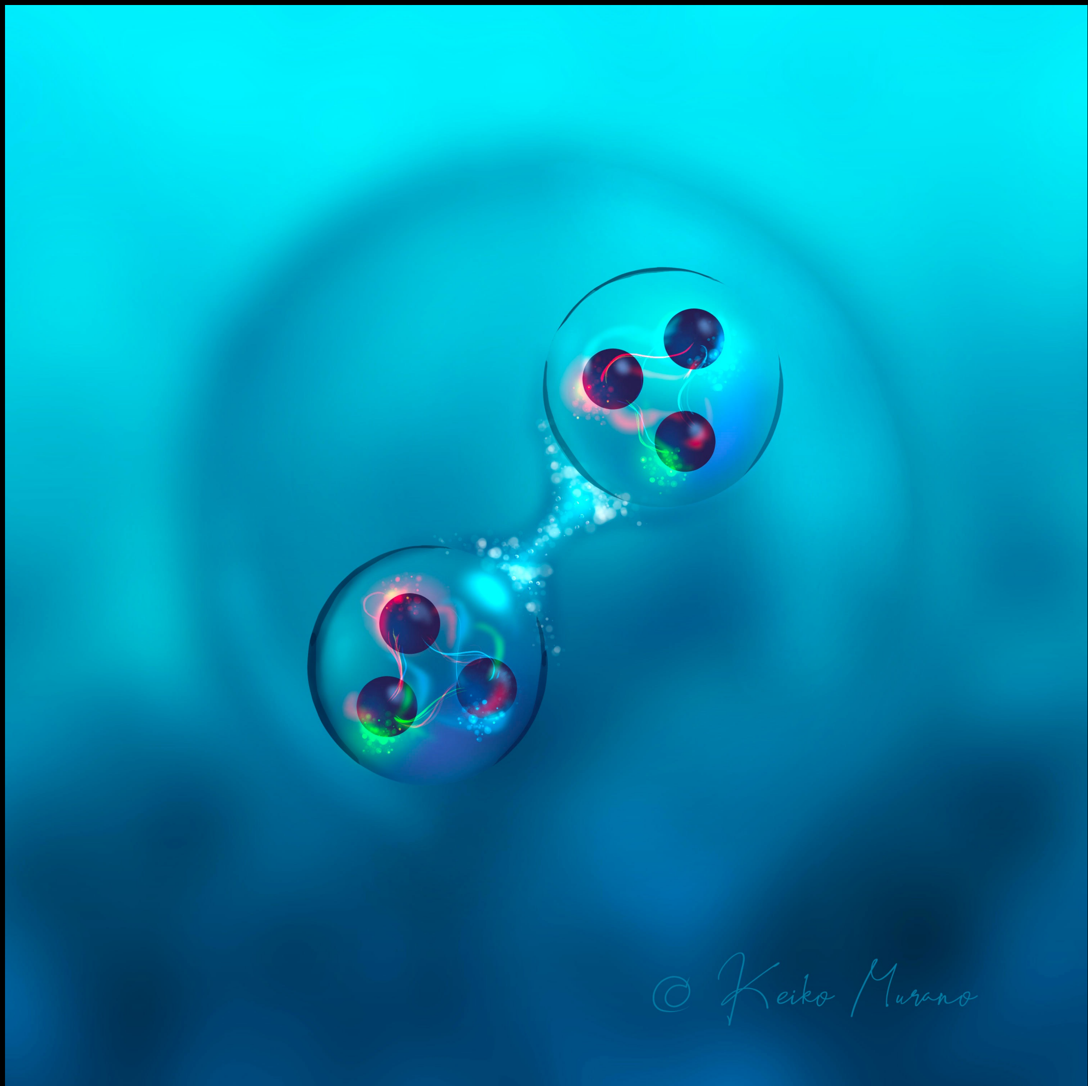
Hyperon Interactions from Lattice QCD
- Theory Meets Experiments -



Tetsuo Hatsuda
(RIKEN iTHEMS)

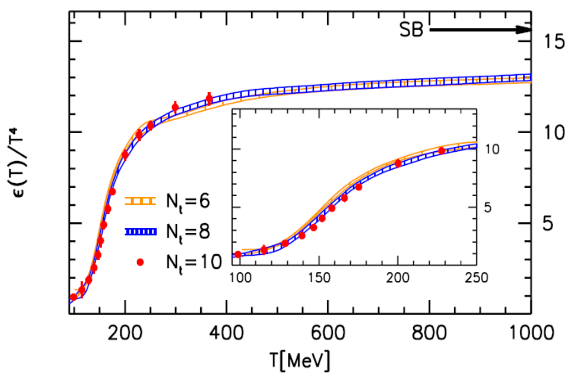
iTHEMS
RIKEN interdisciplinary Theoretical & Mathematical Sciences

Cond-Mat QCD
(March 21, 2024)

From QCD to Hot/Dense Matter

Quantum Chromo Dynamics

LQCD



LQCD

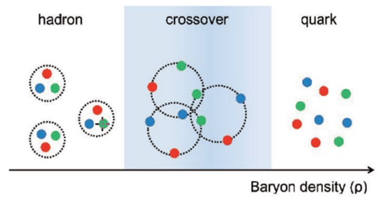
sign problem

LQCD

ChEFT

Baryon interactions

Many-body methods
+ assumptions
on QM



Equation of State for Hot Matter

relativistic hydrodynamics

Relativistic heavy Ion collisions

Equation of State of Dense Matter

general relativity

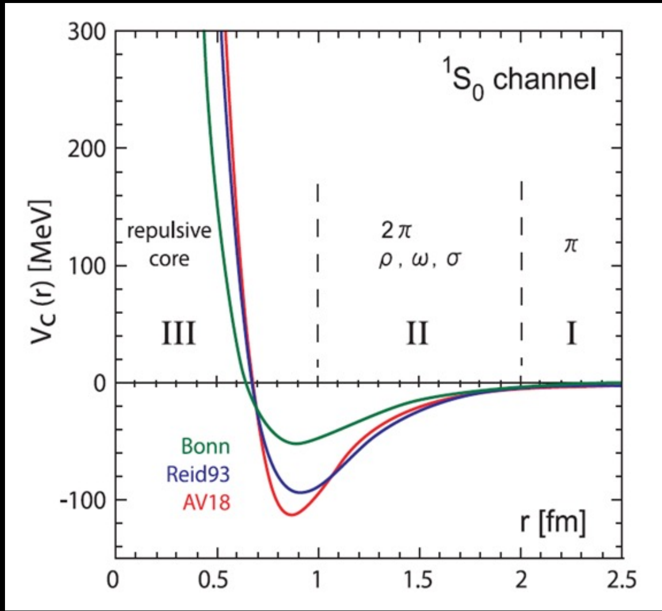
Neutron star

Baryon interactions: Phenomenology vs. LQCD

- NN int.: about 4500 np and pp scatt. data

"high precision" NN interactions		# of parameters
CD Bonn	(p space)	38
AV18	(r space)	40
EFT in N^3LO	(nπ+contact)	24

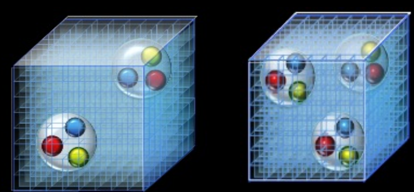
R. Machleidt, arXiv:0704.0807 [nucl-th]



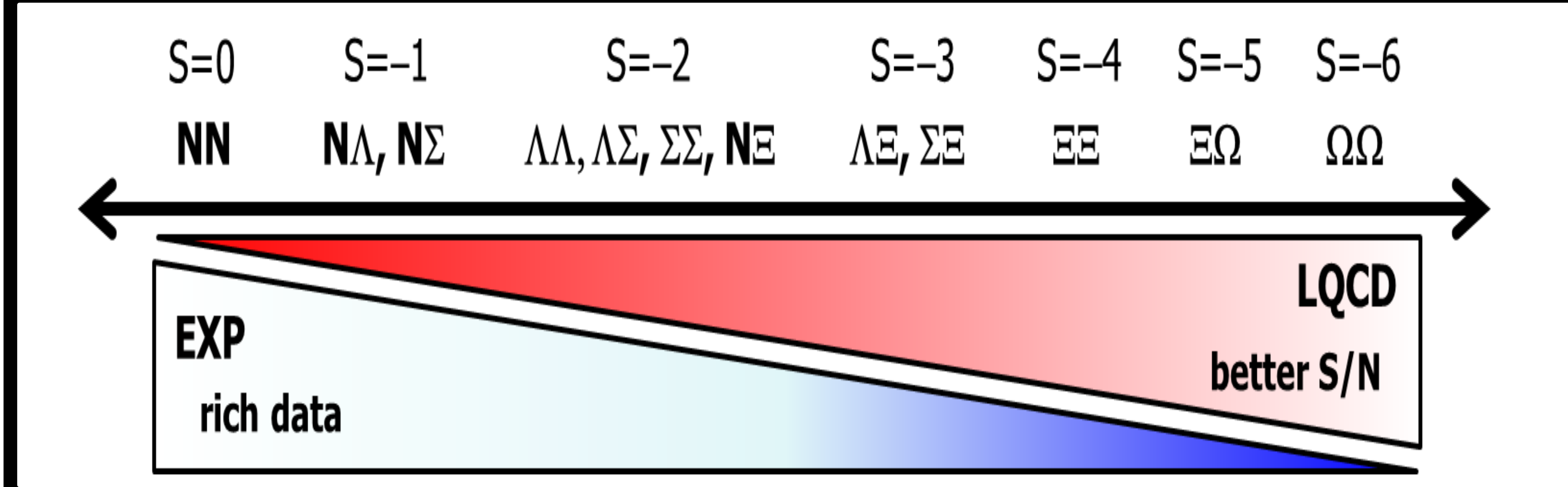
- NNN, YN, YY : data very limited
- YYN, YNN, YYY : data none

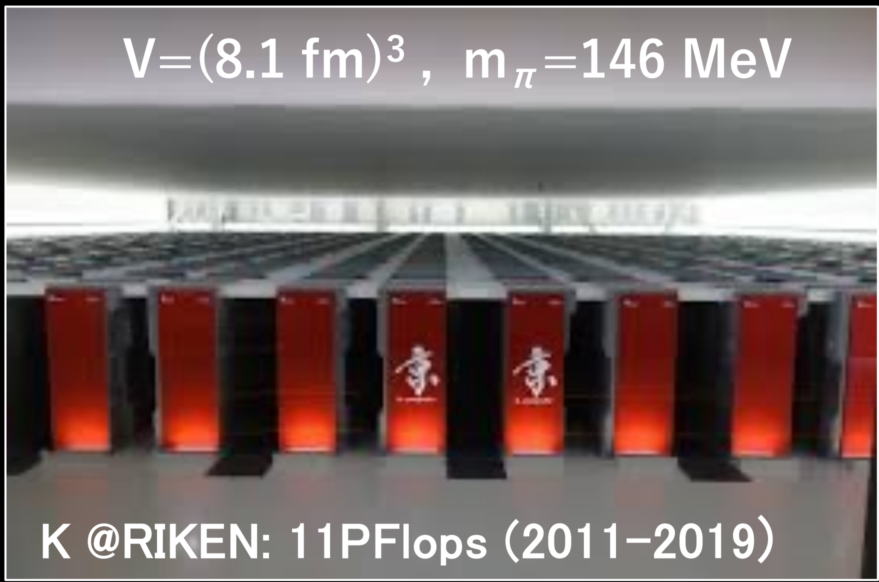
QCD has only 4 parameters: g , $m_{u,d,s}$

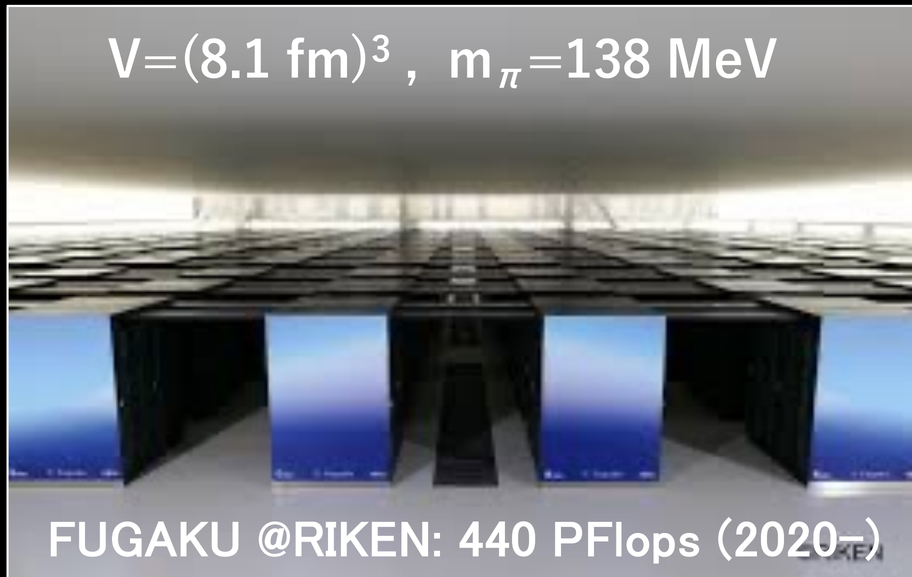
→ BB and BBB forces from LQCD



Large scale LQCD simulations for Hadron interactions







Interaction between compositive particles in QFT

- Haag-Nishijima-Zimmermann reduction formula (1958)
- Borchers Theorem (1960)

