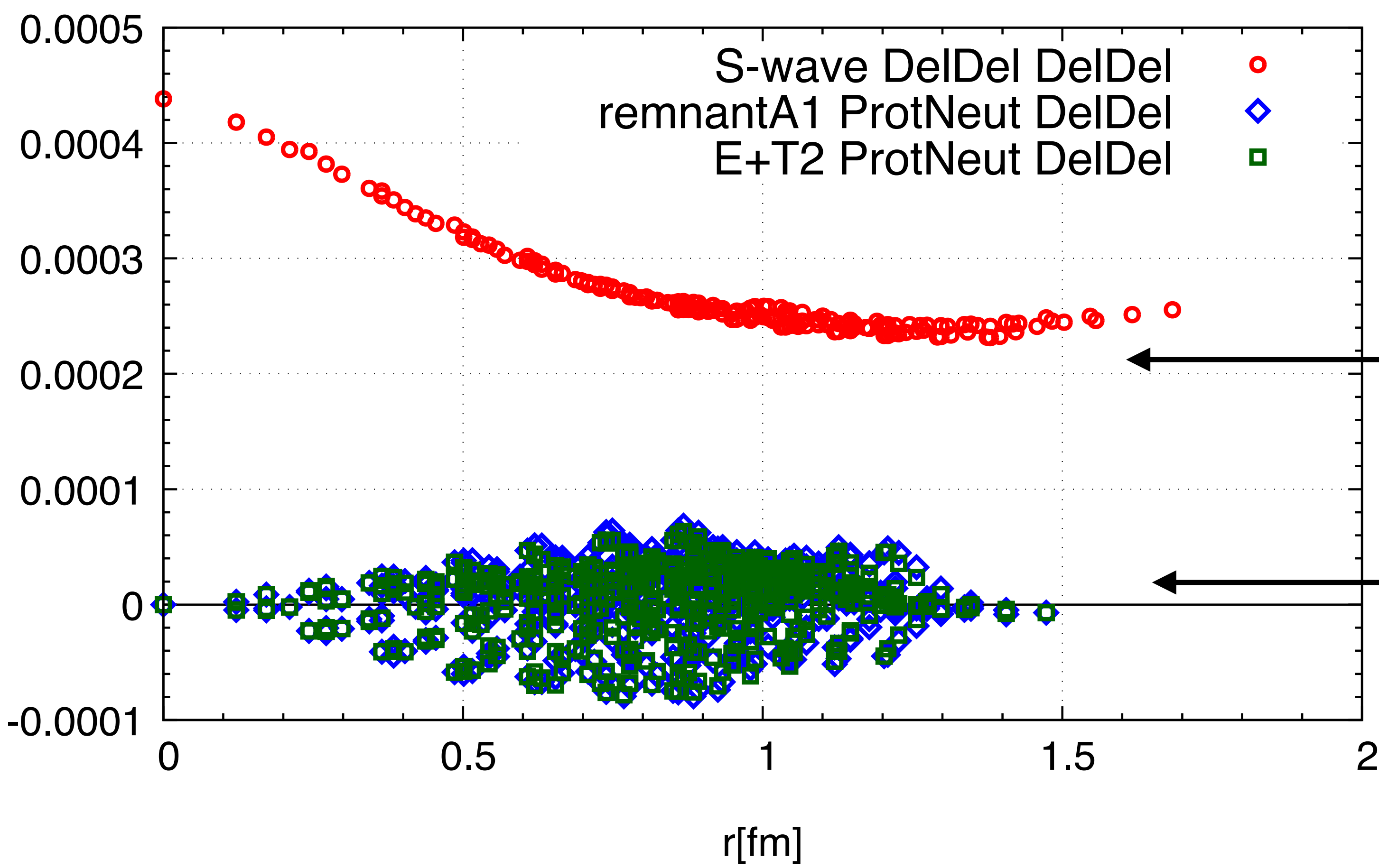
ΩΩ also shows
the similar behavior?

Coupled channel effects

Nf = 2+1 full QCD with L = 1.93fm, m_π=1015MeV, SU(3) limit

$$m_\Delta \simeq 2230\mathrm{MeV}$$
$$m_N \simeq 2030\mathrm{MeV}$$

Rcorrelators



$\Delta\Delta(^7S_3)$-$\Delta\Delta(^7S_3)$

$\Delta\Delta(^7S_3)$-$NN(^3D_3)$

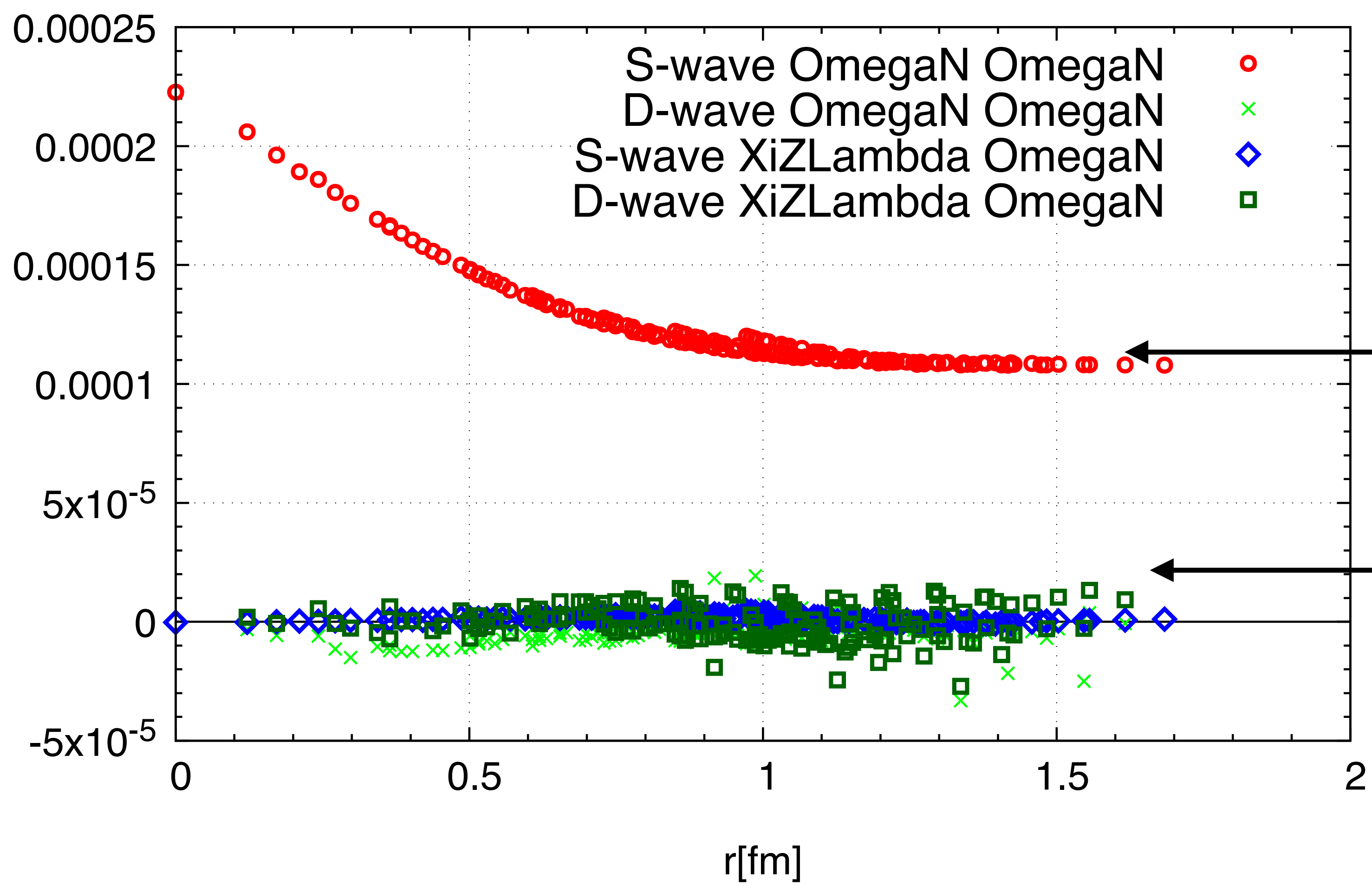
coupling between $\Delta\Delta(^7S_3)$-$NN(^3D_3)$ is small

Coupled channel effects

Nf = 2+1 full QCD with L = 1.93fm, m_π=1015MeV, SU(3) limit

Rcorrelators

$$m_\Omega = m_\Delta \simeq 2230\mathrm{MeV}$$
$$m_\Xi = m_\Lambda \simeq 2030\mathrm{MeV}$$

