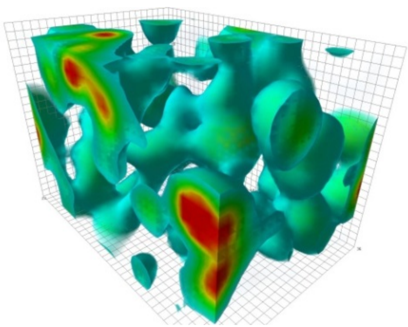
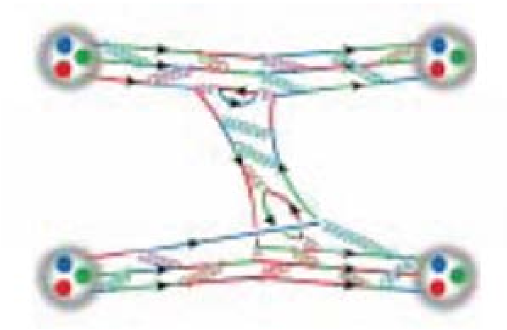
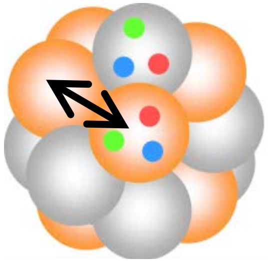
Lattice QCD study of hadron interactions with strangeness

Takumi Doi

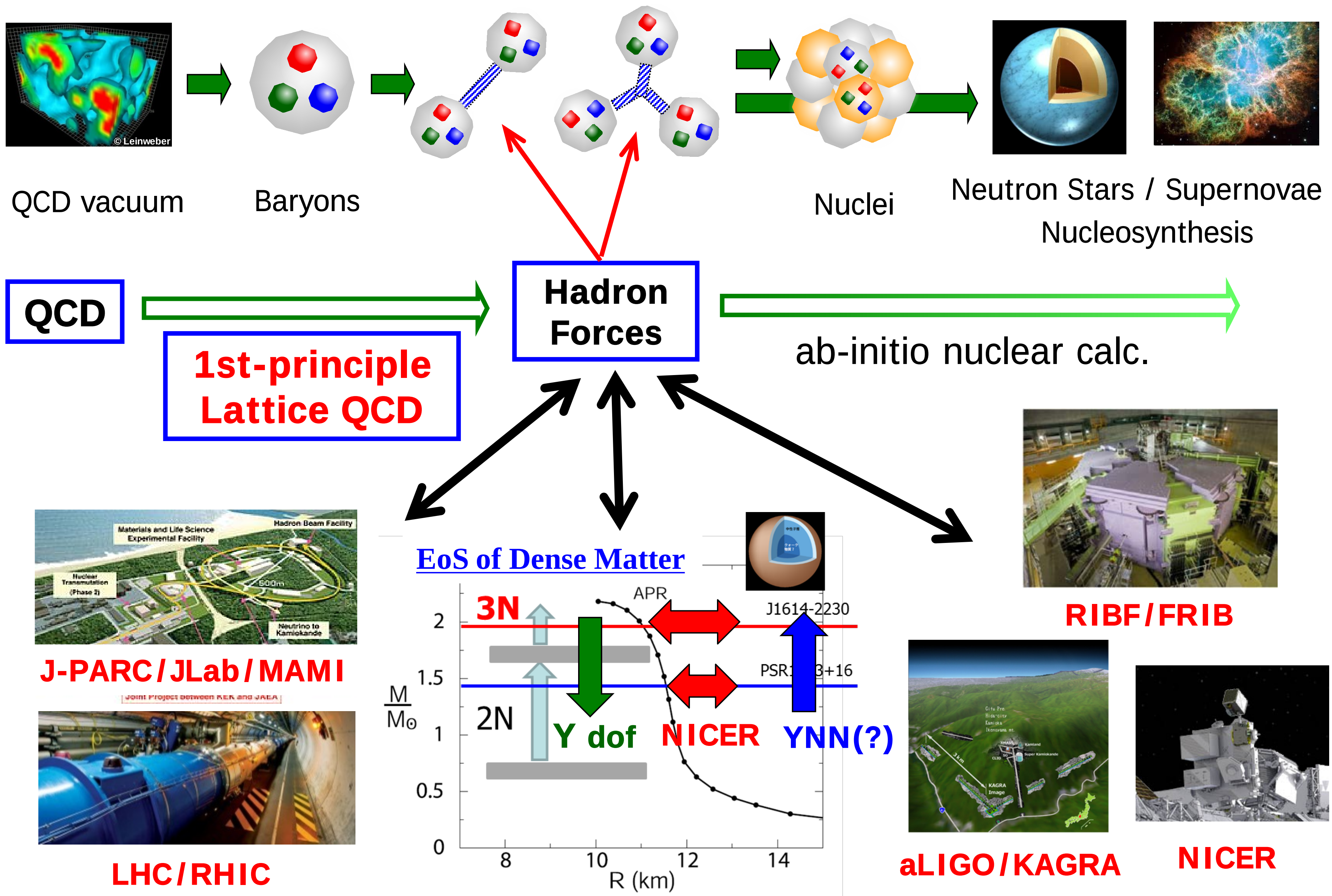
(RIKEN iTHEMS)