Correlation of almost-local composite operators → the same S-matrix

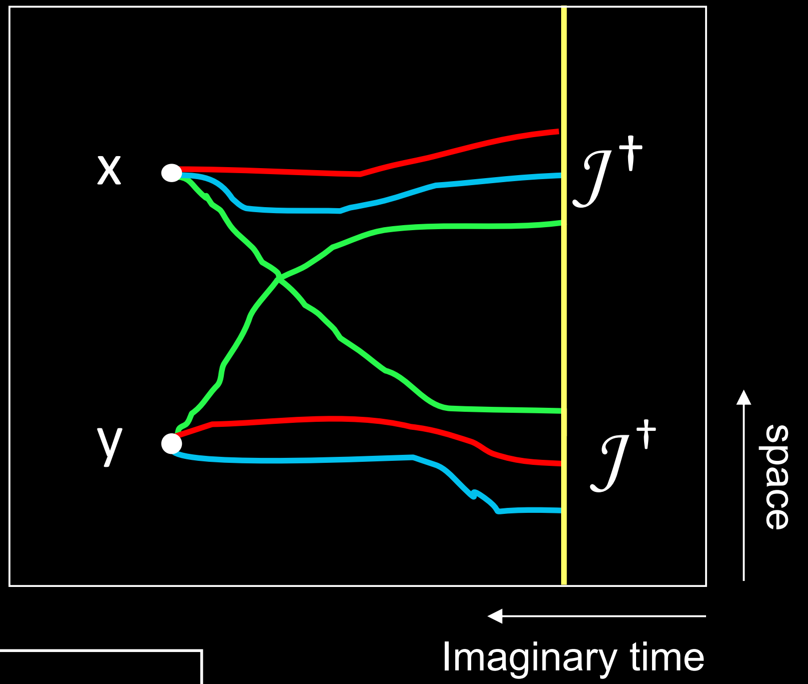
Luscher's Method: Luscher, NPB 354 (1991) 531

HAL QCD Method:

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

Ishii+ [HAL QCD Coll.], PLB 712 (2012) 437

$$\langle N_1(\mathbf{x},t)N_2(\mathbf{y},t)\mathcal{J}_1^\dagger(0)\mathcal{J}_2^\dagger(0)\rangle$$
$$= \sum_n \langle 0|N_1(\mathbf{x})N_2(\mathbf{y})|n\rangle a_n e^{-E_n t}$$
$$\xrightarrow{t>t^*} F^J(\mathbf{r},t) = \sum_n a_n^J \psi_n(\mathbf{r}) e^{-E_n t}$$

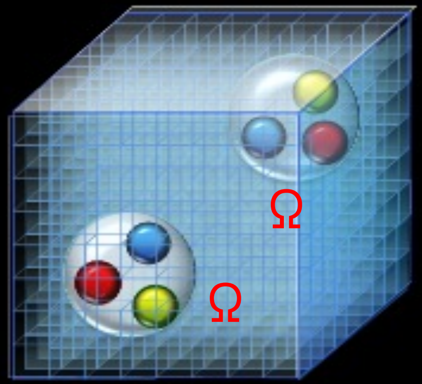


$$(\nabla^2 + \partial_{2t}^2 - m^2)F^J(\mathbf{r},t) = m\int d^3r\, U(\mathbf{r},\mathbf{r}')F^J(\mathbf{r}',t)$$

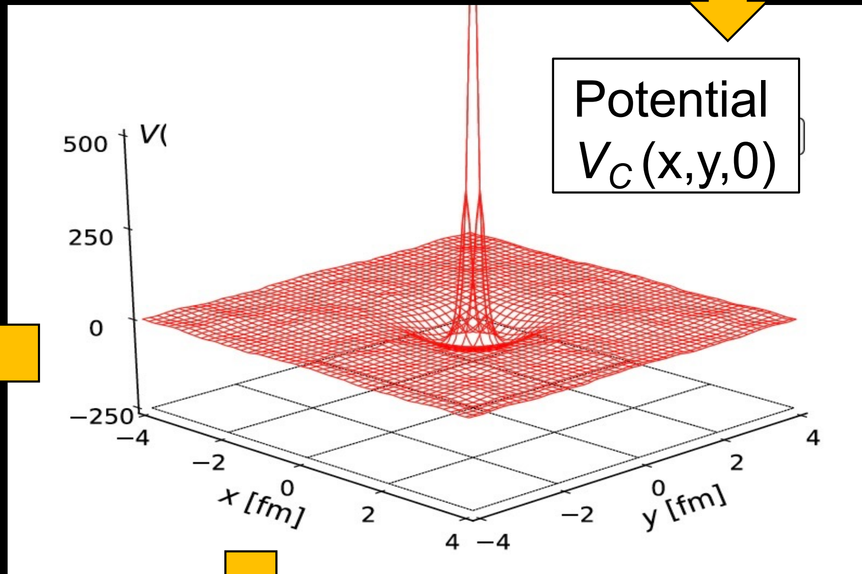
$$U(\mathbf{r},\mathbf{r}') = V(\mathbf{r},\mathbf{v})\delta(\mathbf{r}-\mathbf{r}'),$$
$$V(\mathbf{r},\mathbf{v}) = \underbrace{V_C(r) + V_T(r)S_{12}}_{\text{LO}} + \underbrace{V_{LS}(r)\mathbf{L}\cdot\mathbf{S}}_{\text{NLO}} + \underbrace{O(\mathbf{v}^2)}_{\text{N}^2\text{LO}} + \cdots$$

HAL QCD Method: an example
($\Omega\Omega$ at m_π=146MeV)

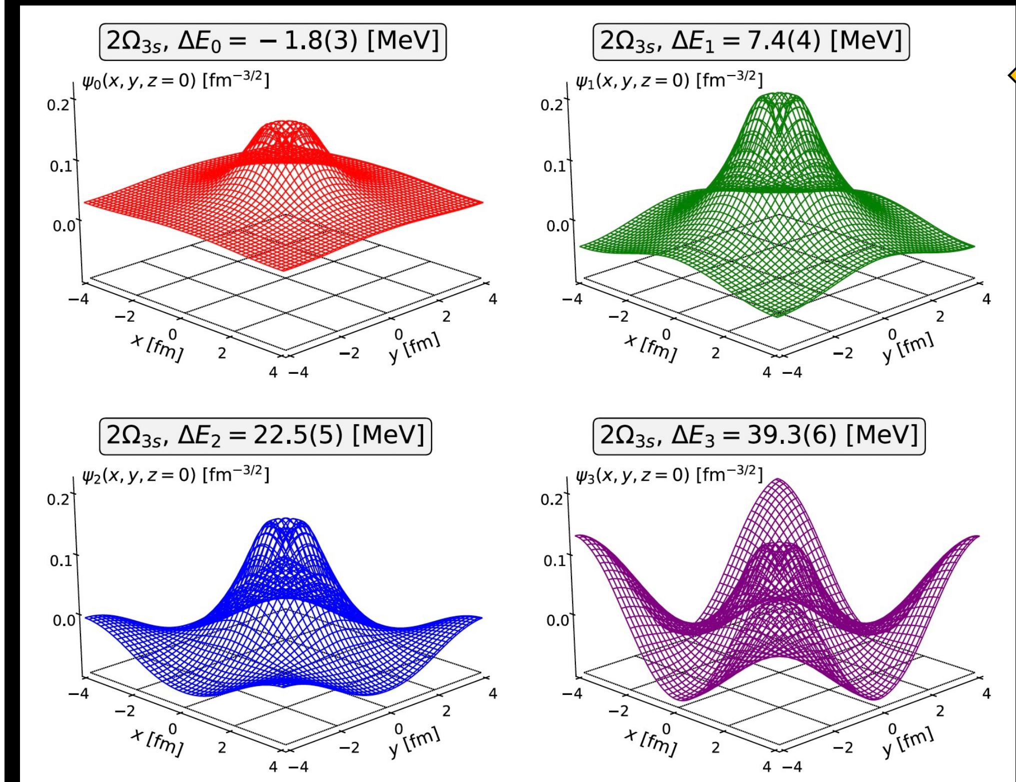
Lyu+ [HAL QCD], PRD 105 (2022) 074512

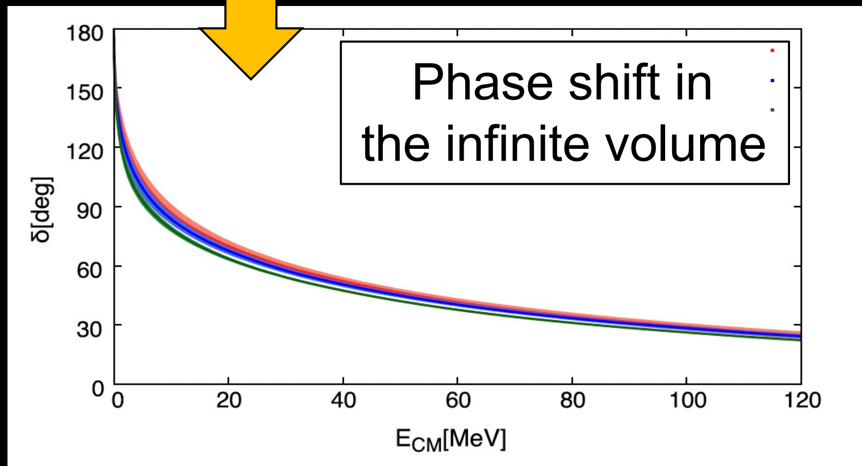


$$F^J(\mathbf{r},t) = \sum_n a_n^J \psi_n(\mathbf{r}) e^{-E_n t} \rightarrow V_C(r)$$



Ψ_n (r) and E_n in a finite volume

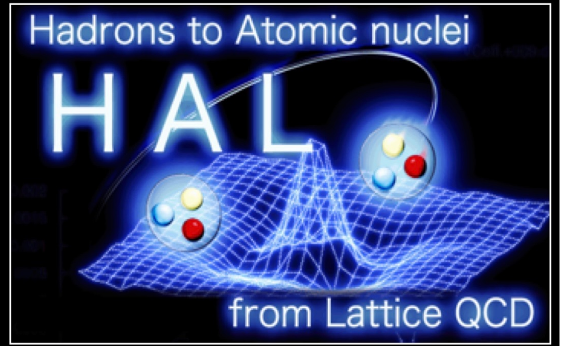




Some recent results from K-computer

(L=8.1 fm， m_π=146 MeV)

vs. LHC experiments



Baryon-Baryon

S=-6 strange dibaryon, ΩΩ
Gongyo+ PRL 120, 212001 (2019)

S=-3 dibaryon, NΩ
Iritani+, PLB 792, 284 (2019)

<-> LHC ALICE, Nature (2020)

S=-2 hyperon interaction, ΛΛ, NΞ
Sasaki+, NPA 998, 121737 (2020)

<-> LHC ALICE, Nature (2020)

C=6 charmed dibaryon, $\Omega_{ccc}\Omega_{ccc}$,
Tong+, PRL 127, 072003 (2021)

Meson-Meson

Double charmed tetraquark T_{cc}
Lyu+, PRL 131, 161901 (2023)

<-> LHCb, Nature (2022)

Meson-Baryon

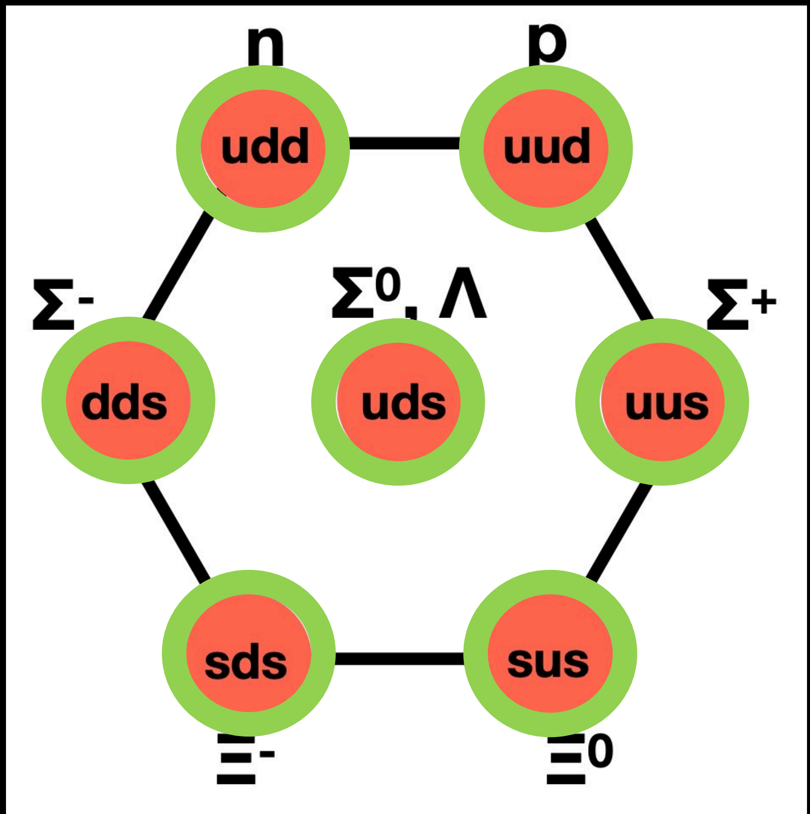
Proton-φ interaction
Lyu+, PRD 106, 074507 (2022)

<-> LHC ALICE, PRL(2021)