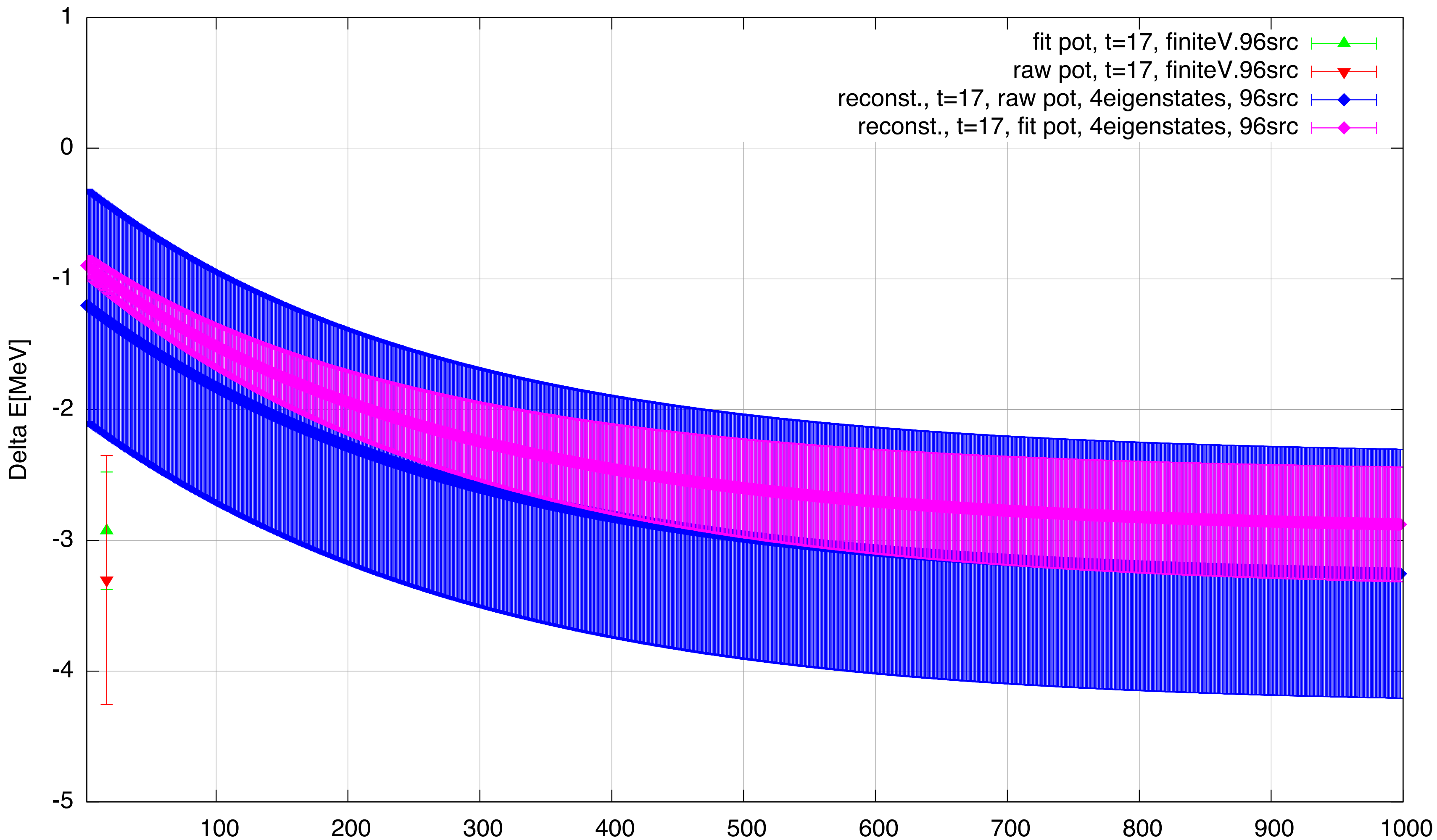


$\Omega N(^5S_2)$-$\Omega N(^5S_2)$

$\Omega N(^5S_2)$-$\Xi\Lambda(^1D_2)$

coupling between $\Omega N(^5S_2)$-$\Xi\Lambda(^1D_2)$ is very small

platux region in Omg-Omg at phys. point



To extract the B.E. using Luscher's method,
t/a >1000 is needed

Results w/ physical masses

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$\Xi\Xi$(S=-4)

$^1S_0$ 27plet $\Leftrightarrow$ Flavor SU(3)-partner of NN($^1S_0$)

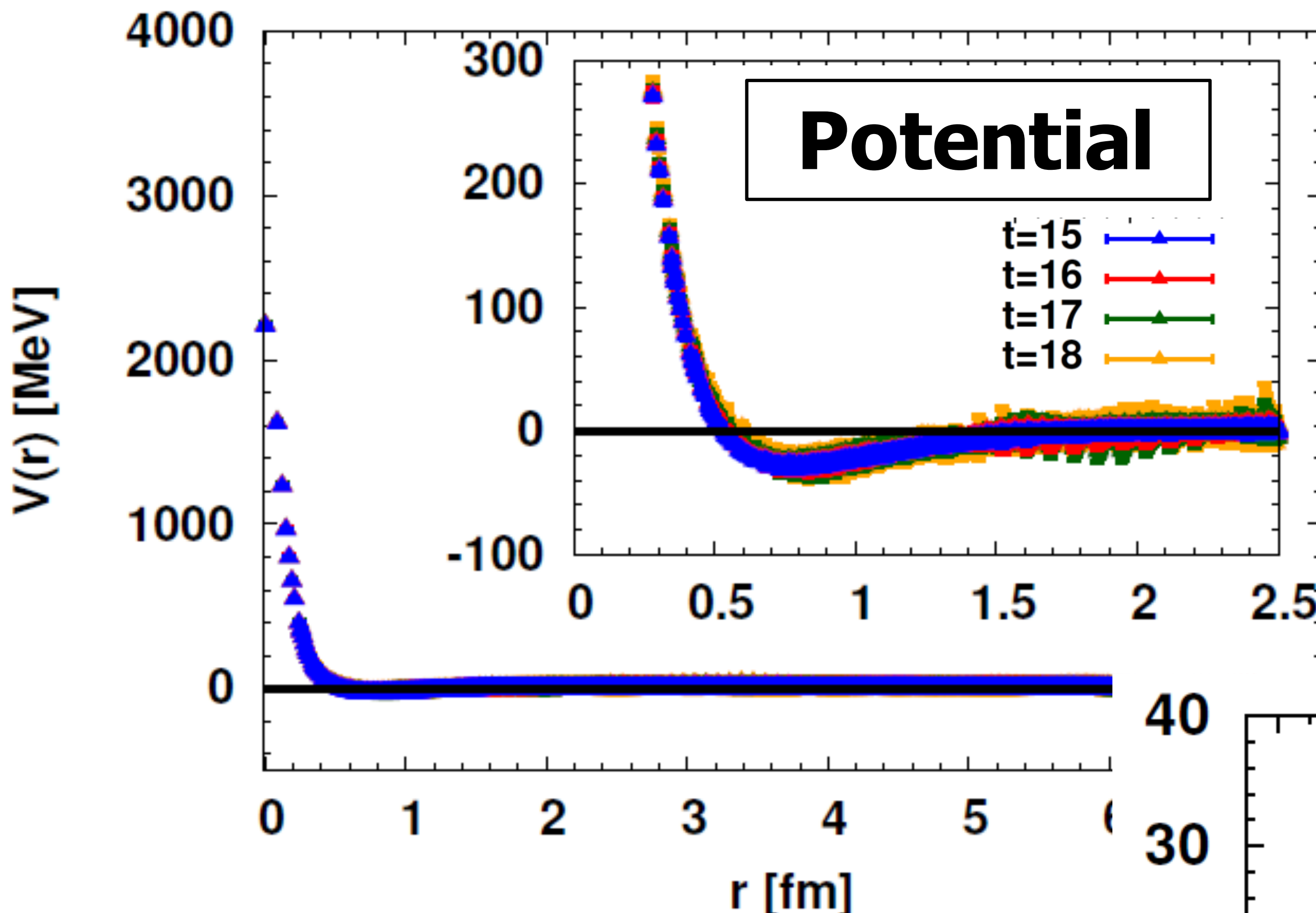
$\Rightarrow$
- Doorway to NN-forces
- Bound by SU(3) breaking ?

$^3S_1$-$^3D_1$ 10plet $\Leftrightarrow$ unique w/ hyperon DoF

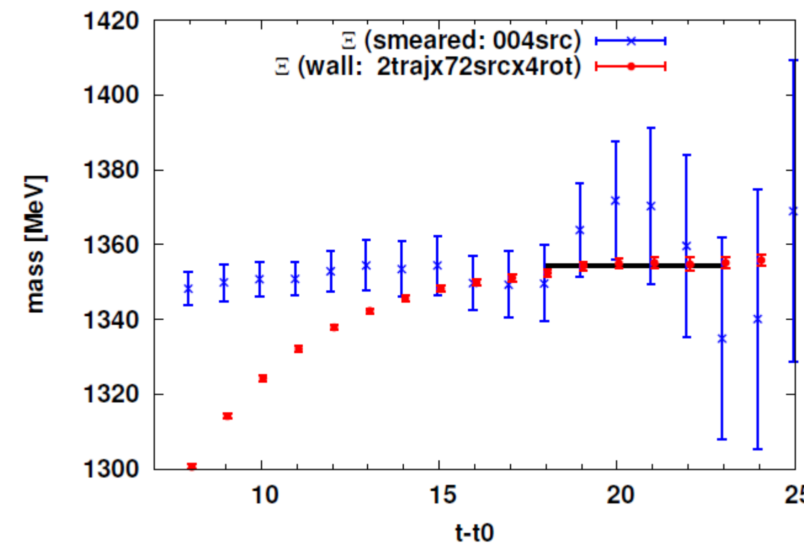
Flavor SU(3)-partner of Σ^- n

$\Rightarrow$
- Σ^- in neutron star ?