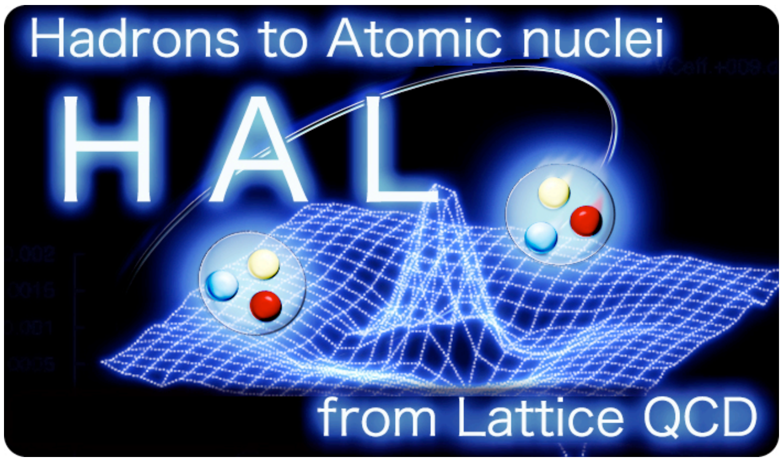




The Odyssey from Quarks to Universe



Hadrons to Atomic nuclei from Lattice QCD
(HAL QCD Collaboration)



Y. Akahoshi, S. Aoki,
K. Murakami, H. Nemura (YITP)
T. Aoyama (ISSP)
T. Doi, T. Hatsuda, T. Sugiura (RIKEN)
T. M. Doi, Y. Ikeda, N. Ishii, K. Sasaki (Osaka Univ.)
F. Etminan (Univ. of Birjand)
T. Inoue (Nihon Univ.)
Y. Lyu (Peking Univ.)
H. Tong (Tianjin Normal Univ.)

「20XX年宇宙の旅」

from Quarks to Universe

+

E. Itou (RIKEN)
I. Kanamori (RIKEN)
K.-I. Ishikawa (Hiroshima Univ.)

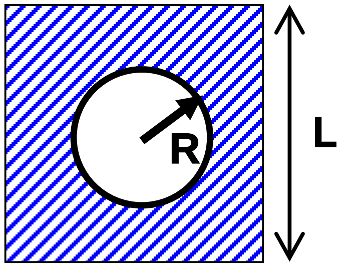
Luscher's formula: Scatterings on the lattice

- Consider Schrodinger eq at asymptotic region

$$(\nabla^2 + k^2)\psi_k(\boldsymbol{r}) = mV_k(\boldsymbol{r})\psi_k(\boldsymbol{r})$$

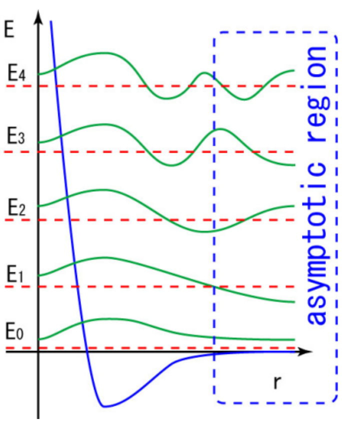
M.Luscher, NPB354(1991)531

$$V_k(\boldsymbol{r}) = 0 \text{ for } r > R$$



  – (periodic) Boundary Condition in finite V
    ➔ constraint on energies of the system