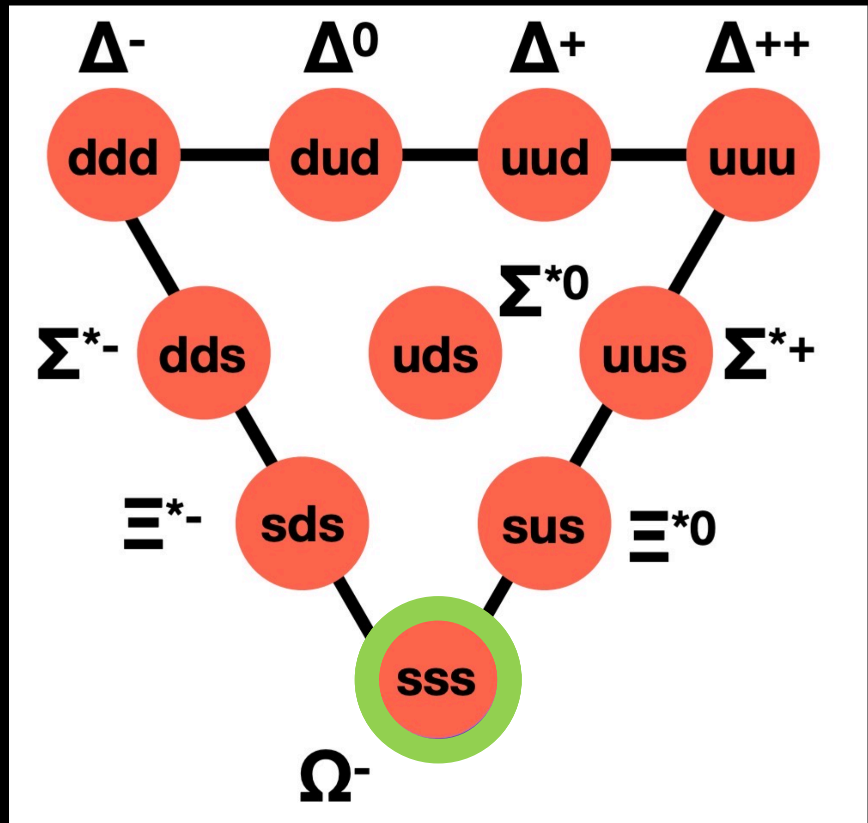
Recent review: Aoki & Doi, Handbook of Nucl. Phys. (2023); arXiv: 2402.11759

Octet & decuplet baryons

8 (Octet)



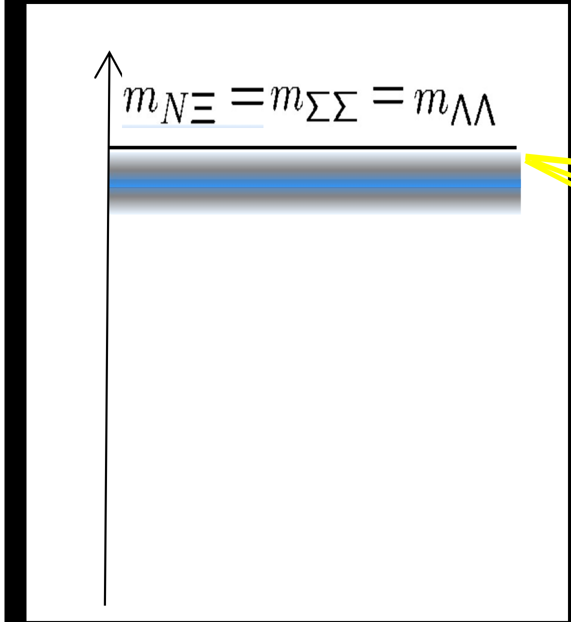
10 (Decuplet)

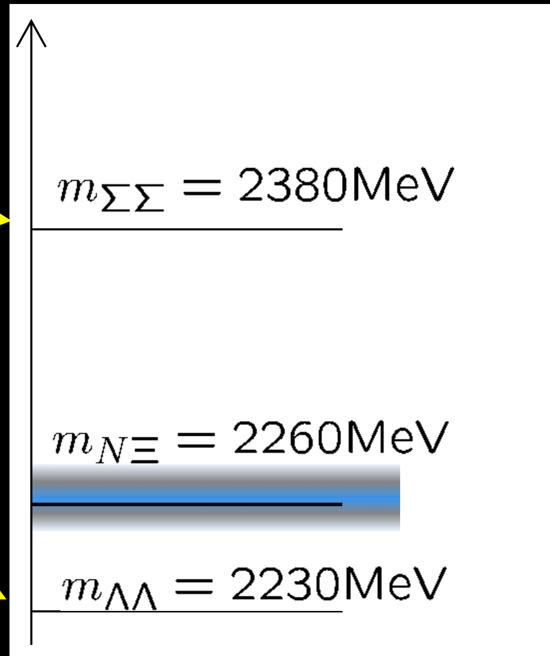


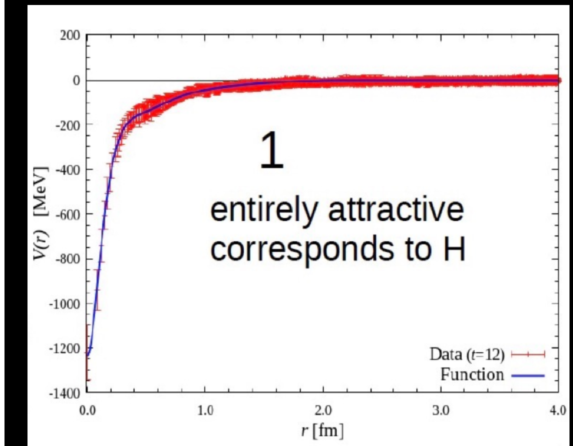
Stable against strong decays

Fate of "H (uuddss)" dibaryon from LQCD

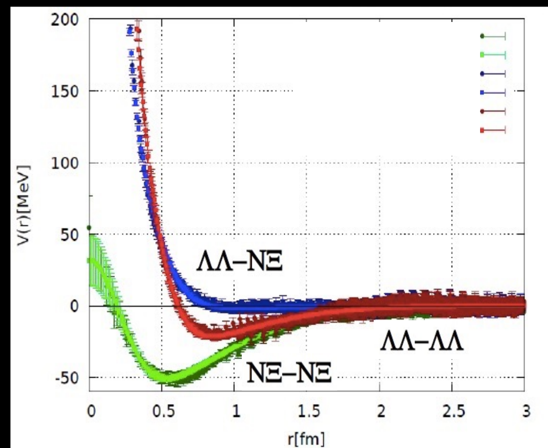
$m_{ud}=m_s$ (~ 100 MeV) $m_{ud} < m_s$ (~10MeV) (~100MeV)







$$\begin{pmatrix} \langle \Lambda\Lambda | \\ \langle \Sigma\Sigma | \\ \langle N\Xi | \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{27}{40}} & -\sqrt{\frac{8}{40}} & -\sqrt{\frac{5}{40}} \\ -\sqrt{\frac{1}{40}} & -\sqrt{\frac{24}{40}} & \sqrt{\frac{15}{40}} \\ \sqrt{\frac{12}{40}} & \sqrt{\frac{8}{40}} & \sqrt{\frac{20}{40}} \end{pmatrix} \begin{pmatrix} \langle \mathbf{27} | \\ \langle \mathbf{8}_s | \\ \langle \mathbf{1} | \end{pmatrix}$$



Inoue et al., [HAL QCD Coll.]
Nucl. Phys. A881 (2012) 28

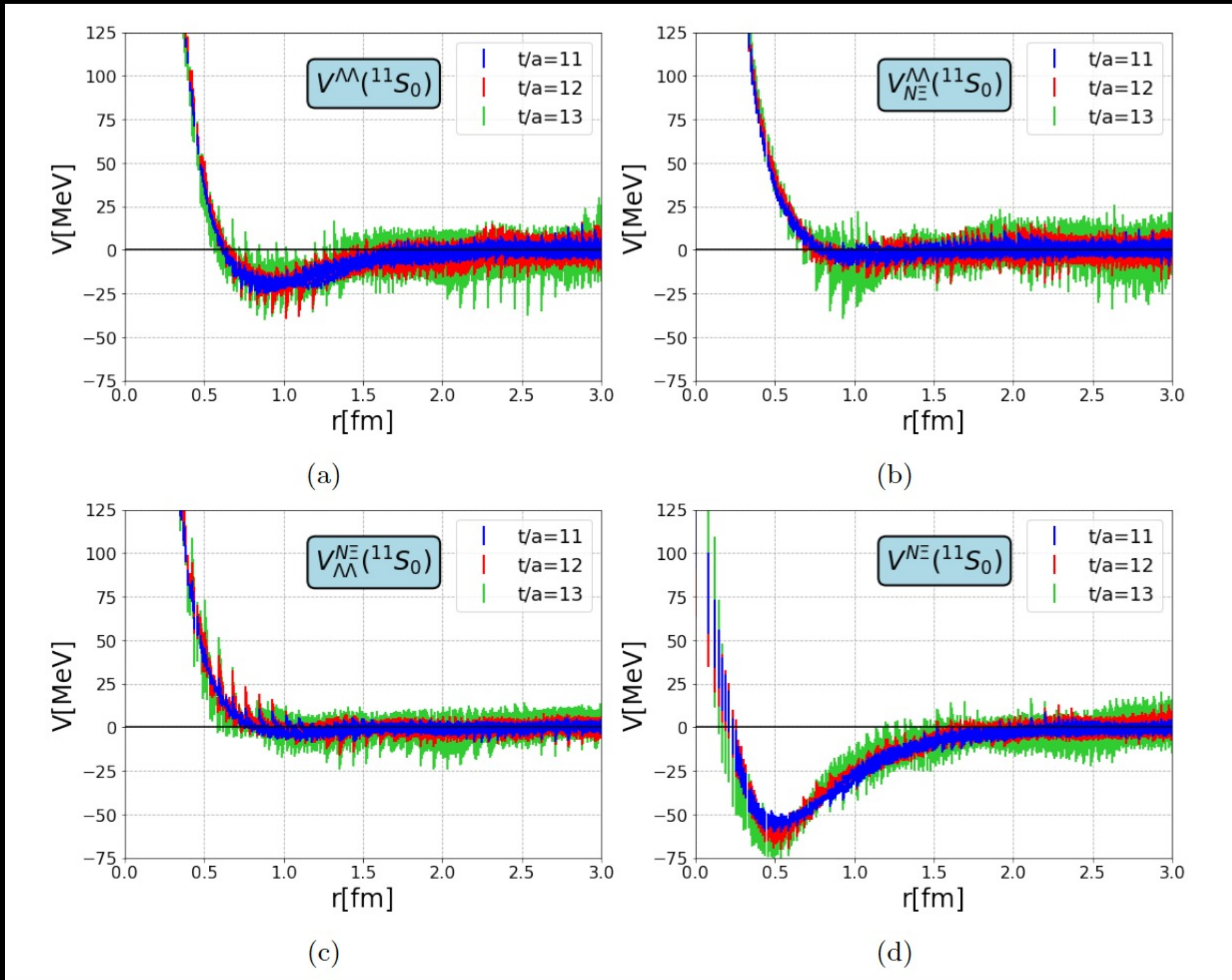
Sasaki et al., [HAL QCD Coll.]
Nucl. Phys. A998 (2020) 121737

Coupled Channel S=-2 system ($^{11}S_0$)

K. Sasaki+ [HAL QCD Coll.]
Nucl. Phys. **A998** (2020)

Small ΛΛ attraction

Short-range NΞ-ΛΛ coupling



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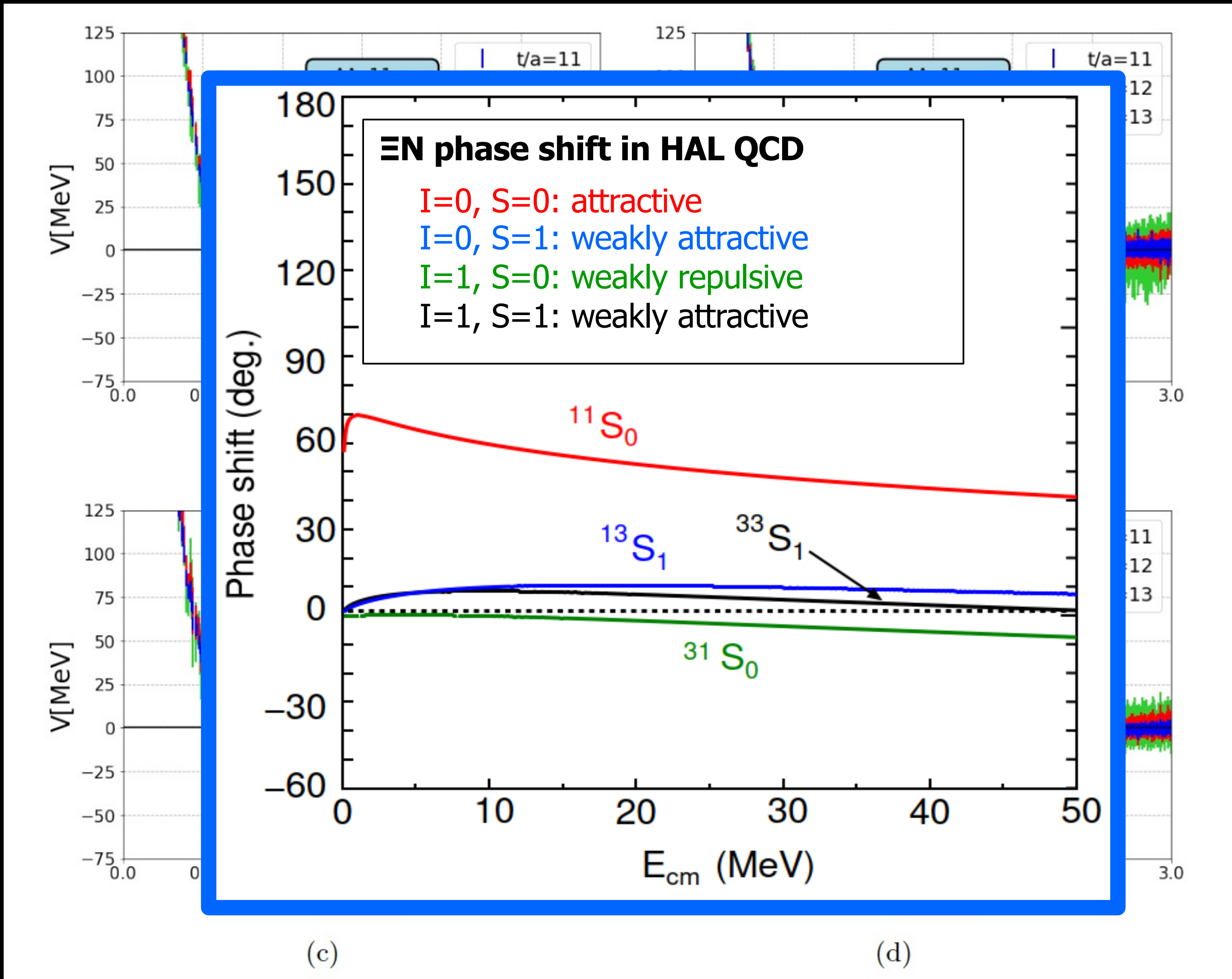
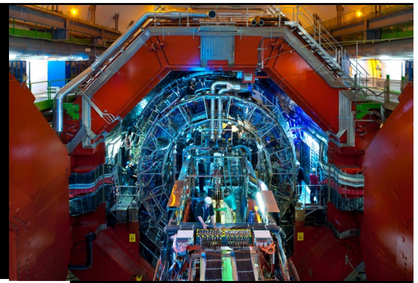