ΞΞ system ($^1S_0$)



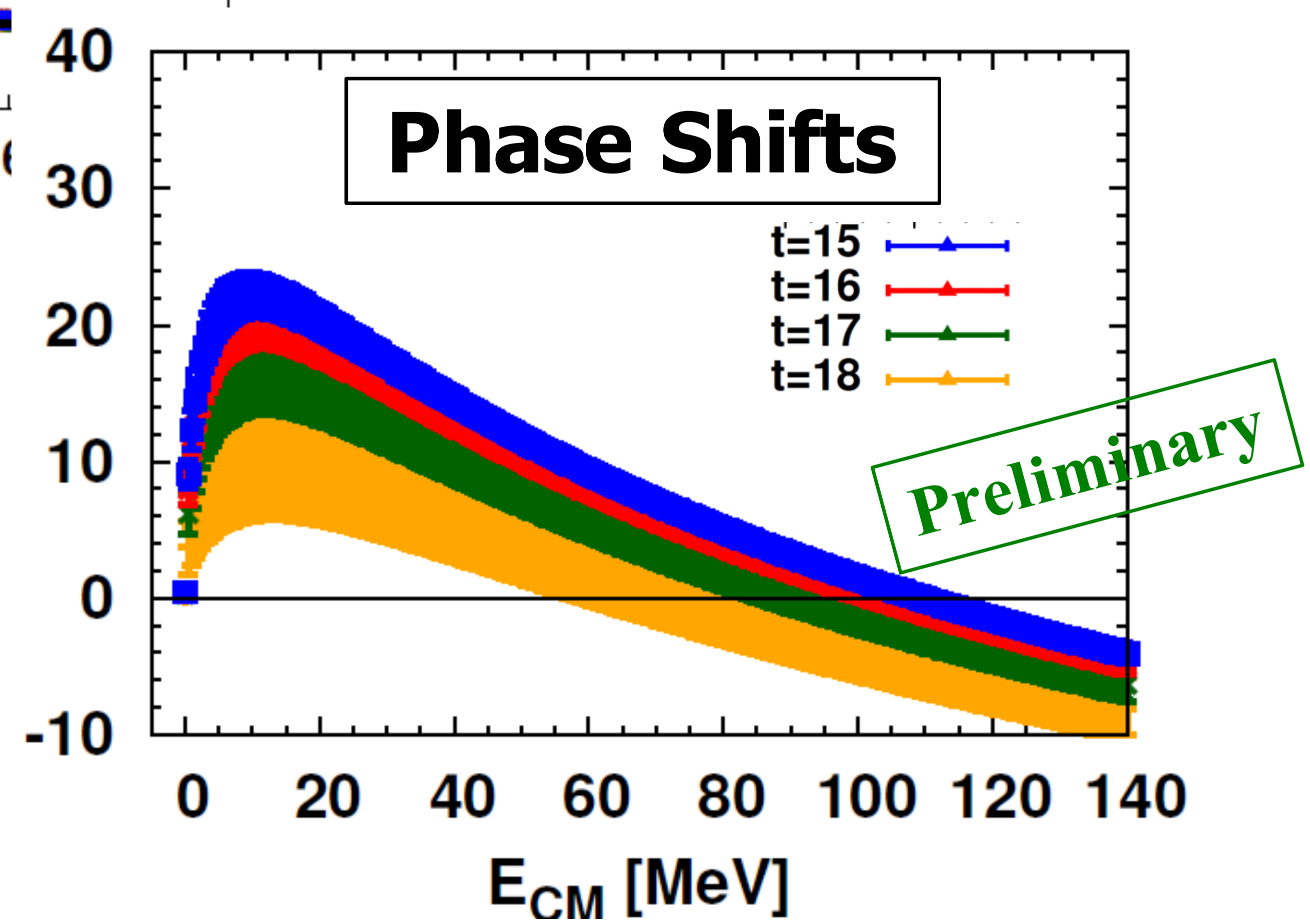
single Ξ



Strong Attraction

yet Unbound

⟺ ΞΞ correlation in HIC

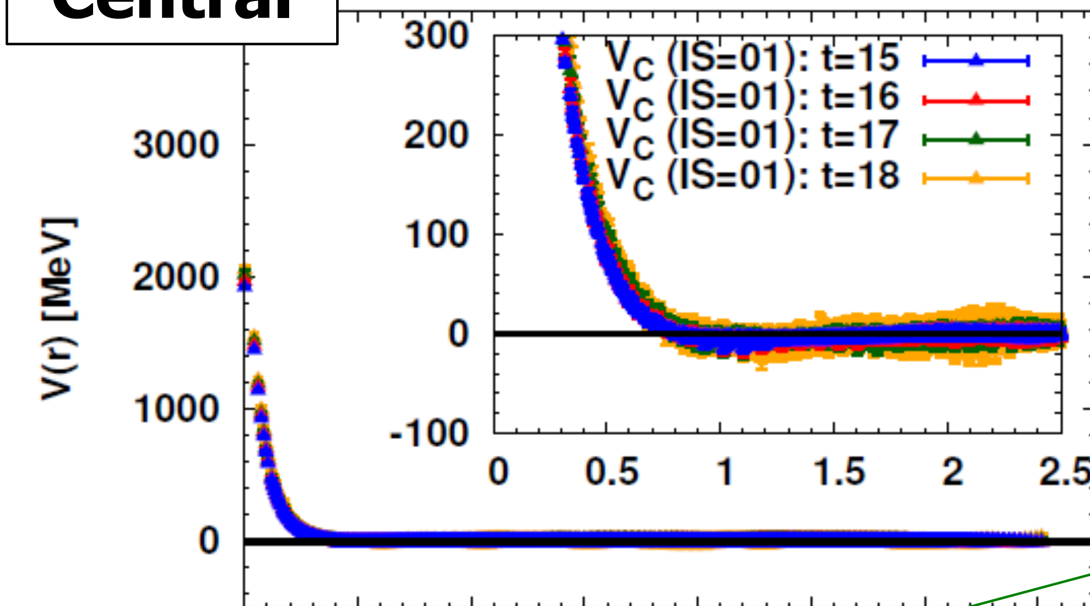


(2-gauss + 2-OBEP)

ΞΞ system ($^3S_1$-$^3D_1$)