  – Quantization condition between
    Energy E and phase shift (at E)



$$k \cot \delta_{\mathbf{E}} = \frac{2}{\sqrt{\pi} L} Z_{00}(1; (kL/2\pi)^2) \qquad E = 2\sqrt{m^2 + k^2}$$

(Lushcer's formula)

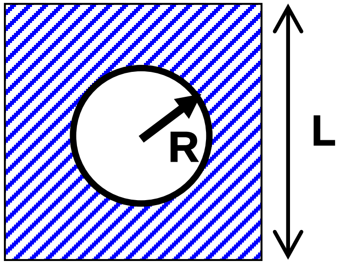
  – Calculate Finite V spectrum
    → convert them to phase shifts via Luscher's formula

[HAL QCD method]

- Nambu-Bethe-Salpeter (NBS) wave function

$$\psi(\vec{r}) = \langle 0|\ N(\vec{r})N(\vec{0})\ |N(\vec{k})N(-\vec{k});W\rangle$$

$$(\nabla^2 + k^2)\psi(\vec{r}) = 0, \quad r > R$$



  - phase shift at asymptotic region

$$\psi(r) \simeq A\frac{\sin(kr - l\pi/2 + \delta(k))}{kr}$$

M.Luscher, NPB354(1991)531

C.-J.Lin et al., NPB619(2001)467

N.Ishizuka, PoS LAT2009 (2009) 119

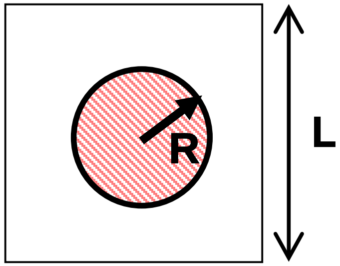
CP-PACS Coll., PRD71(2005)094504

Extended to multi-particle systems

S. Aoki et al., PRD88(2013)014036

- Consider the wave function at "interacting region"

$$(\nabla^2 + k^2)\psi(\boldsymbol{r}) = m\int d\boldsymbol{r}' U(\boldsymbol{r},\boldsymbol{r}')\psi(\boldsymbol{r}'), \quad r < R$$



  - U(r,r'): faithful to the phase shift by construction
    - U(r,r'): E-independent, while non-local in general
      - Non-locality ➔ derivative expansion

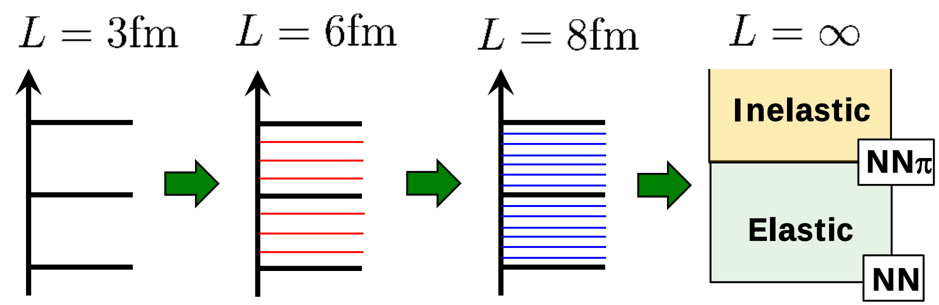
Aoki-Hatsuda-Ishii PTP123(2010)89

The Challenge in multi-baryons on the lattice

Existence of elastic scatt. states

➔ (almost) No Excitation Energy

➔ LQCD method based on G.S. saturation impossible



"Sign Problem"

Signal/Noise issue

$$S/N \sim \exp[-\mathbf{A} \times (\mathbf{m_N} - \mathbf{3/2m_\pi}) \times \mathbf{t}]$$

Parisi('84), Lepage('89)

L=8fm @ physical point $(E_1 - E_0) \simeq 25\text{MeV} \Longrightarrow t > 10\text{fm}$

$$S/N \sim 10^{-32}$$

Direct method (naïve plateau fit @ t ~ 1fm + Luscher's formula)

→ Does it really reliable? (excited state contaminations)

[Time-dependent HAL QCD method]

E-indep of potential U(r,r') ➔ *(excited) scatt states share the same U(r,r')*

$$\int d\boldsymbol{r}' U(\boldsymbol{r},\boldsymbol{r}')R(\boldsymbol{r}',t) = \left(-\frac{\partial}{\partial t} + \frac{1}{4m}\frac{\partial^2}{\partial t^2} - H_0\right)R(\boldsymbol{r},t)$$

	Ground state	Excited (elastic)	Excited (inelastic)
Direct method	Signal	Noise	Noise
HAL method	Signal	Signal	Noise

Partial solution of Sign Problem

HAL method → Exponentially better S/N

→ Coupled channel formalism above inelastic threshold → YN/YY (!)