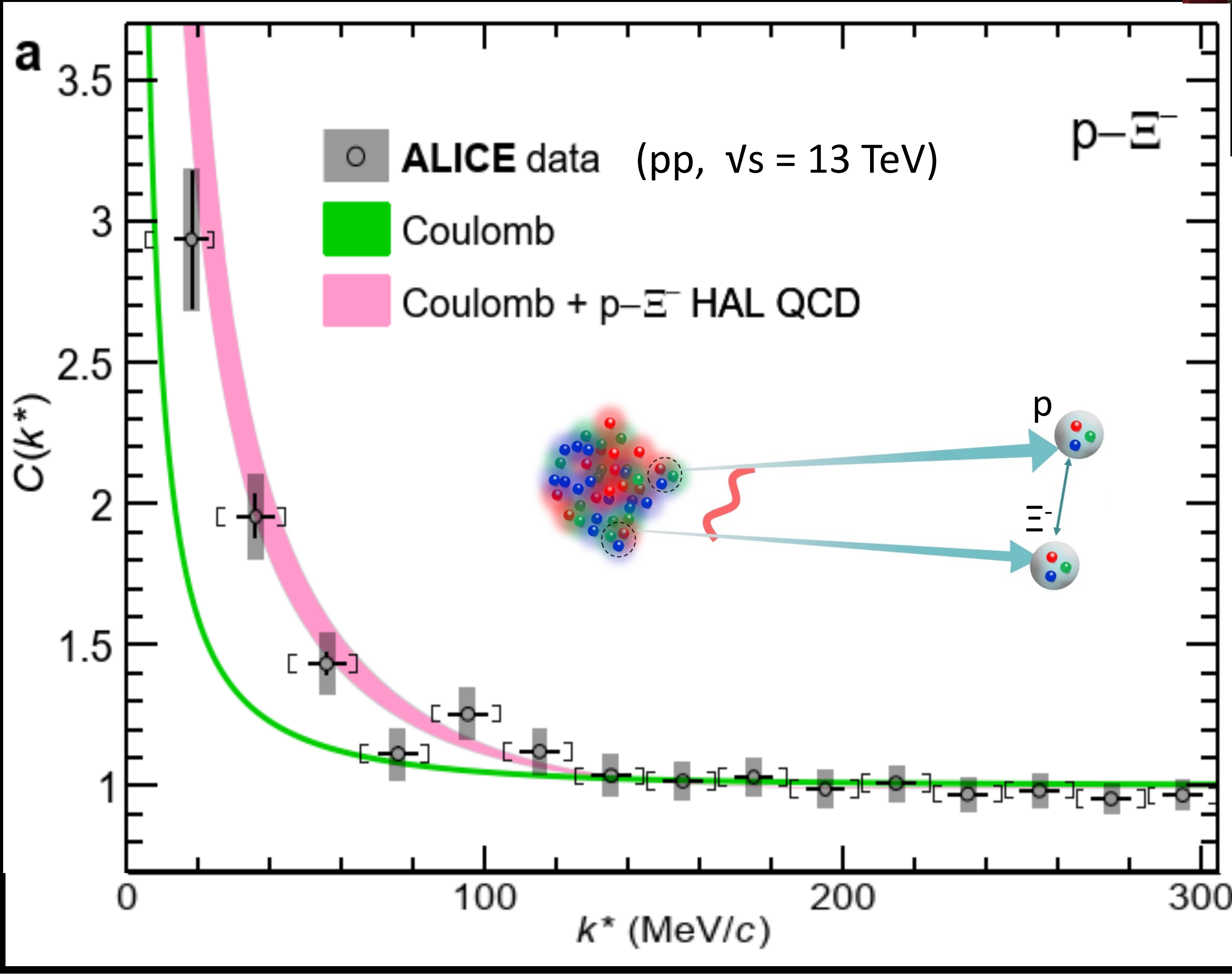
Short-range NΞ-ΛΛ coupling

Large NΞ attraction

NΞ correlation in pp

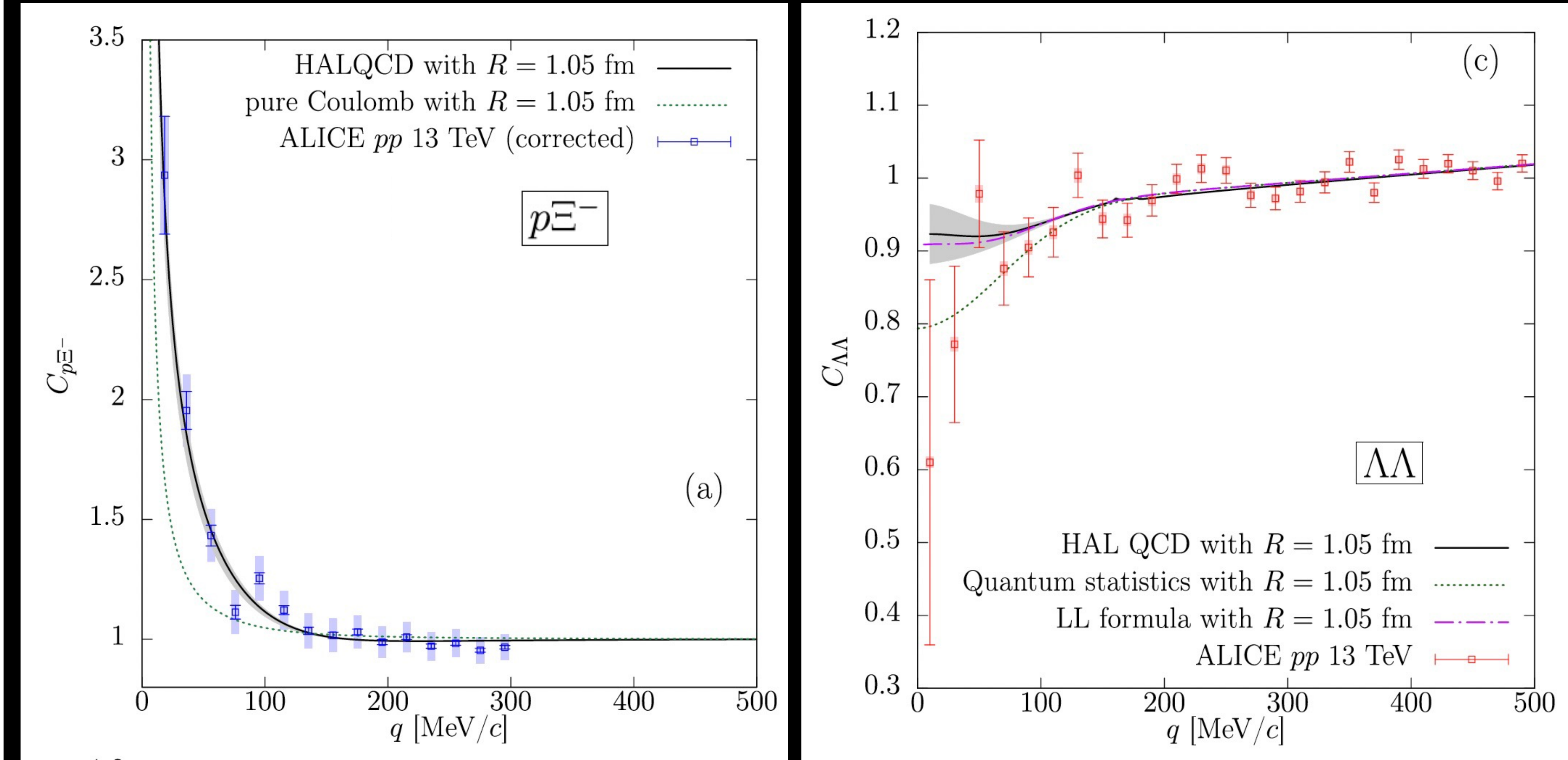
ALICE Coll., Nature 588 (2020) 232



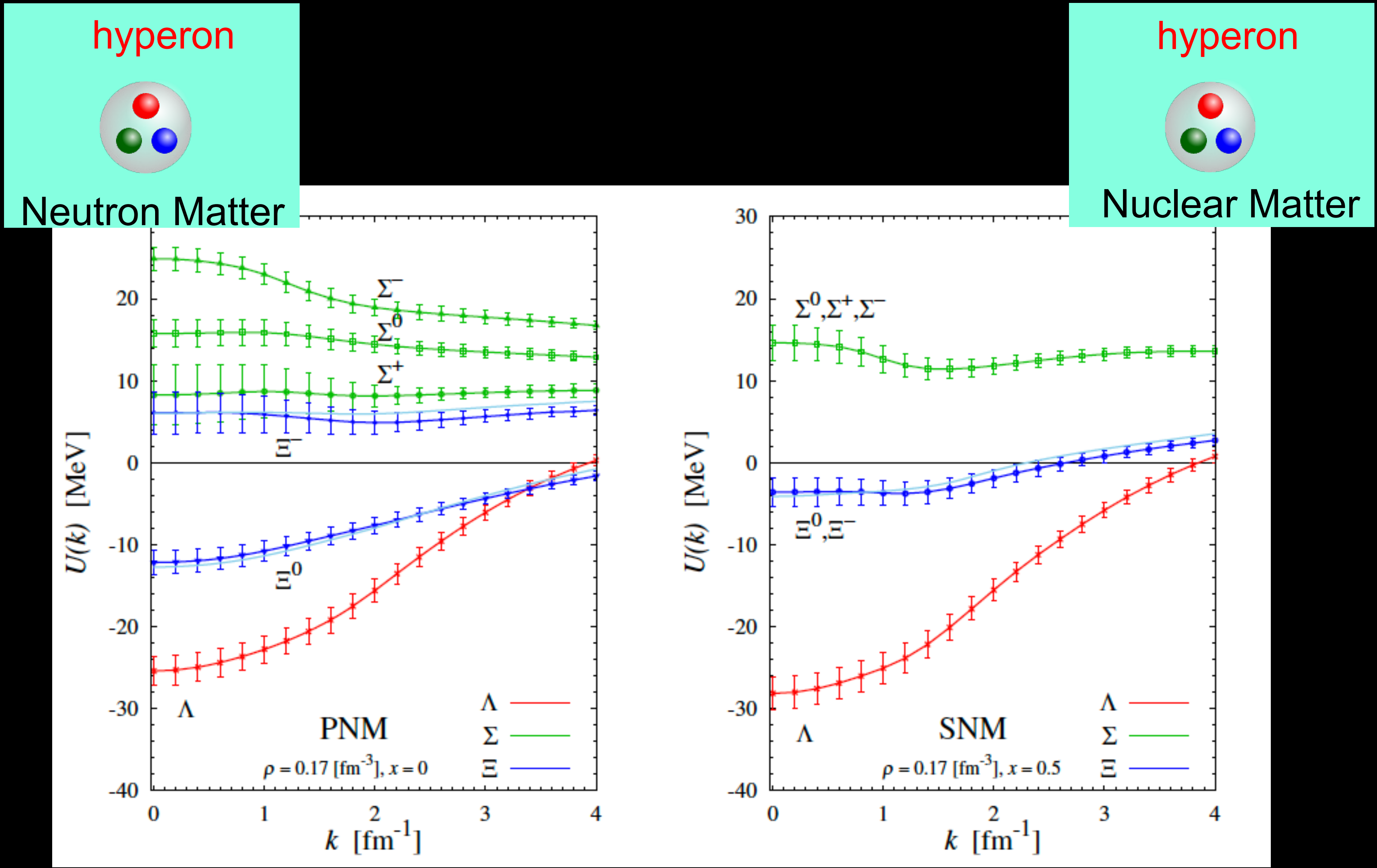


Fully coupled channel analysis

Kamiya+, Phys. Rev. C 105 (2022) 014915



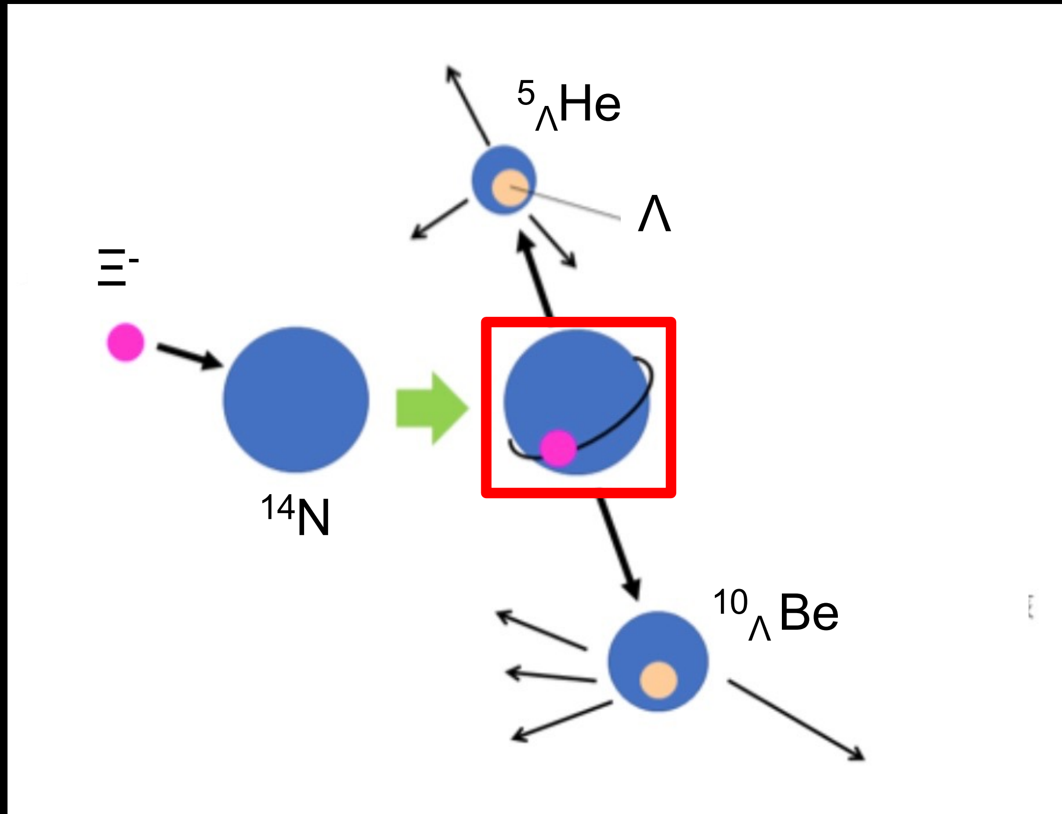
Hyperon embedded in cold nuclear matter (HAL QCD + BHF)