Potentials

Central

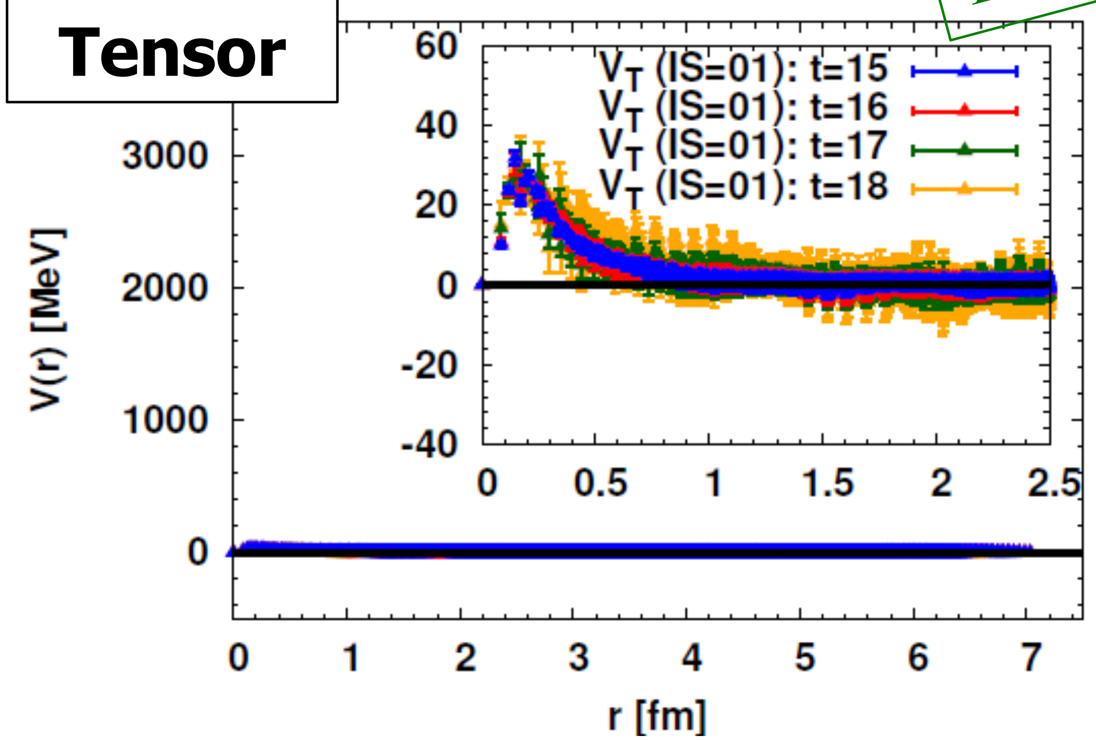


Central: Strong Repulsion

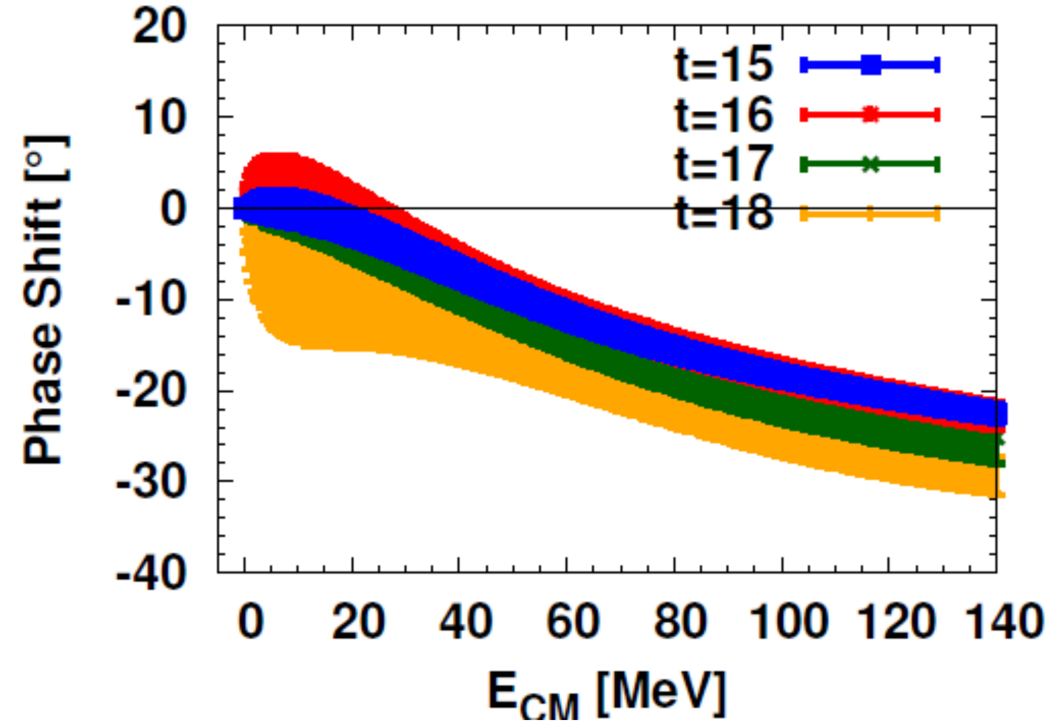
Tensor: Weak

Preliminary

Tensor



Phase Shifts (effective $^3S_1$)



H-dibaryon channel (S= –2)

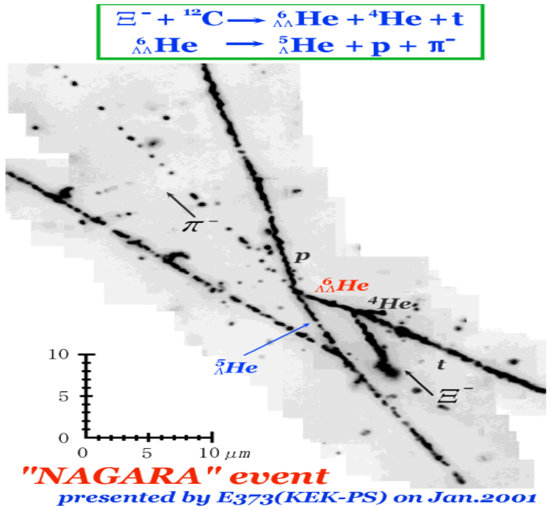
($^1S_0$, $\Lambda\Lambda$–$N\Xi$–$\Sigma\Sigma$, Coupled Channel)

R. Jaffe (1977), **"Perhaps a Stable Dihyperon"**

NAGARA-event (2001)

$$\Xi^- + {}^{12}\mathrm{C} \to {}_{\Lambda\Lambda}{}^6\mathrm{He} + {}^4\mathrm{He} + t$$

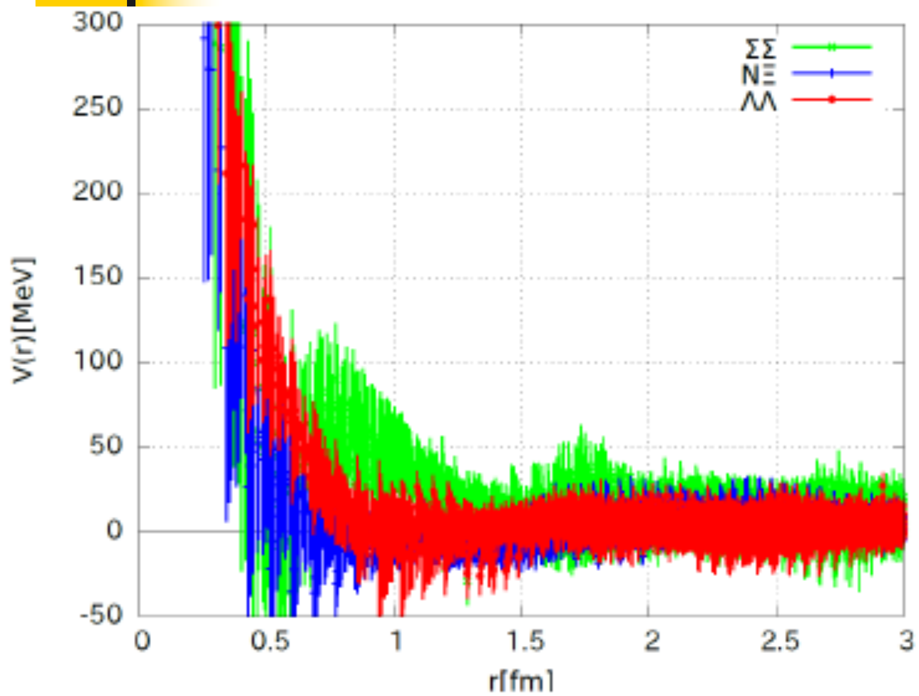
- $\Lambda\Lambda$ weak attraction
- No deeply bound H-dibaryon



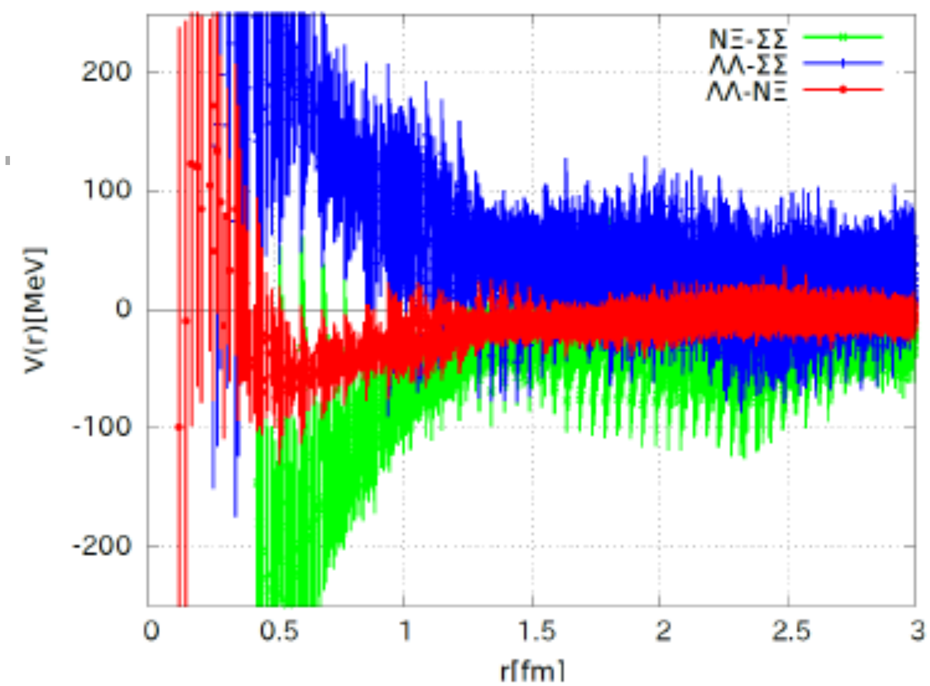
H-dibaryon @ Nf=2+1, m_π=146 MeV

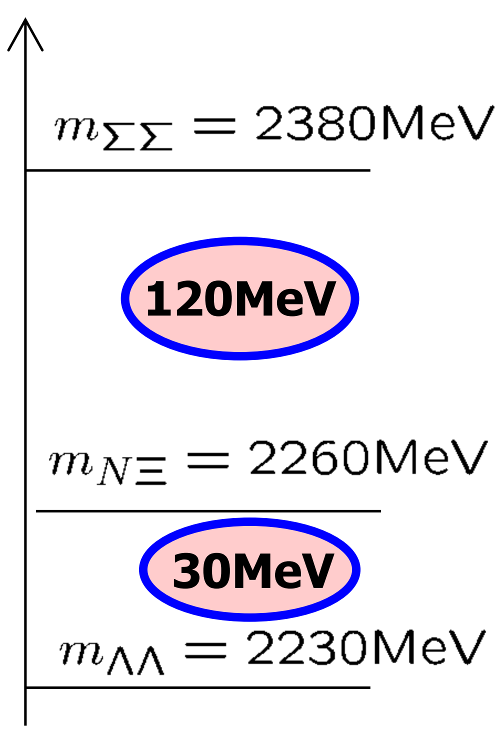
[K. Sasaki]