Reliability test of LQCD methods

T. Iritani et al. (HAL) JHEP10(2016)101, PRD96(2017)034521, PRD99(2019)014514, JHE03(2019)007

NN @ heavy quark masses

- HAL method (HAL) : unbound
- Direct method (NPL/CalLat/PACS-CS(Yamazaki et al.)): bound
- Semi-improved calc w/ Luscher's formula (Mainz2019) : unbound
- Variational calc w/ Luscher's formula (CalLat2020) : unbound
- Variational calc w/ Luscher's formula (NPL2021) : (unbound)

- Baryon Forces from LQCD — Ishii-Aoki-Hatsuda (2007)
- Exponentially better S/N — Ishii et al. (2012)
- Coupled channel systems — Aoki et al. (2011,13)

[Theory] = HAL QCD method

Baryon Interactions near the Physical Point

[Hardware]

= K-computer [10PFlops]

+ FX100 [1PFlops] @ RIKEN
+ HA-PACS [1PFlops] @ Tsukuba

- HPCI Field 5 / Post K Priority Issue 9

[Software]

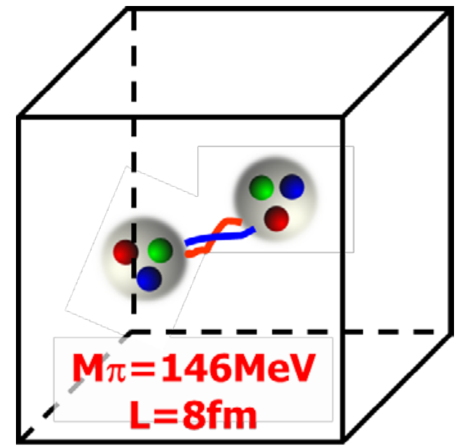
= Unified Contraction Algorithm

- Exponential speedup — Doi-Endres (2013)

$$^{3}\mathrm{H}/^{3}\mathrm{He} \quad : \quad \times 192$$
$$^{4}\mathrm{He} \quad : \quad \times 20736$$
$$^{8}\mathrm{Be} \quad : \quad \times 10^{11}$$

Lattice QCD Setup

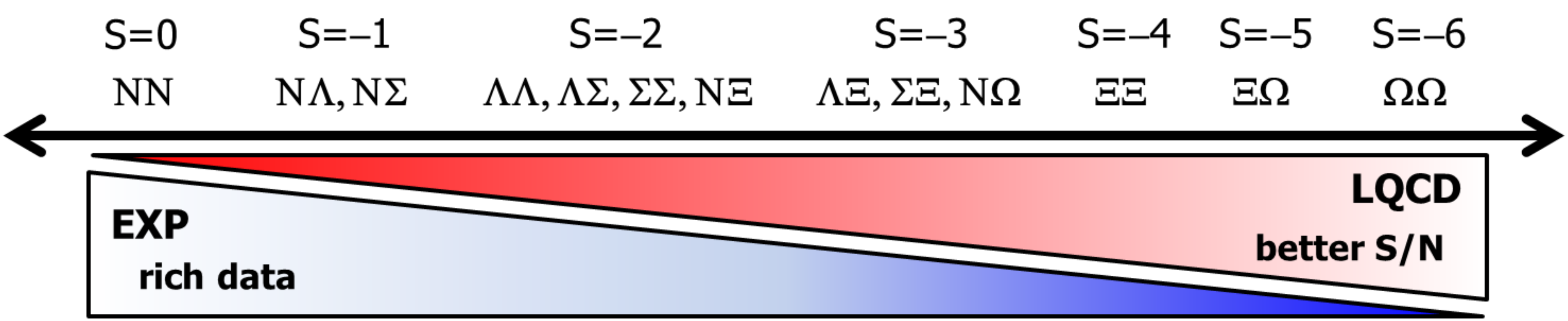
- **Nf = 2 + 1 gauge configs**
  - clover fermion + Iwasaki gauge w/ stout smearing
  - V=(8.1fm)^4, a=0.085fm (1/a = 2.3 GeV)
  - **m(pi) ~= 146 MeV, m(K) ~= 525 MeV**
  - #traj ~= 2000 generated