Inoue+ [HAL QCD Coll.], Few-body Syst. 62 (2021) 106

Ξ hypernuclei at J-PARC

E07 Coll. at J-PARC,
Phys.Rev.Lett. 126 (2021) 062501

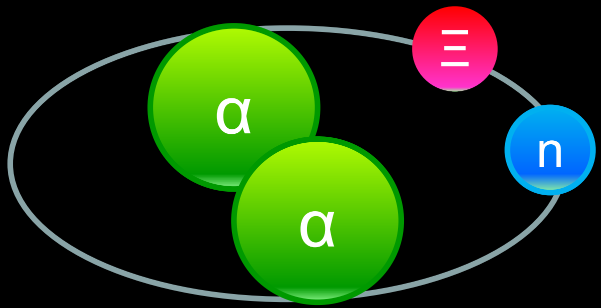


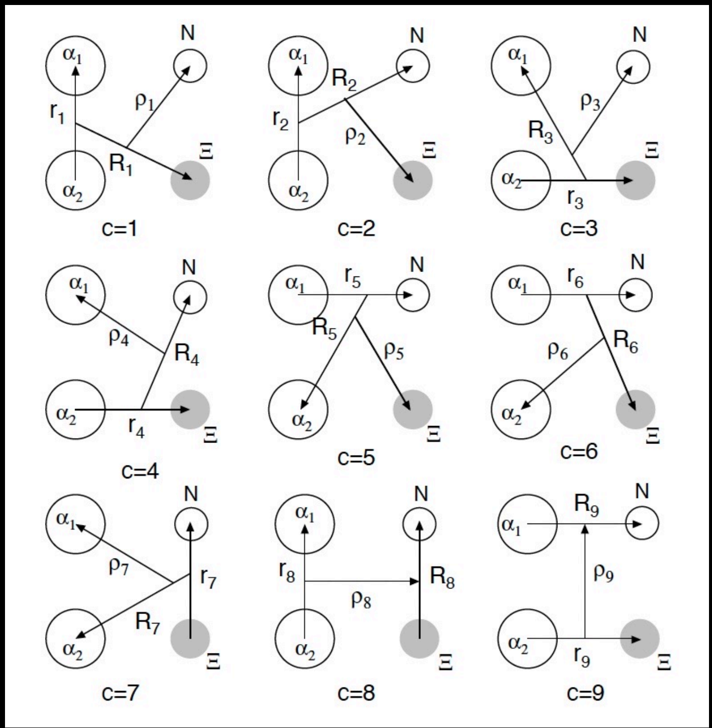
Attraction in NΞ
Weak NΞ- ΛΛ coupling

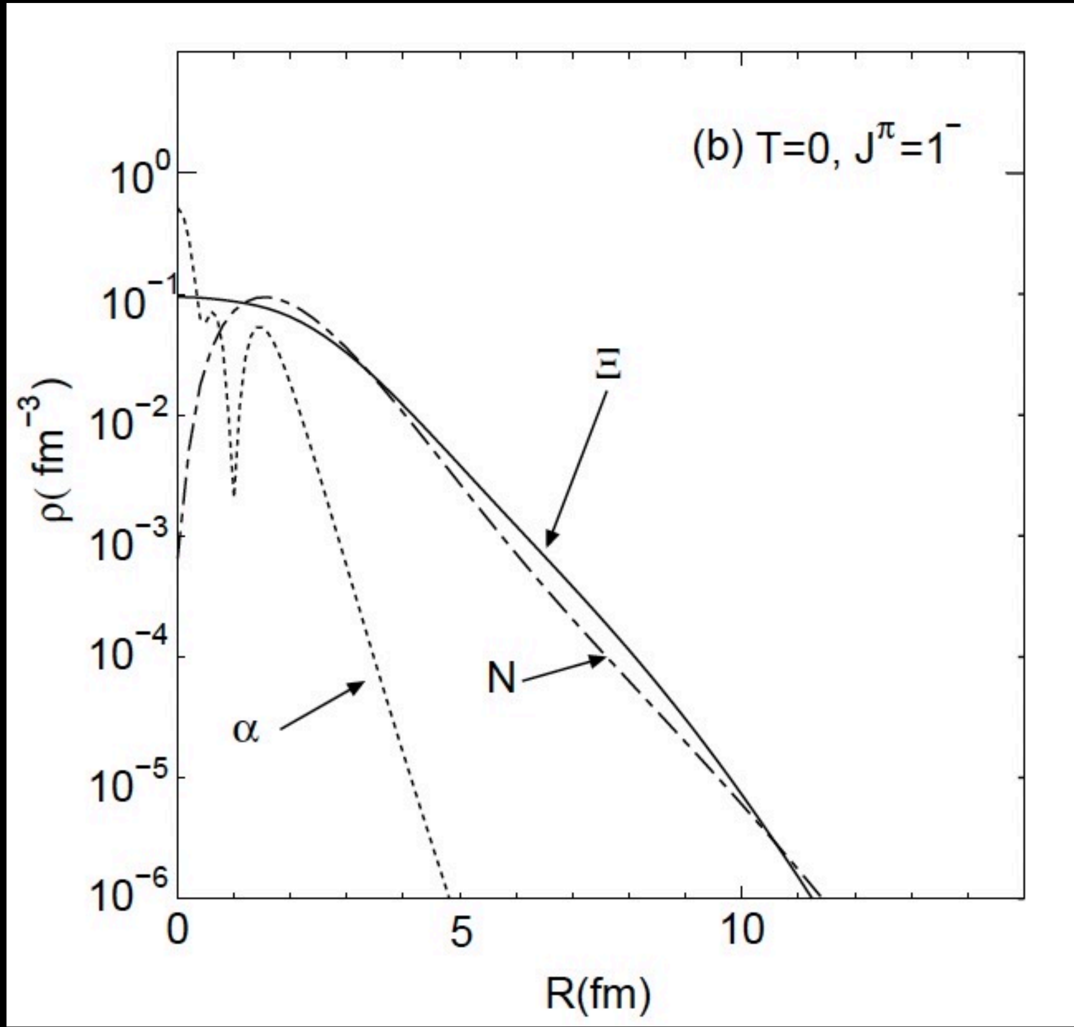
Consistent with HAL QCD prediction

Q2. Can we test the spin-isospin dependence of ΞN int.?

Hiyama, Isaka, Doi, Hatsuda, Phys. Rev. C 106 (2022) 064318

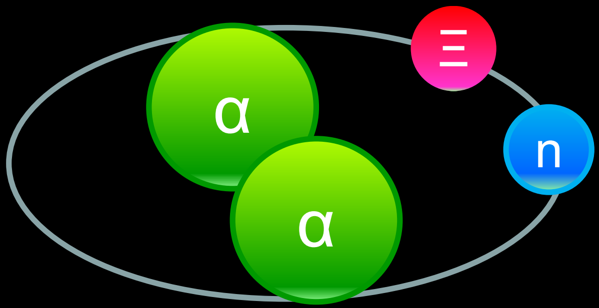




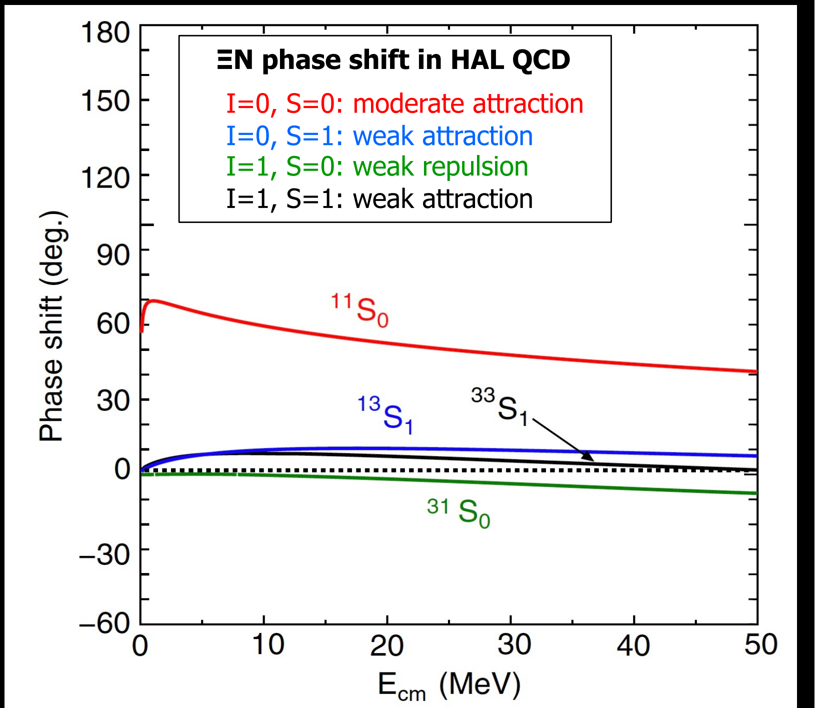


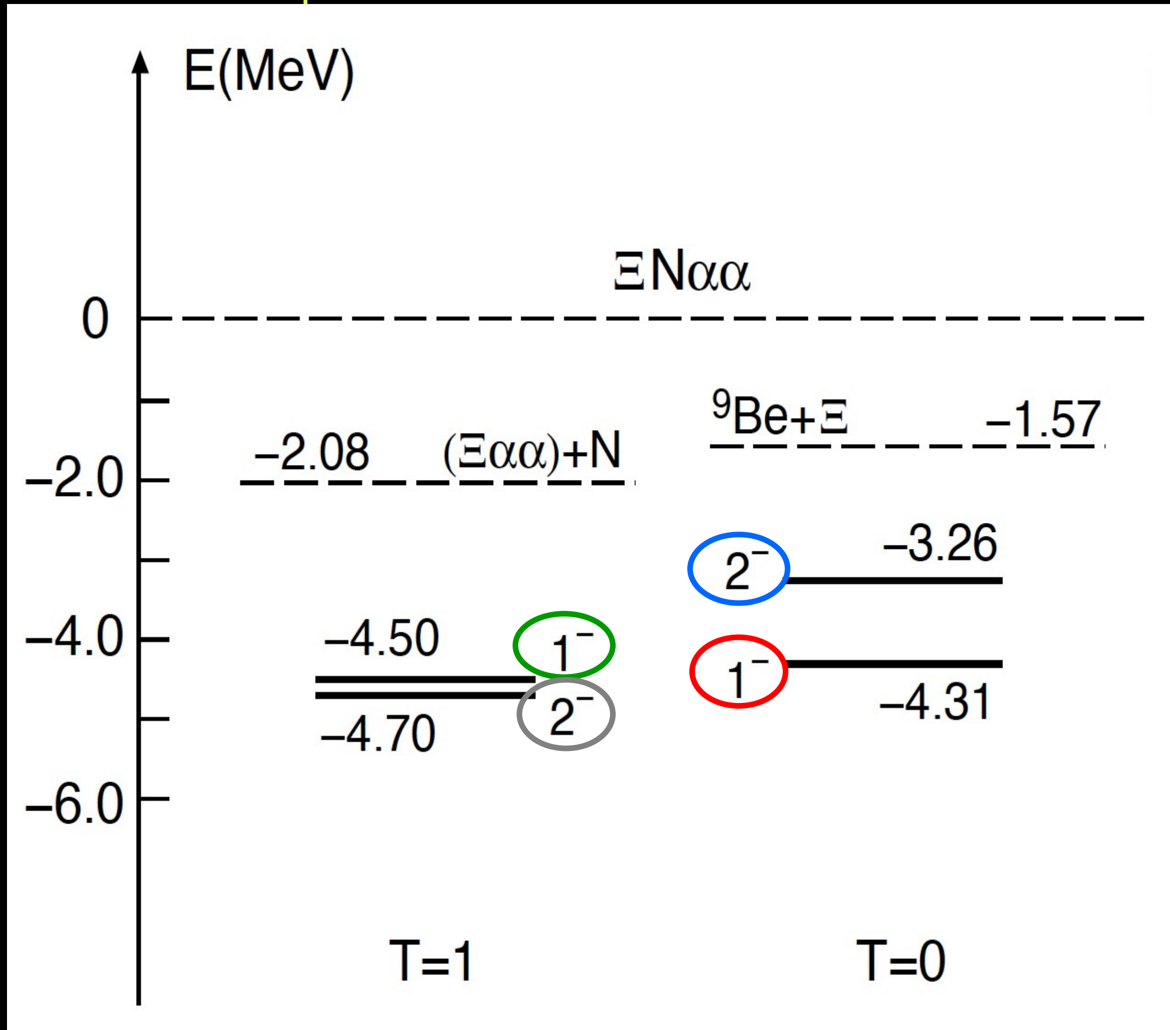
Gaussian expansion method (Hiyama et al., 2003)