diagonal



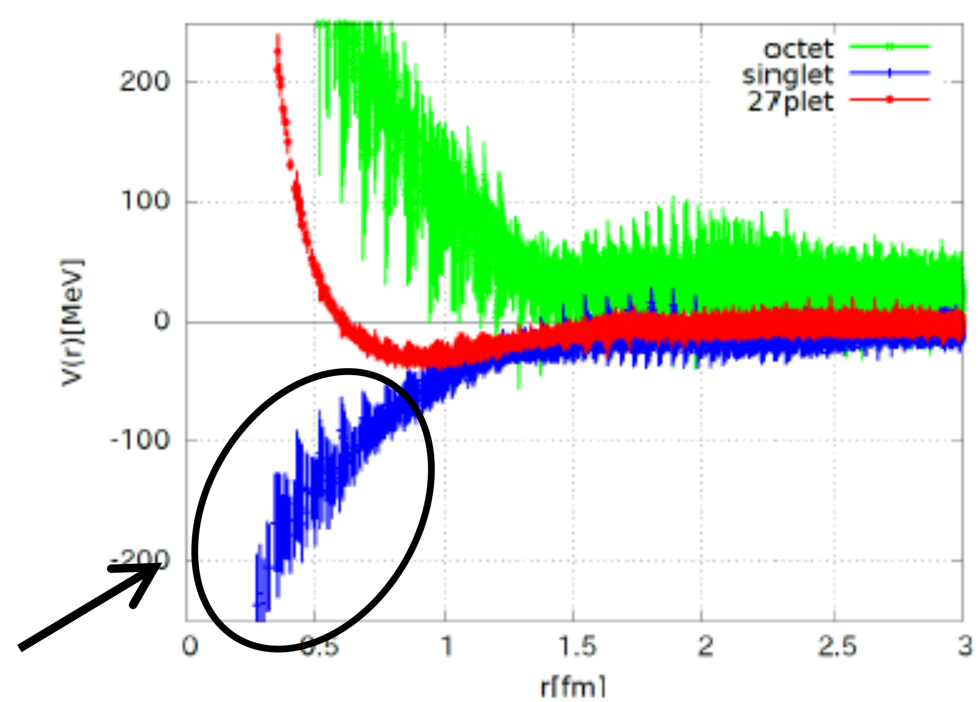
off-diagonal





diagonal in SU(3)-irrep base

Strong Attraction in flavor-singlet channel



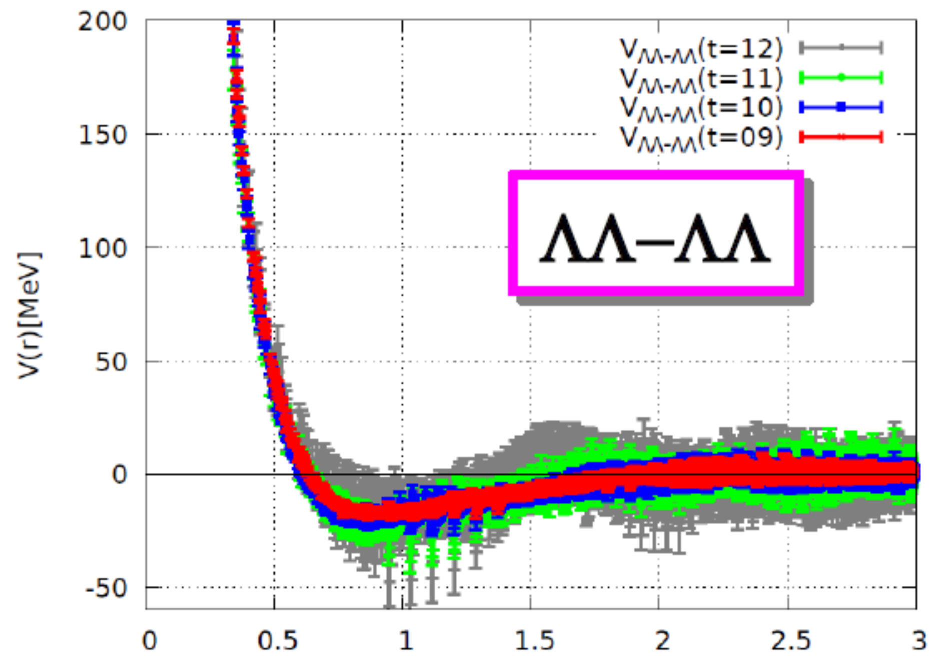
(400conf x 4rot x 28src, t=11)

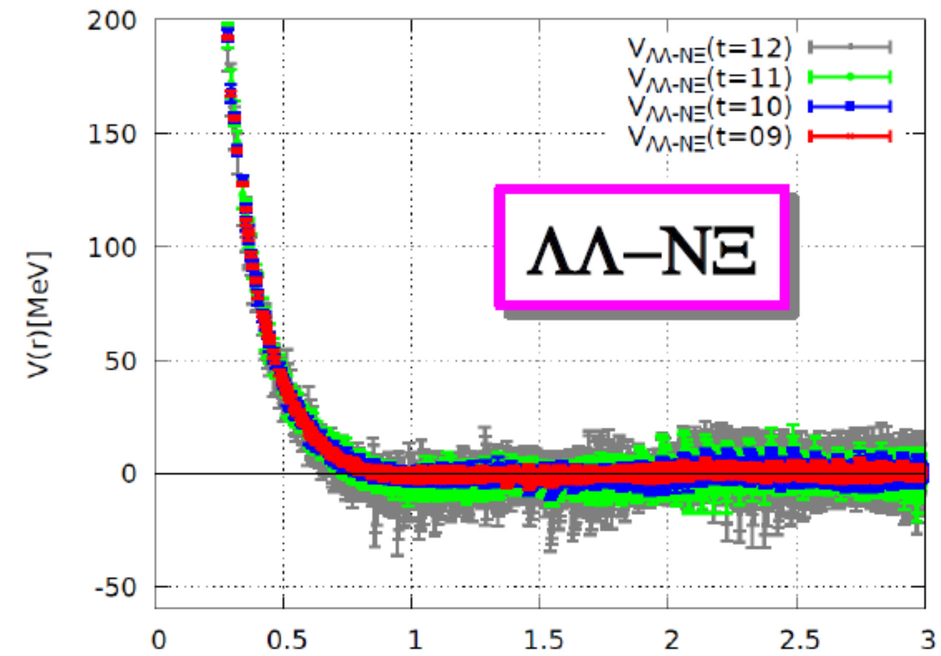
ΛΛ, NΞ (effective) 2x2 coupled channel analysis

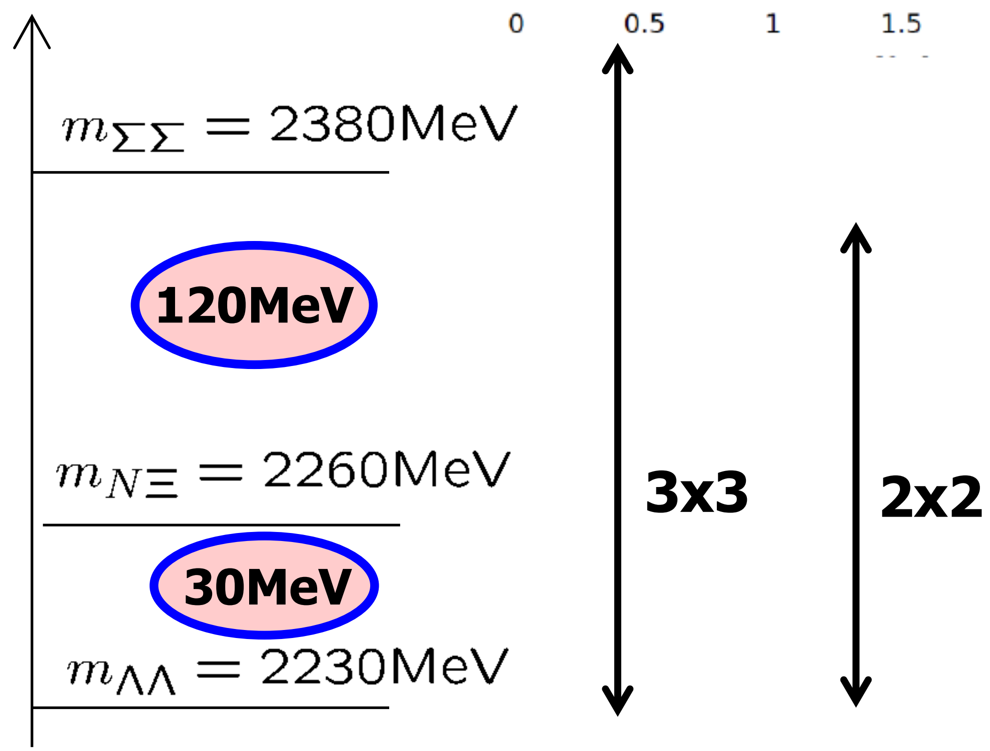
ΣΣ channel ←→ couples strongly to flavor octet channel

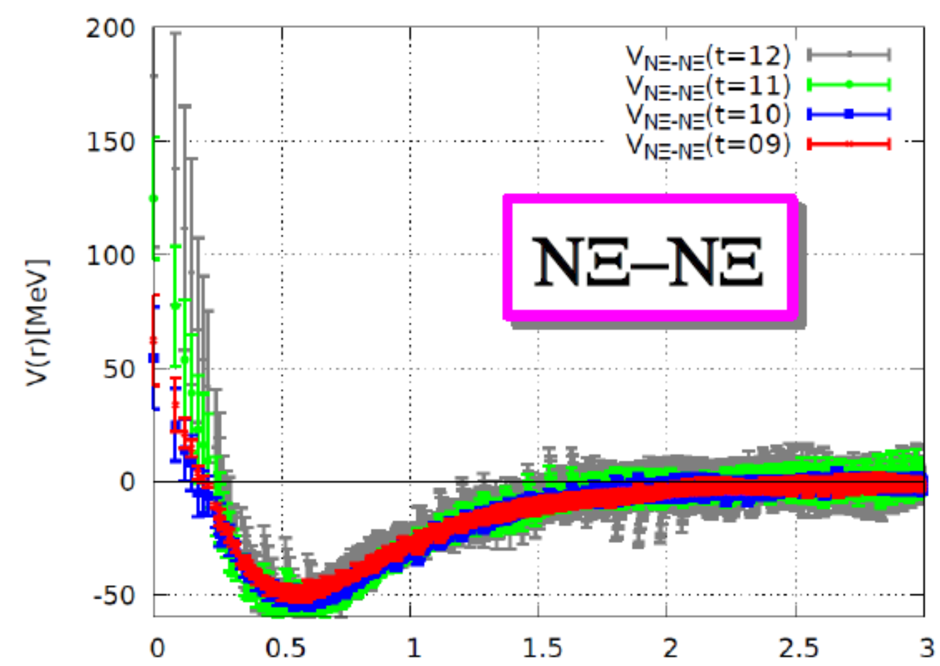
←→ noisy because they are quark-Pauli forbidden