PACS Coll., PoS LAT2015, 075

- **Measurement**
  - All of NN/YN/YY for central/tensor forces in P=(+) (S, D-waves)

Predictions for Hyperon forces

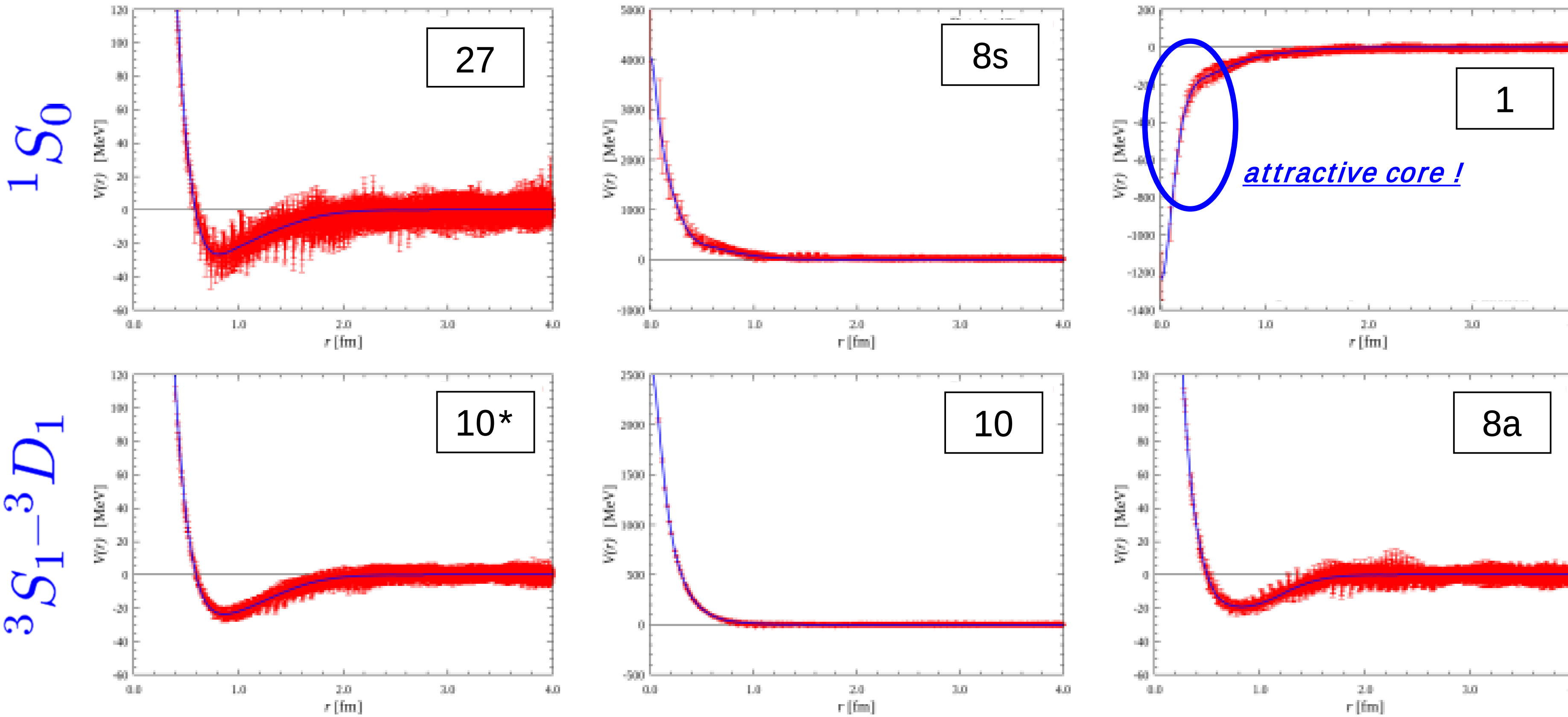


Birds-eye View: diag-Pot in SU(3) base in S=-2

8 X 8 = 27 + 8s + 1 + 10* + 10 + 8a

T.Inoue (HAL), AIP Conf. Proc. 2130 (2019) 020002

(off-diag pot relatively small)