Inversion of spin-doublets in ΞNαα system



Hiyama, Isaka, Doi, Hatsuda, Phys. Rev. C 106 (2022) 064318





Γ=20-40 keV

irreducible BB source operator

$$\overline{BB^{(27)}} = +\sqrt{\frac{27}{40}}\,\overline{\Lambda\Lambda} - \sqrt{\frac{1}{40}}\,\overline{\Sigma\Sigma} + \sqrt{\frac{12}{40}}\,\overline{N\Xi} \quad \text{or} \quad +\sqrt{\frac{1}{2}}\,\overline{p}\,\overline{n} + \sqrt{\frac{1}{2}}\,\overline{n}\,\overline{p}$$

$$\overline{BB^{(8s)}} = -\sqrt{\frac{1}{5}}\,\overline{\Lambda\Lambda} - \sqrt{\frac{3}{5}}\,\overline{\Sigma\Sigma} + \sqrt{\frac{1}{5}}\,\overline{N\Xi}$$

$$\overline{BB^{(1)}} = -\sqrt{\frac{1}{8}}\,\overline{\Lambda\Lambda} + \sqrt{\frac{3}{8}}\,\overline{\Sigma\Sigma} + \sqrt{\frac{4}{8}}\,\overline{N\Xi}$$

with

$$\overline{\Sigma\Sigma} = +\sqrt{\frac{1}{3}}\,\overline{\Sigma^+}\,\overline{\Sigma^-} - \sqrt{\frac{1}{3}}\,\overline{\Sigma^0}\,\overline{\Sigma^0} + \sqrt{\frac{1}{3}}\,\overline{\Sigma^-}\,\overline{\Sigma^+}$$

$$\overline{N\Xi} = +\sqrt{\frac{1}{4}}\,\overline{p}\,\overline{\Xi^-} + \sqrt{\frac{1}{4}}\,\overline{\Xi^-}\,\overline{p} - \sqrt{\frac{1}{4}}\,\overline{n}\,\overline{\Xi^0} - \sqrt{\frac{1}{4}}\,\overline{\Xi^0}\,\overline{n}$$

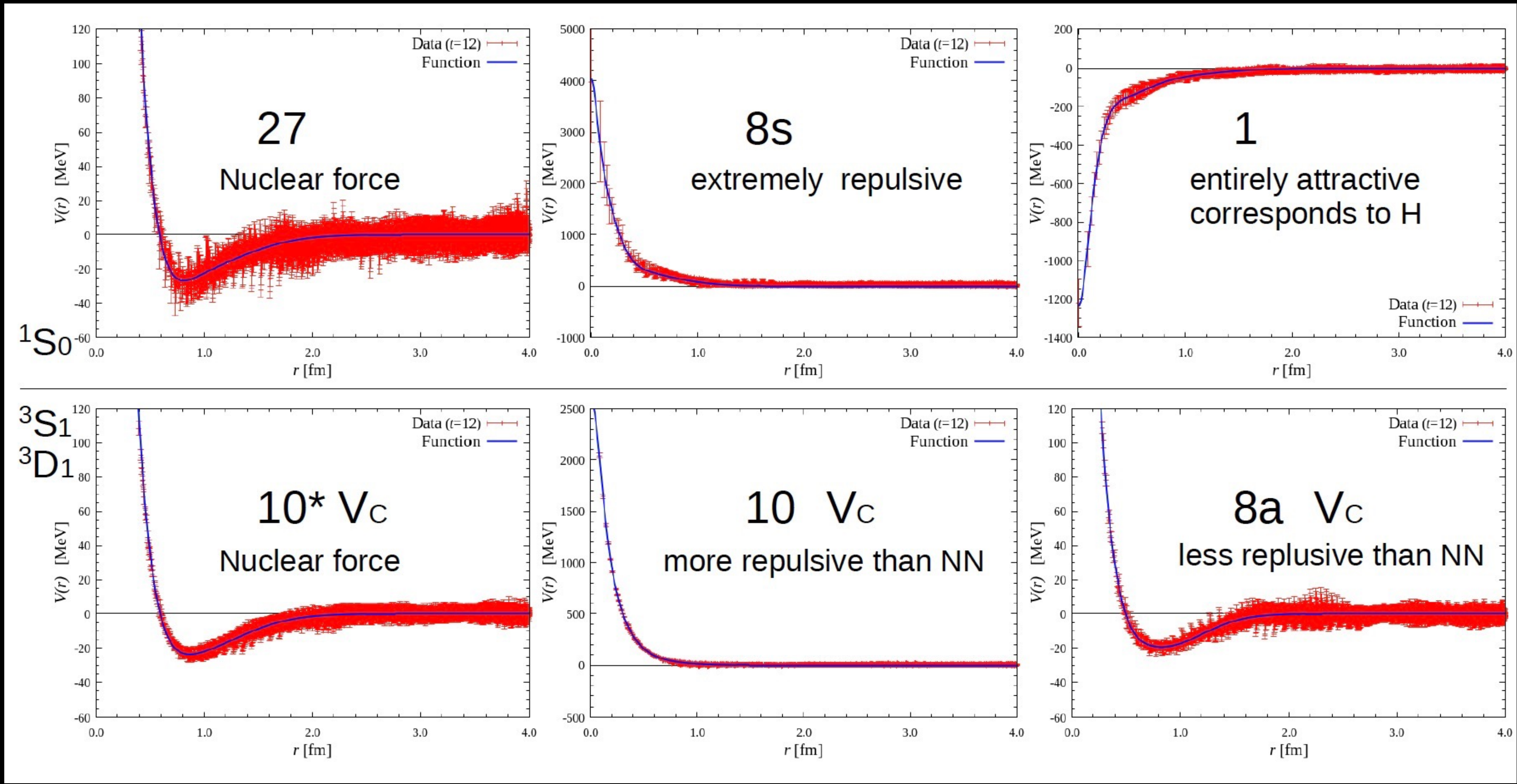
$$\overline{BB^{(10^*)}} = +\sqrt{\frac{1}{2}}\,\overline{p}\,\overline{n} - \sqrt{\frac{1}{2}}\,\overline{n}\,\overline{p}$$

$$\overline{BB^{(10)}} = +\sqrt{\frac{1}{2}}\,\overline{p}\,\overline{\Sigma^+} - \sqrt{\frac{1}{2}}\,\overline{\Sigma^+}\,\overline{p}$$

$$\overline{BB^{(8a)}} = +\sqrt{\frac{1}{4}}\,\overline{p}\,\overline{\Xi^-} - \sqrt{\frac{1}{4}}\,\overline{\Xi^-}\,\overline{p} - \sqrt{\frac{1}{4}}\,\overline{n}\,\overline{\Xi^0} + \sqrt{\frac{1}{4}}\,\overline{\Xi^0}\,\overline{n}$$

Central BB interactions in the flavor basis

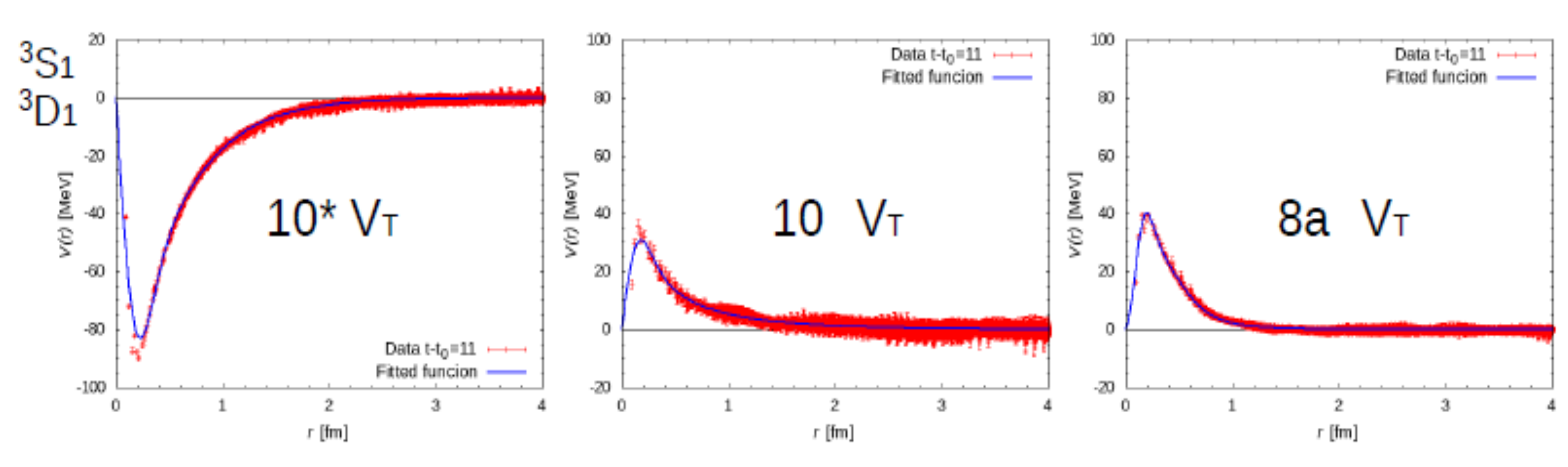
$$8 \times 8 = 27 + 8_s + 1 + 10^* + 10 + 8_a$$



T. Inoue [HAL QCD Coll.], Few-body Syst. 62 (2021) 106

Tensor BB interactions in the flavor basis

$8 \times 8 = 27 + 8_s + 1 + 10^* + 10 + 8_a$



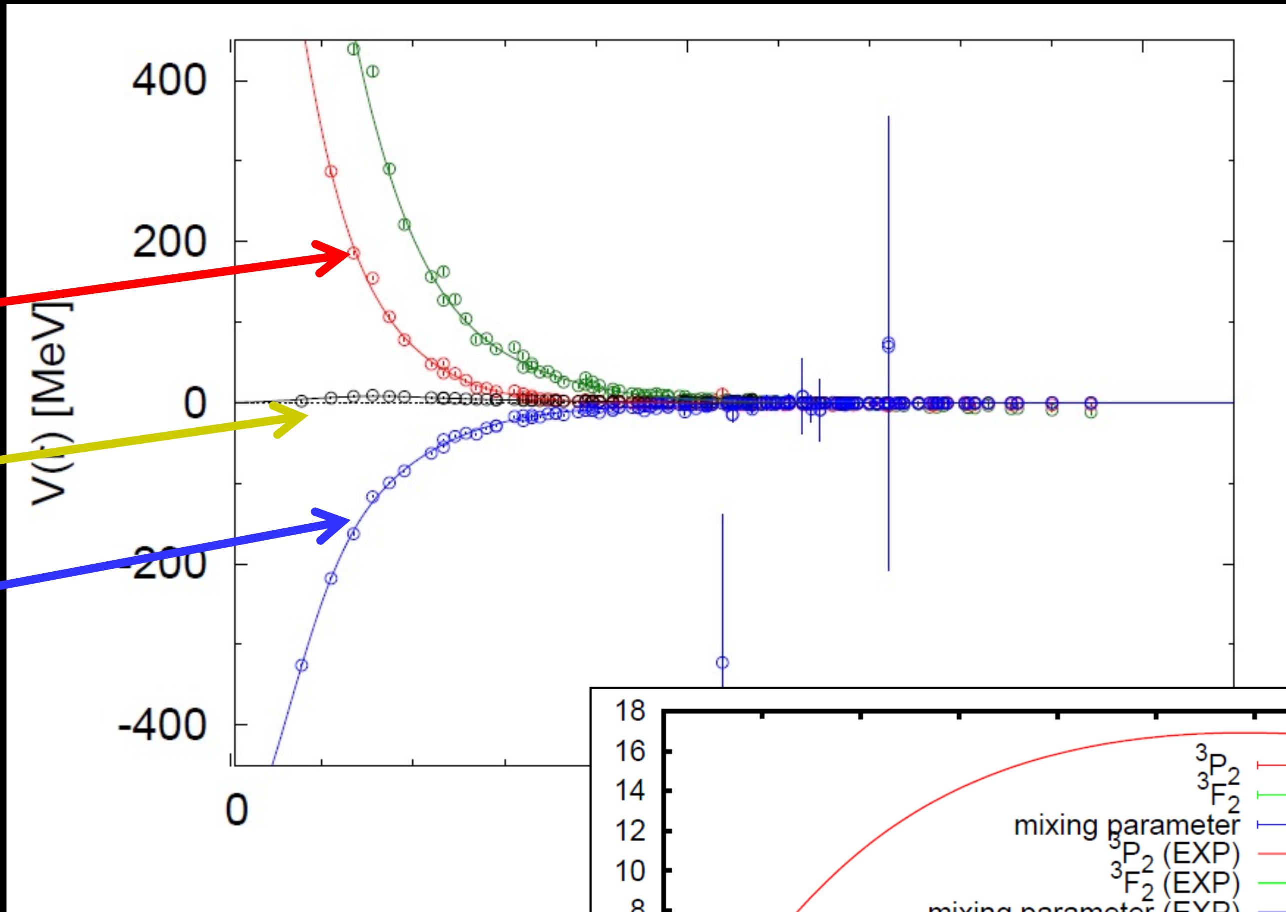
$$U(\mathbf{r}, \mathbf{r}') = V(\mathbf{r}, \mathbf{v})\delta(\mathbf{r} - \mathbf{r}'),$$