➔ Improve the S/N by considering only ΛΛ, NΞ dof at low energies



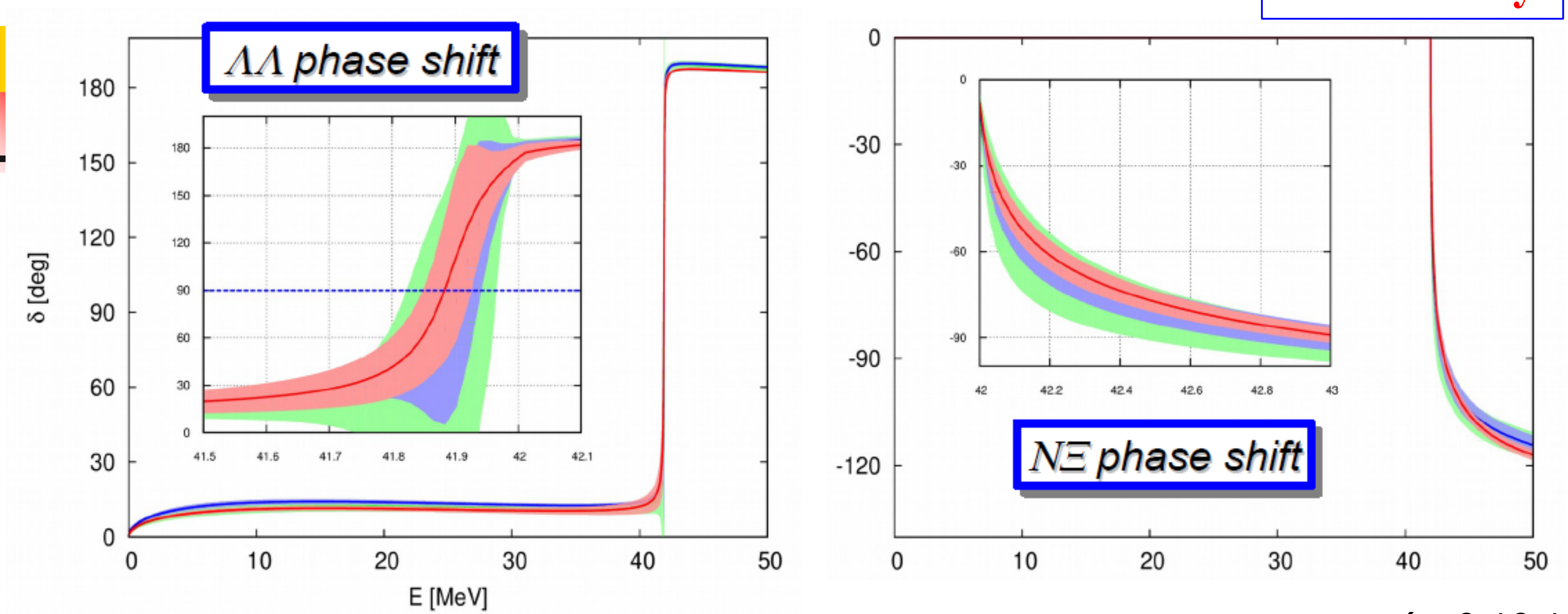




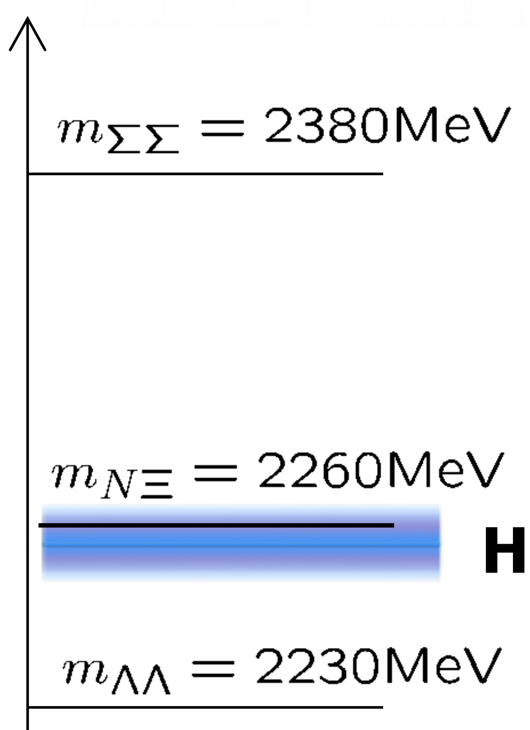


ΛΛ, NΞ (effective) 2x2 coupled channel analysis

Preliminary



(t=9,10,11)



H-resonance

<u>"Perhaps a Resonant Dihyperon"</u>

➔ J-PARC experiment (E42)

N.B. t-dep should be checked;
single m_B has ~3% sys @ t=10

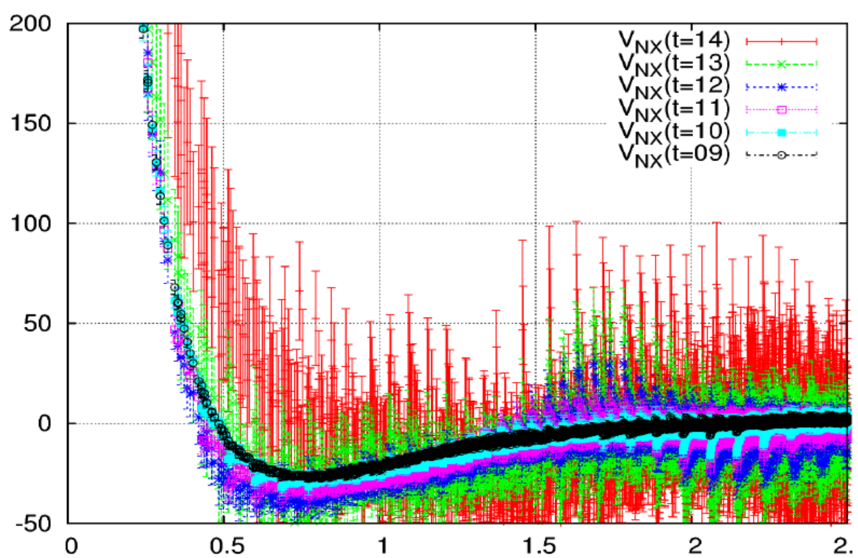
[K. Sasaki]

NΞ-Potentials

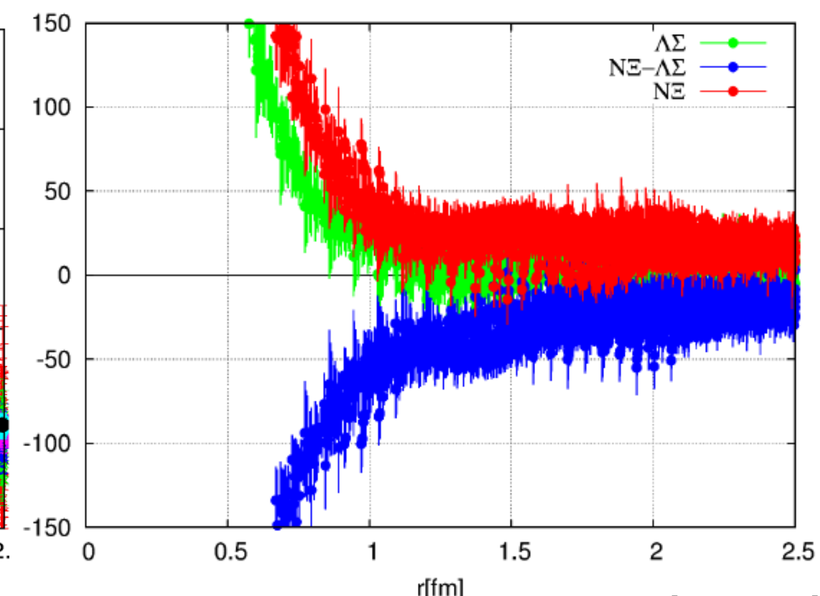
[K. Sasaki]

(200conf x 4rot x 20src, t=10)