27,10*:
NN-type

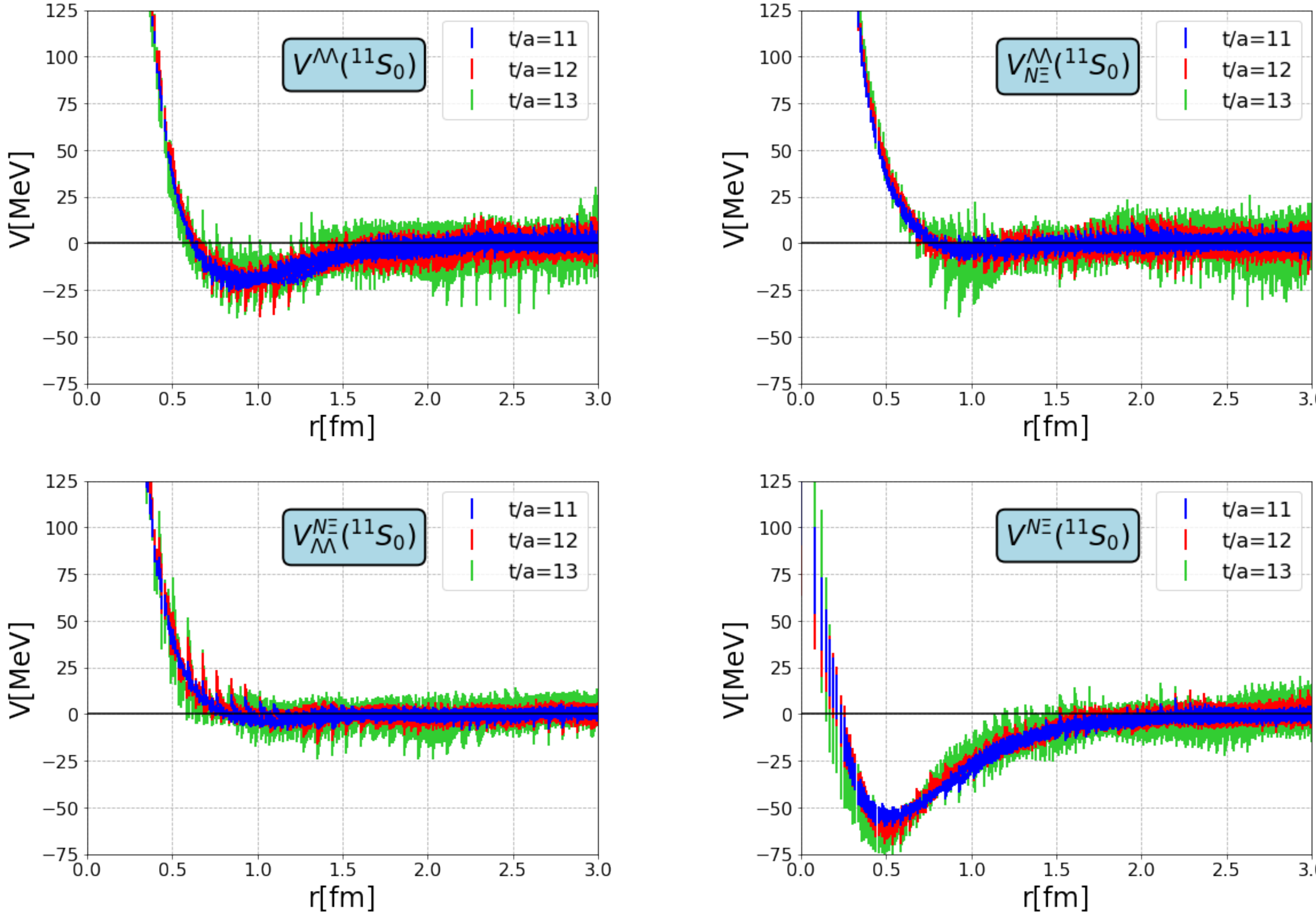
8s,10:
strong repulsive core

1s: deep attractive pocket
8a: weak repulsive core

Quark Pauli repulsion + OGE for short range

M.Oka et al., NPA464(1987)700

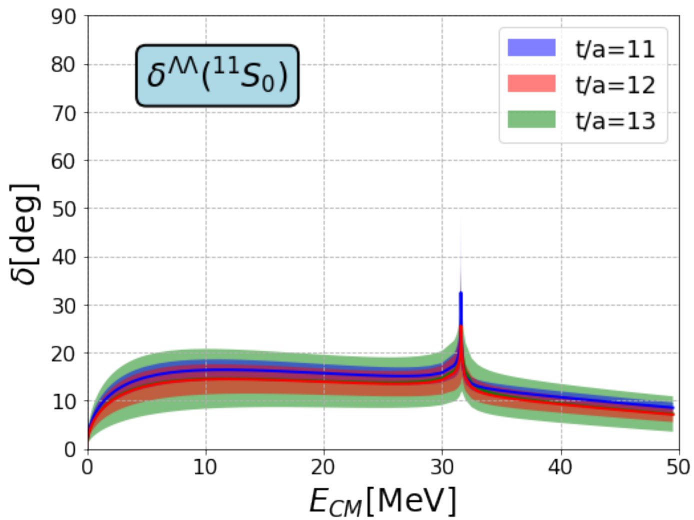
ΛΛ, NΞ (effective) 2x2 coupled channel analysis

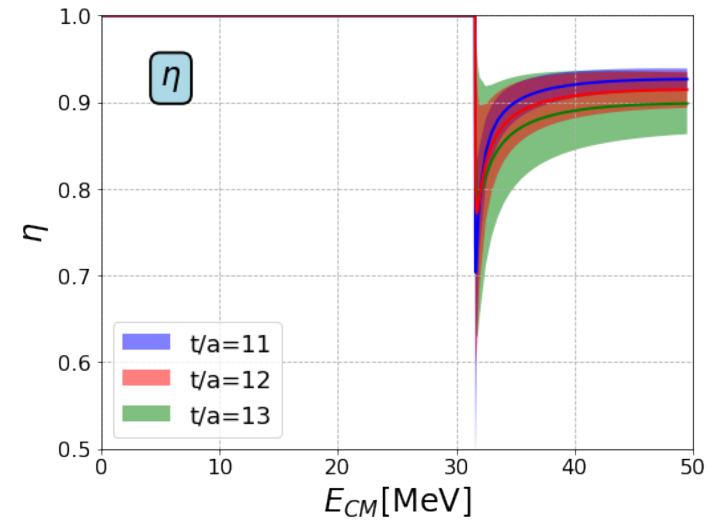