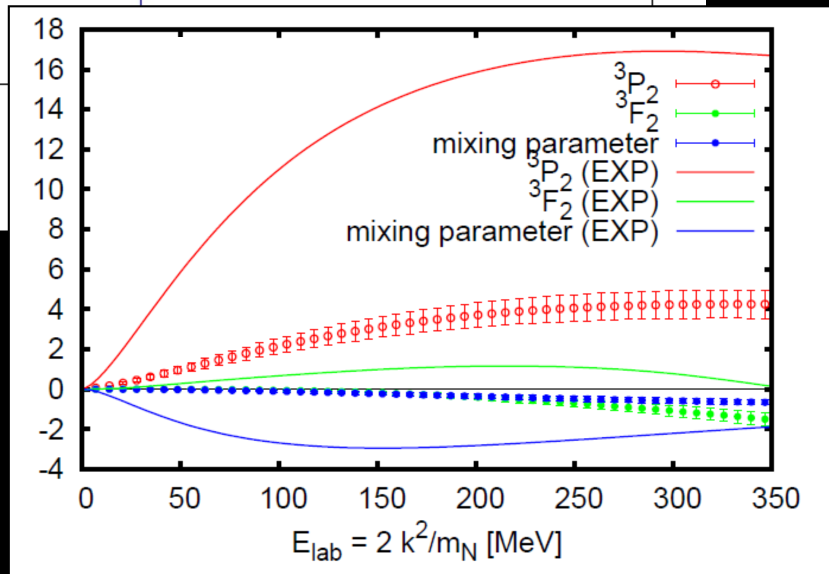
$$V(\mathbf{r}, \mathbf{v}) = \underbrace{V_C(r) + V_T(r)S_{12}}_{\text{LO}} + \underbrace{V_{LS}(r)\mathbf{L}\cdot\mathbf{S}}_{\text{NLO}} + \underbrace{O(\mathbf{v}^2)}_{\text{N}^2\text{LO}} + \cdots$$

T. Inoue+ [HAL QCD Coll.], Few-body Syst. 62 (2021) 106

First Result on the Spin-Orbit Force in 2-flavor QCD

$$V(r;\ {}^3P_2) = V^{I=1}_{\mathrm{C},S=1}(r) - \frac{2}{5} V^{I=1}_{\mathrm{T}}(r) + V^{I=1}_{\mathrm{LS}}(r)$$



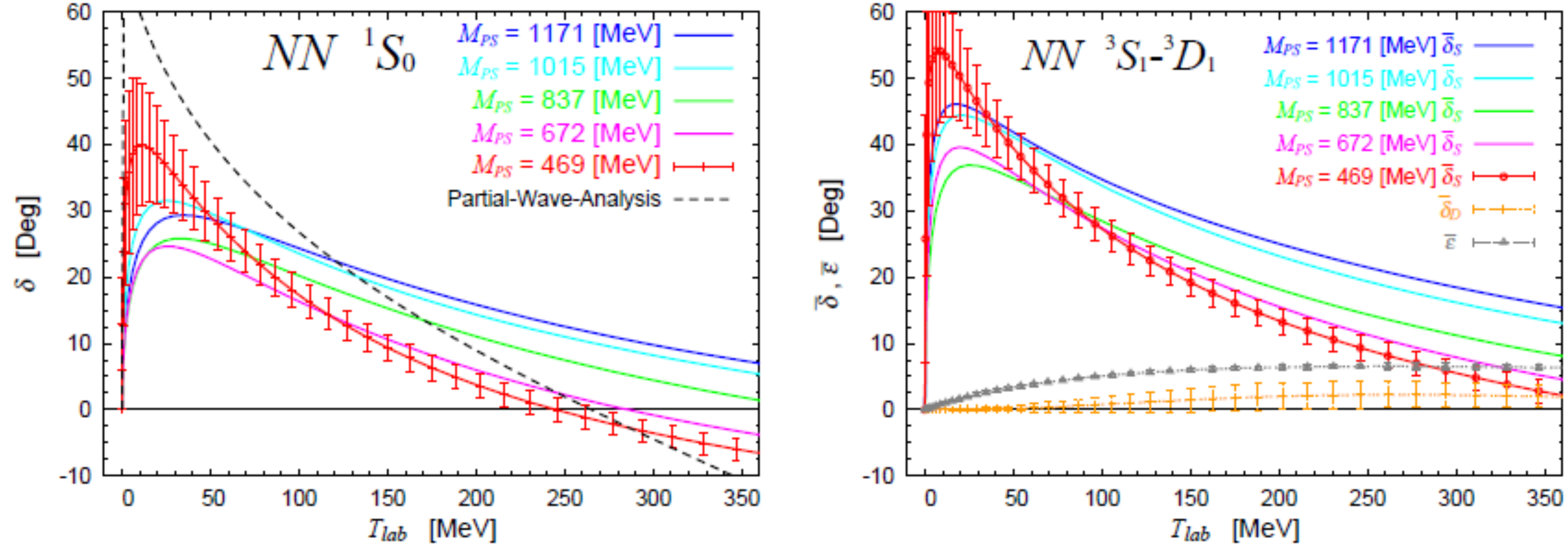


L = 2.5 fm

m_π = 1133MeV, m_N = 2158 MeV,

HAL QCD Coll., arXiv: 1305.2293 [hep-lat]

NN phase shifts in 3-flavor QCD



Stronger attraction in the deuteron channel

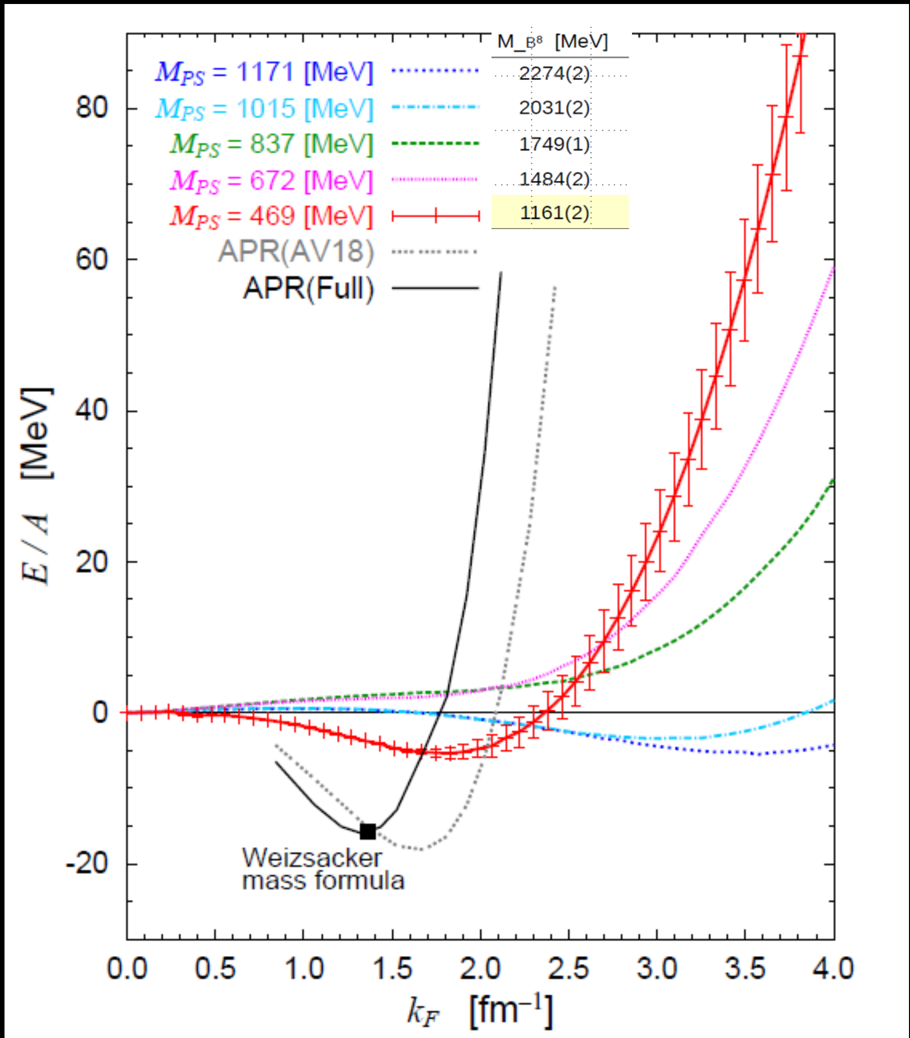
HAL QCD Coll.,
Phys. Rev. Lett. 106 (2011) 162002
Nucl. Phys. A881 (2012) 28

Nuclear EOS from Lattice NN force + BHF calculation

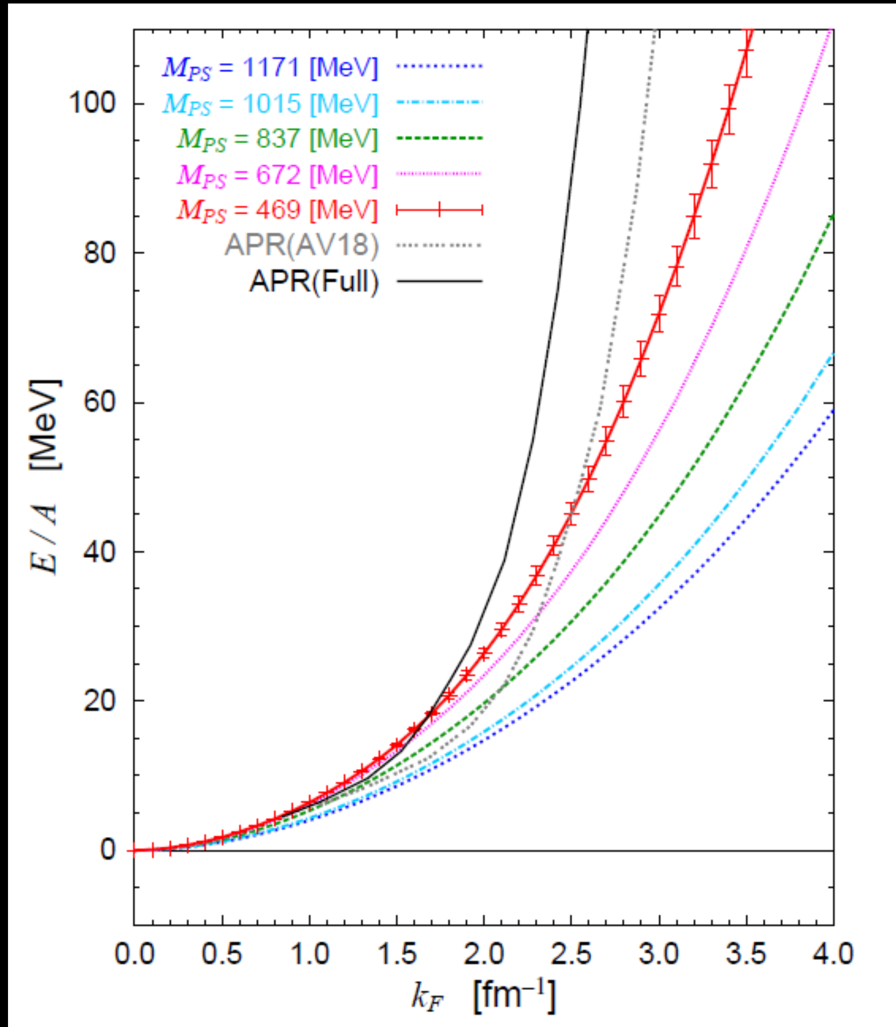
(NN force: $^1S_0$, $^3S_1$, $^3D_1$ channels only)

HAL QCD Coll., Phys. Rev. Lett. 111 (2013) 112503

Nuclear Matter

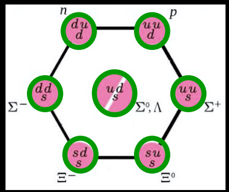
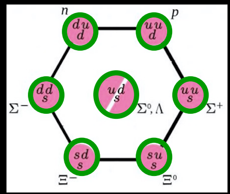


Neutron Matter



Flavor SU(3) Classification : B=2

c.f. Dyson & Xoung, PRL 14 (1965)

 x 

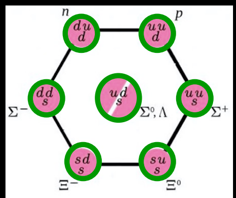
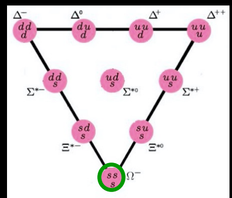
$$8 \times 8 = 27 + 8_s + 1 + 10^* + 10 + 8_a$$

$H_{\Lambda\Lambda-N\Xi-\Lambda\Sigma}$ (J=0) → 1

Jaffe (1977)