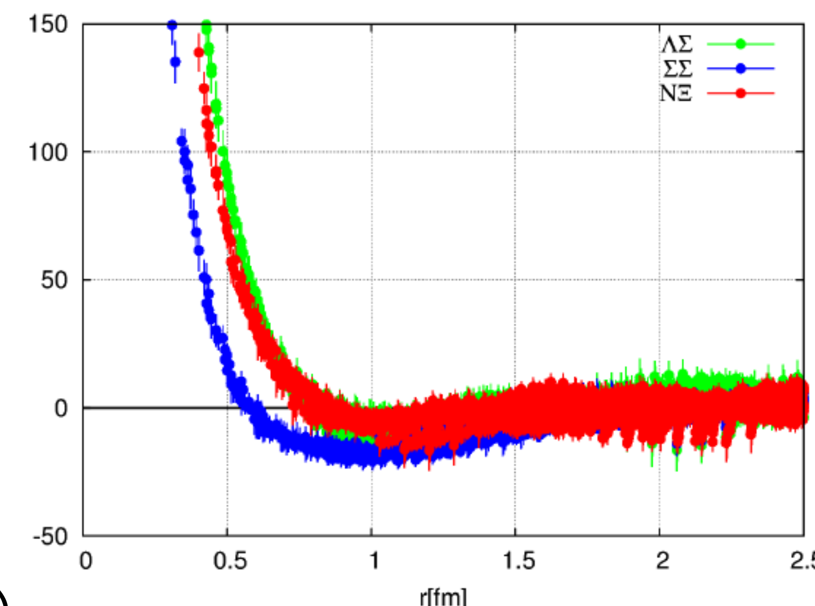
NΞ (I=0, $^3S_1$)	NΞ–ΛΣ (I=1, $^1S_0$)	NΞ–ΛΣ–ΣΣ (I=1, $^3S_1$)



(8a)



(8s, 27)



(8a, 10, 10bar)

Attractive **Repulsive** **Attractive**

(ΛΛ–NΞ–ΣΣ (I=0, $^1S_0$))

Is interaction net attractive ? Stay tuned !

c.f. Net attractive @ m(pi)=0.66-88GeV (K. Sasaki et al., PTEP2015, 113B01)

$S = -1$ systems

←→ strangeness nuclear physics (Λ-hypernuclei @ J-PARC)

Λ should (?) appear in the core of Neutron Star

←→ Huge impact on EoS of high dense matter

- **$\Lambda N - \Sigma N$ (I=1/2) : coupled channel**
  - $^1S_0$ $\sim$ **27-plet & 8s-plet**
  - $\boxed{^3S_1\text{-}^3D_1 \sim 10^*\text{-plet \& 8a-plet}}$
- **ΣN (I=3/2)**
  - $^1S_0$ $\sim$ **27-plet**
    ⇔ NN($^1S_0$) + SU(3) breaking
  - $^3S_1\text{-}^3D_1$ $\sim$ **10-plet**

75

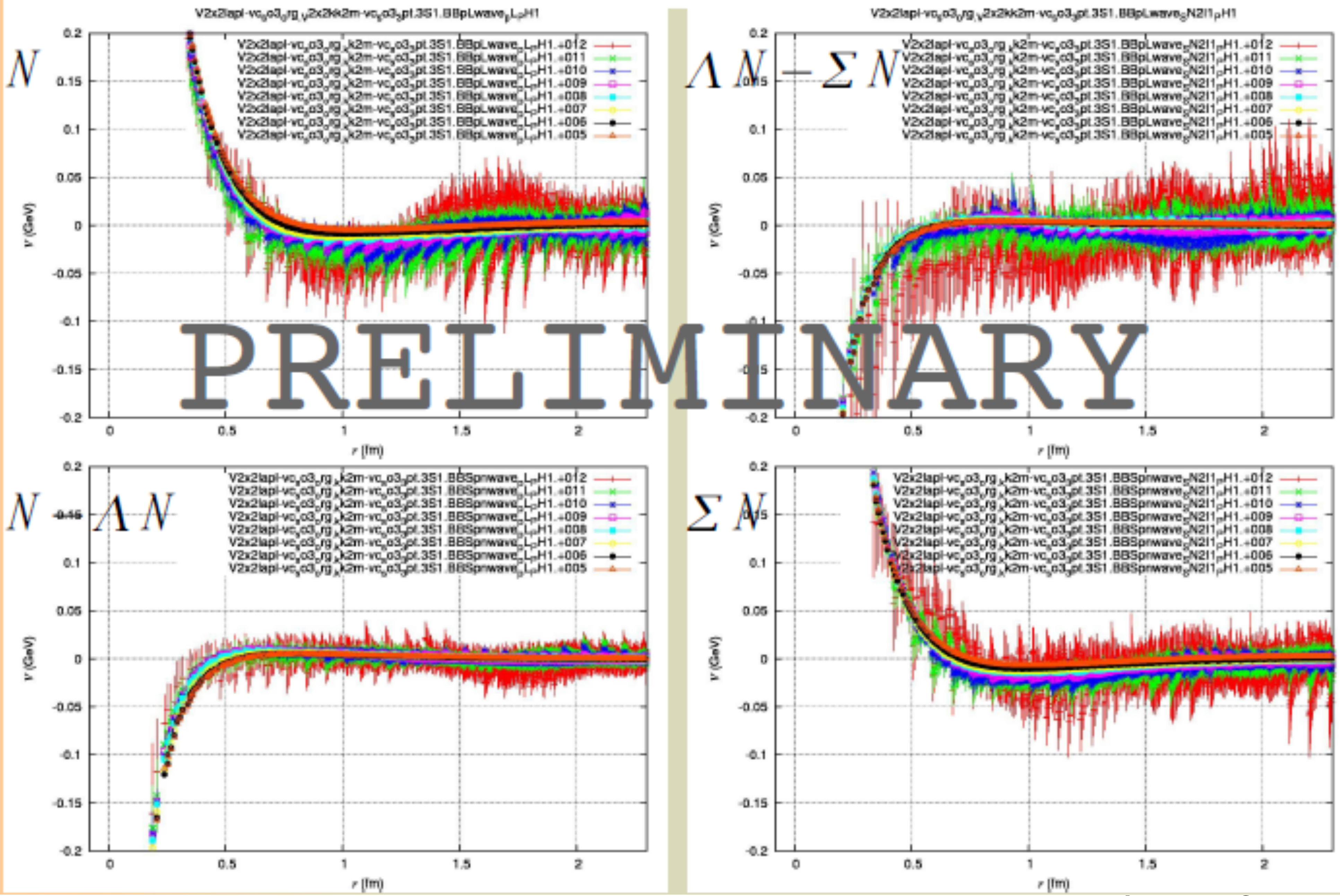
ΛN–ΣN Vc potential in $^3S_1$–$^3D_1$

[H. Nemura]

Very preliminary result of LN potential at the physical point

$$V_C(^3S_1 - {}^3D_1)$$

$$\left(\frac{\nabla^2}{2\mu} - \frac{\partial}{\partial t}\right) R(\vec{r},t) \;=\; \int d^3r'\, U(\vec{r},\vec{r}')R(\vec{r}',t) + O(k^4) = V_{\rm LO}(\vec{r})R(\vec{r},t) + \cdot (8)$$



(200conf x 4rot x 52src)

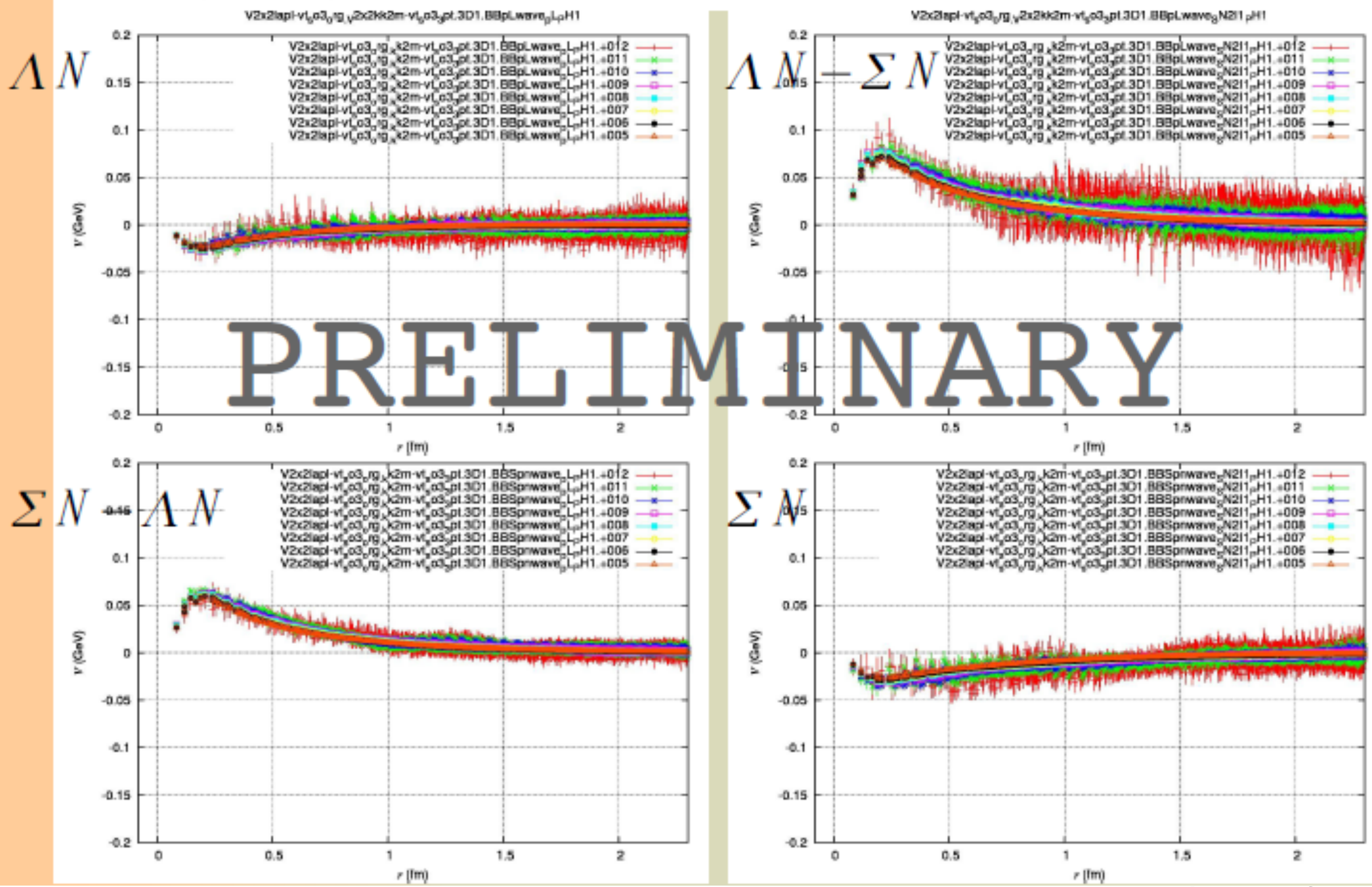
ΛN–ΣN Vt potential in $^3S_1$–$^3D_1$

[H. Nemura]