NΞ ($^{11}S_0$) channel is attractive
NΞ–ΛΛ coupling is small

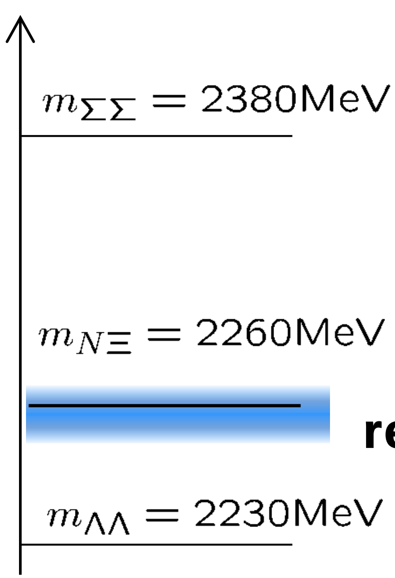
K. Sasaki et al., (HAL Coll.), NPA998(2020)12137

ΛΛ, NΞ 2x2 coupled channel analysis

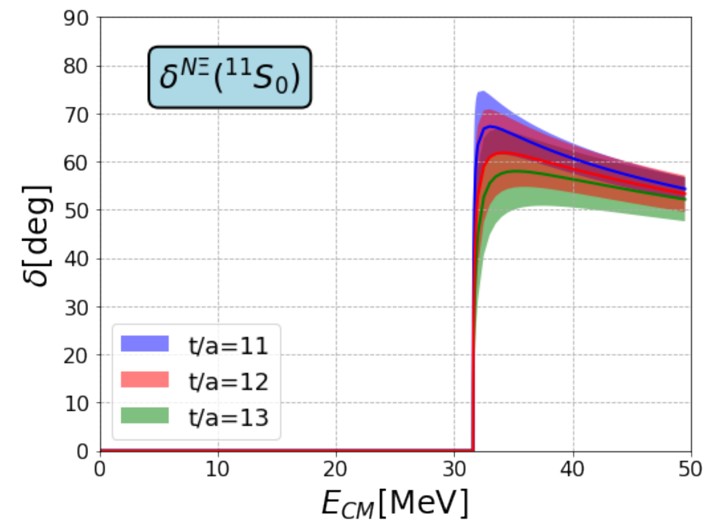




a_0 = -0.81(23)(+0.00/-0.13) [fm]
r_{eff} = 5.47(78)(+0.09/-0.55) [fm]