D_{pn} (J=1) → 10^*

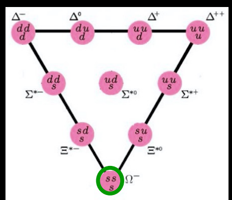
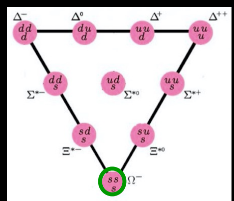
Rarita-Schwinger (1941)

 x 

$$8 \times 10 = 35 + 8 + 10 + 27$$

$N\Omega$ (J=2) → 8

Goldman et al (1987)

 x 

$$10 \times 10 = 28 + 27 + 35 + 10^*$$

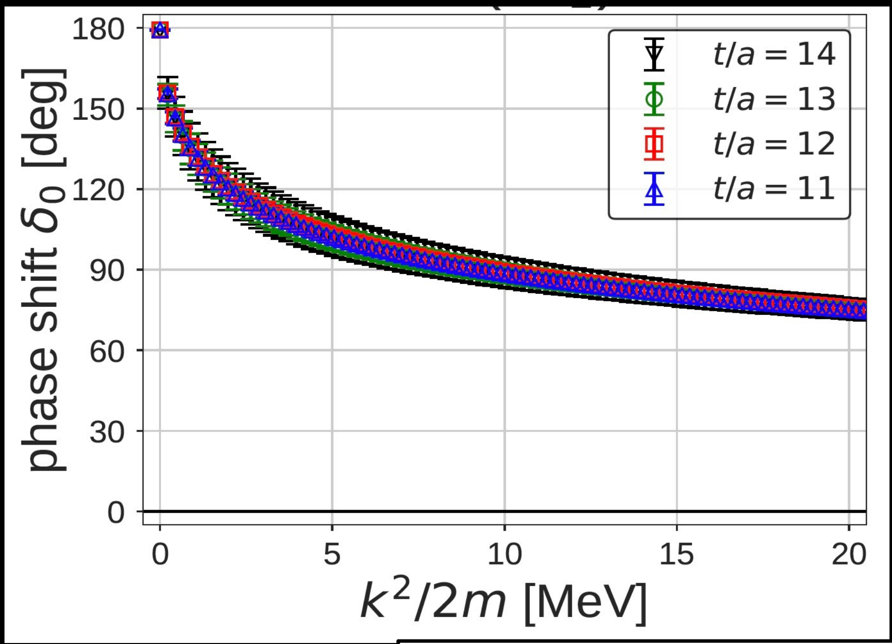
Zhang et al (1997)

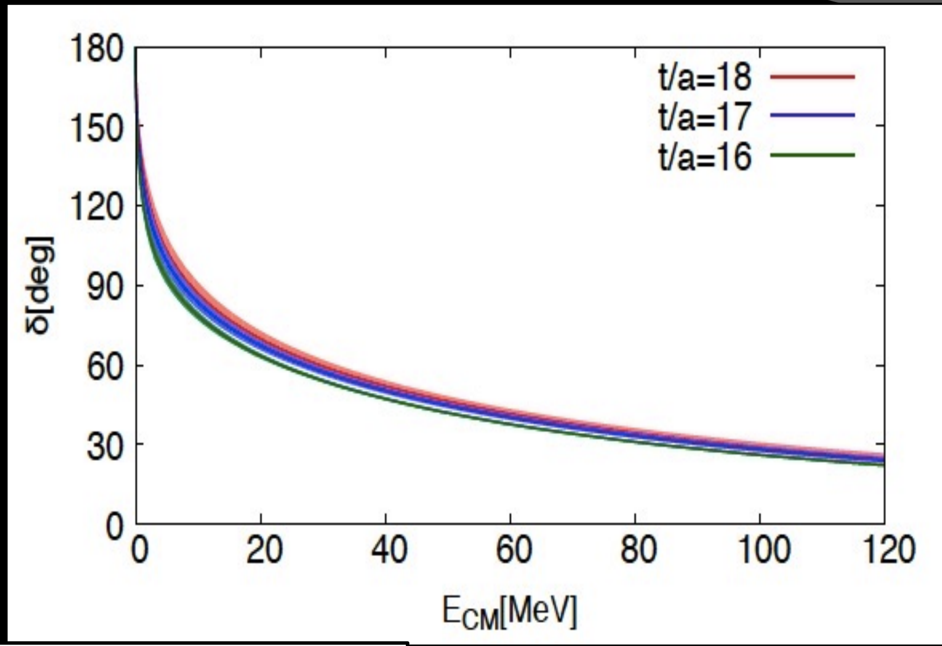
$\Omega\Omega$(J=0) → 28

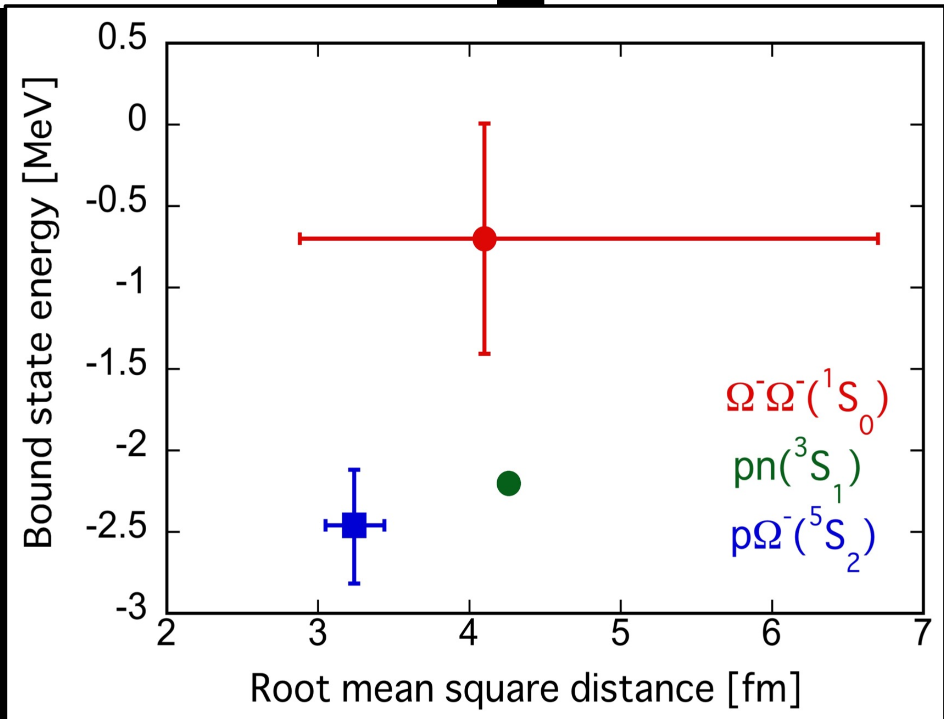
$\Delta\Delta(^7S_3)$ → 10^*

Dyson+ (1964)

quasi-bound NΩ and bound ΩΩ ?







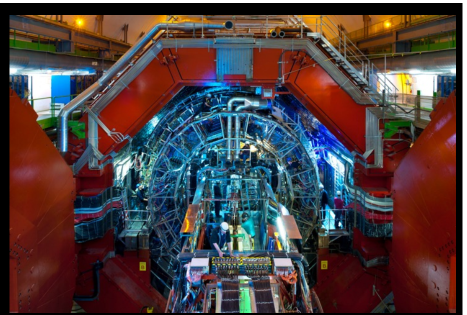
Iritani+ [HAL QCD Coll.], PLB 792 (2019) 284

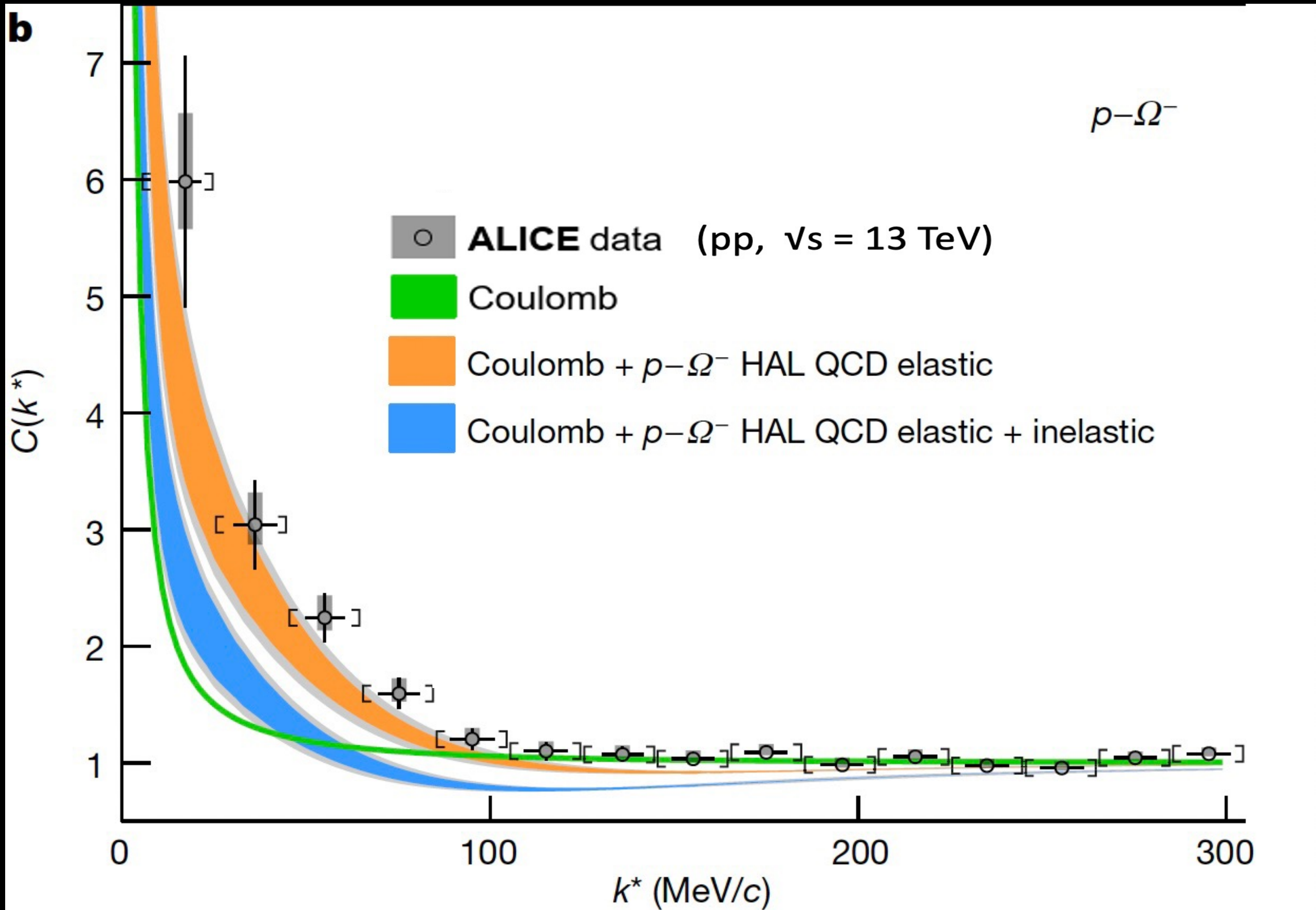
Gongyo+ [HAL QCD Coll.], PRL 120 (2018) 212001

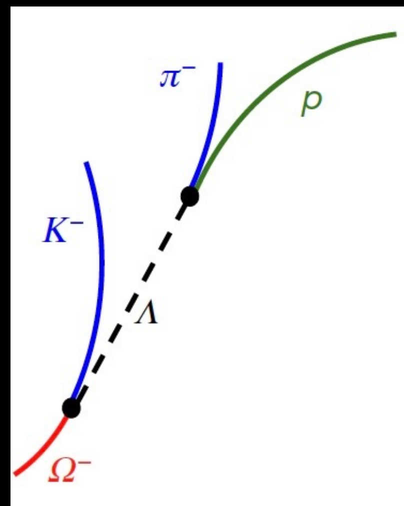
Tong+ [HAL QCD Coll.], PRL 127 (2021) 072003

NΩ correlation in pp

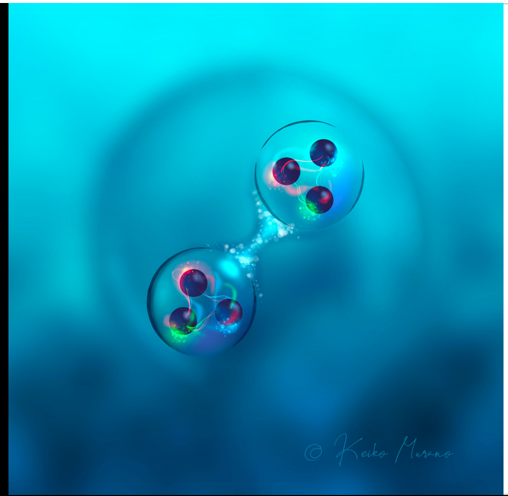
LHC ALICE Coll., Nature <u>588</u> (2020) 232





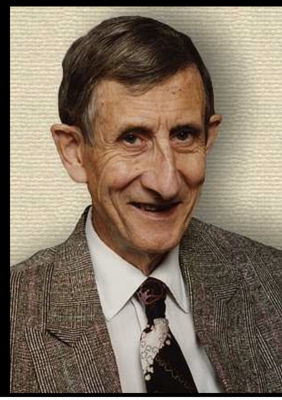


e-mail from Freeman Dyson,
(Sep. 13, 2017)



Thank you very much for sending me your paper on the Omega-Omega calculation. This is a beautiful piece of work, and it will be a big step forward if the experimenters are able to confirm it.

Thank you also for referring to our 1964 paper. I am amazed that you remember that paper after 53 years. The predictions that we made in that paper turned out to be wrong, and the SU6 theory was soon abandoned. Luckily you did not assume SU6 symmetry when you made your prediction.



Now I wish you the joy of seeing it confirmed.

Yours sincerely,

Freeman Dyson.

Y=2 States in Su(6) Theory

Freeman J. Dyson and Nguyen-Huu Xuong
Phys. Rev. Lett. **13**, 815 – Published 28 December 1964; Erratum Phys. Rev. Lett. **14**, 339 (1965)

Summary and future

1. "LQCD → realistic hadron-hadron interactions" became possible.

2. Comparison of LQCD data with femtoscopy and hypernuclei has been started.

3. H(uuddss) dibaryon is not likely to exist below ΛΛ.

4. ΩΩ(ssssss) dibaryon may exist and should be searched experimentally.

5. Hyperon–nucleon interaction & 3-baryon force. <--> neutron star structure.

6. Heavy tetraquarks (e.g. T_{cc}, T_{bb}) are highly interesting in both Exp. and LQCD.

More LQCD results at
the physical pion mass will come soon.

Thank you!