Very preliminary result of LN potential at the physical point

$V_T(^3S_1 - ^3D_1)$

$$\left(\frac{\nabla^2}{2\mu} - \frac{\partial}{\partial t}\right) R(\vec{r},t) = \int d^3r'\, U(\vec{r},\vec{r}')R(\vec{r}',t) + O(k^4) = V_{\rm LO}(\vec{r})R(\vec{r},t) + \cdots (8)$$



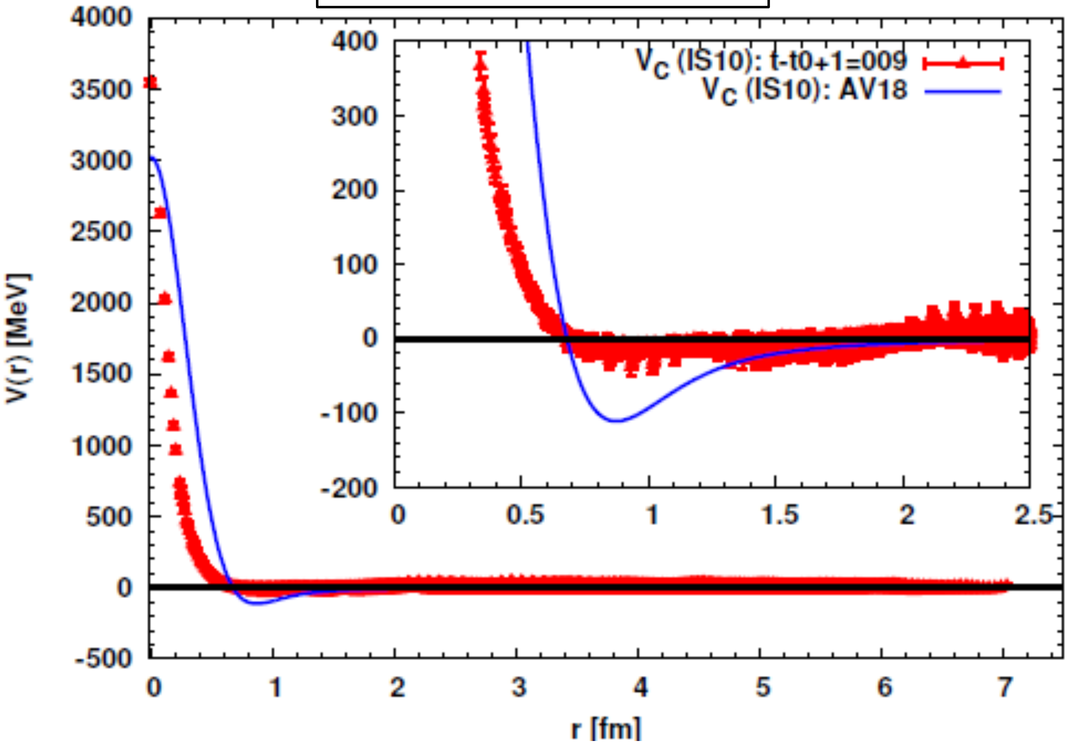
(200conf x 4rot x 52src)

NN system (S= 0)

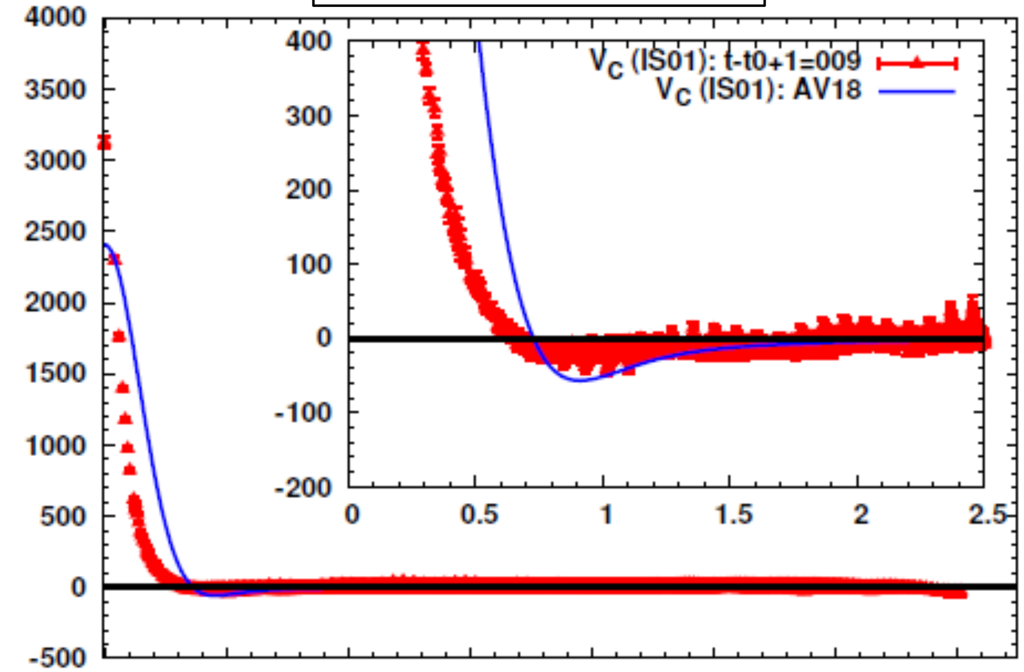
Naïve comparison w/ AV18

NN

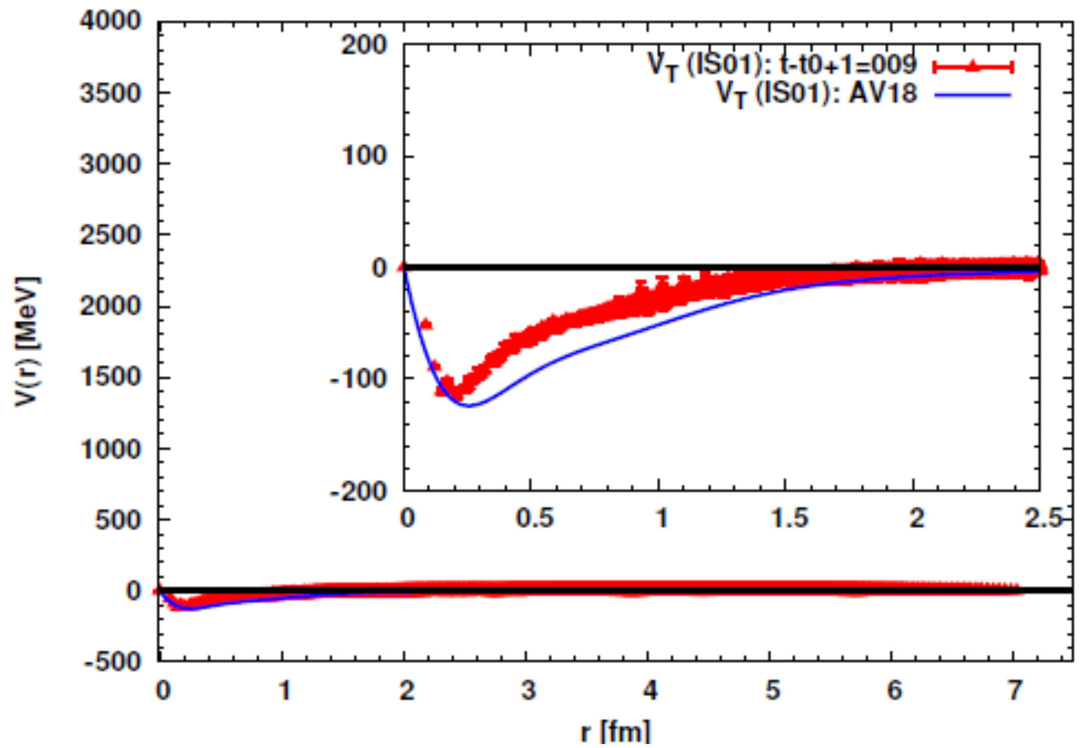
1S0



3S1-3D1



Central



Tensor

t-t0=8

(400conf x 4rot x 48src)

WASA@COSY PRL 106, 242302 (2011) June

PRL 106, 242302 (2011) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2011

Abashian-Booth-Crowe Effect in Basic Double-Pionic Fusion: A New Resonance?

$m = 2.37$ GeV, $\Gamma \approx 70$ MeV and $I(J^P) = 0(3^+)$ in both pn and $\Delta\Delta$ systems.