J-PARC E42 (Ahn)



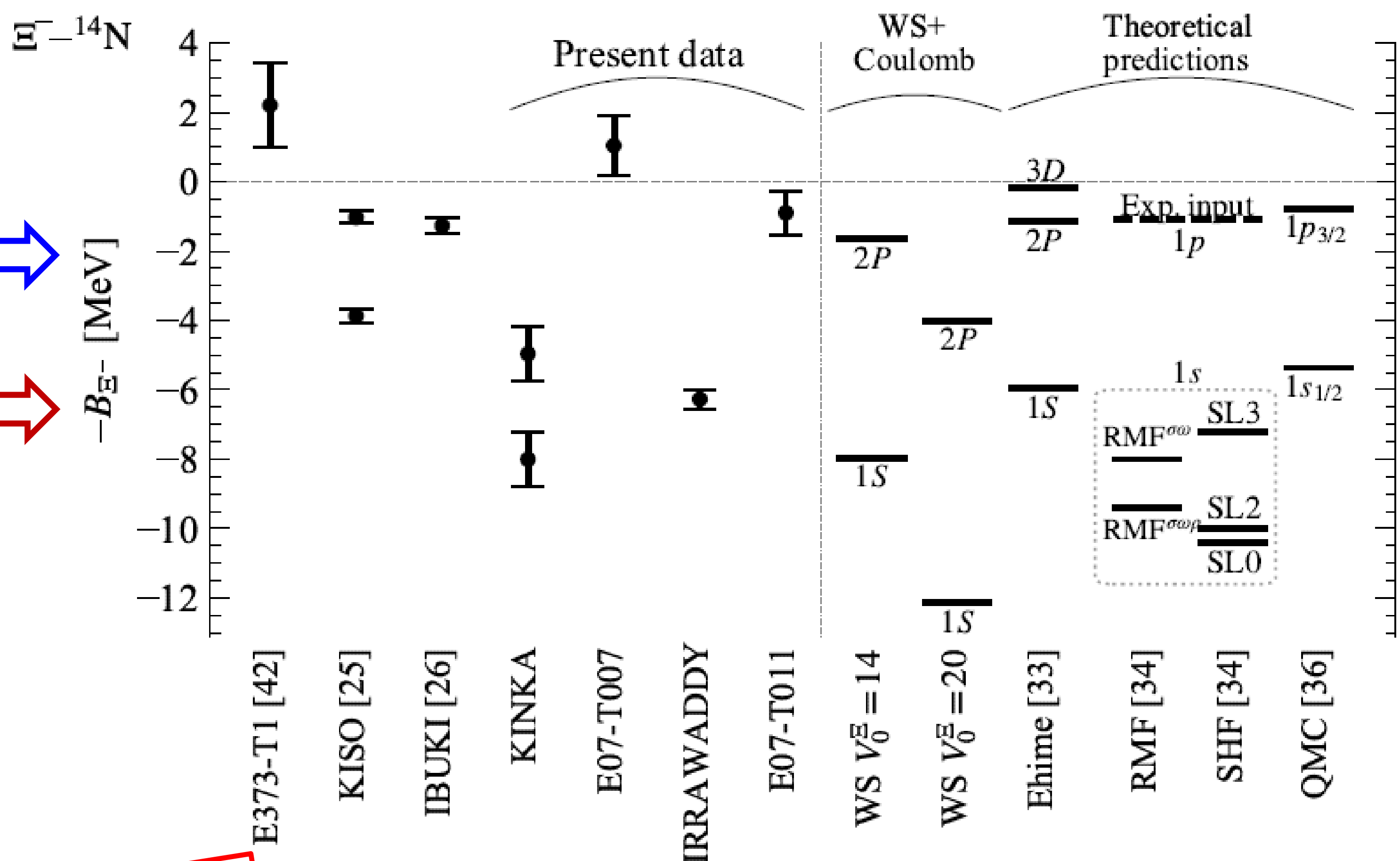
NΞ ~ unitary limit
remnant of "H-dibaryon"

(N.B. NΞ = 1rep 50%, 27rep 30% in SU(3))

Recent experimental progress on Ξ–Hypernuclei

Excited state?

Ground state?

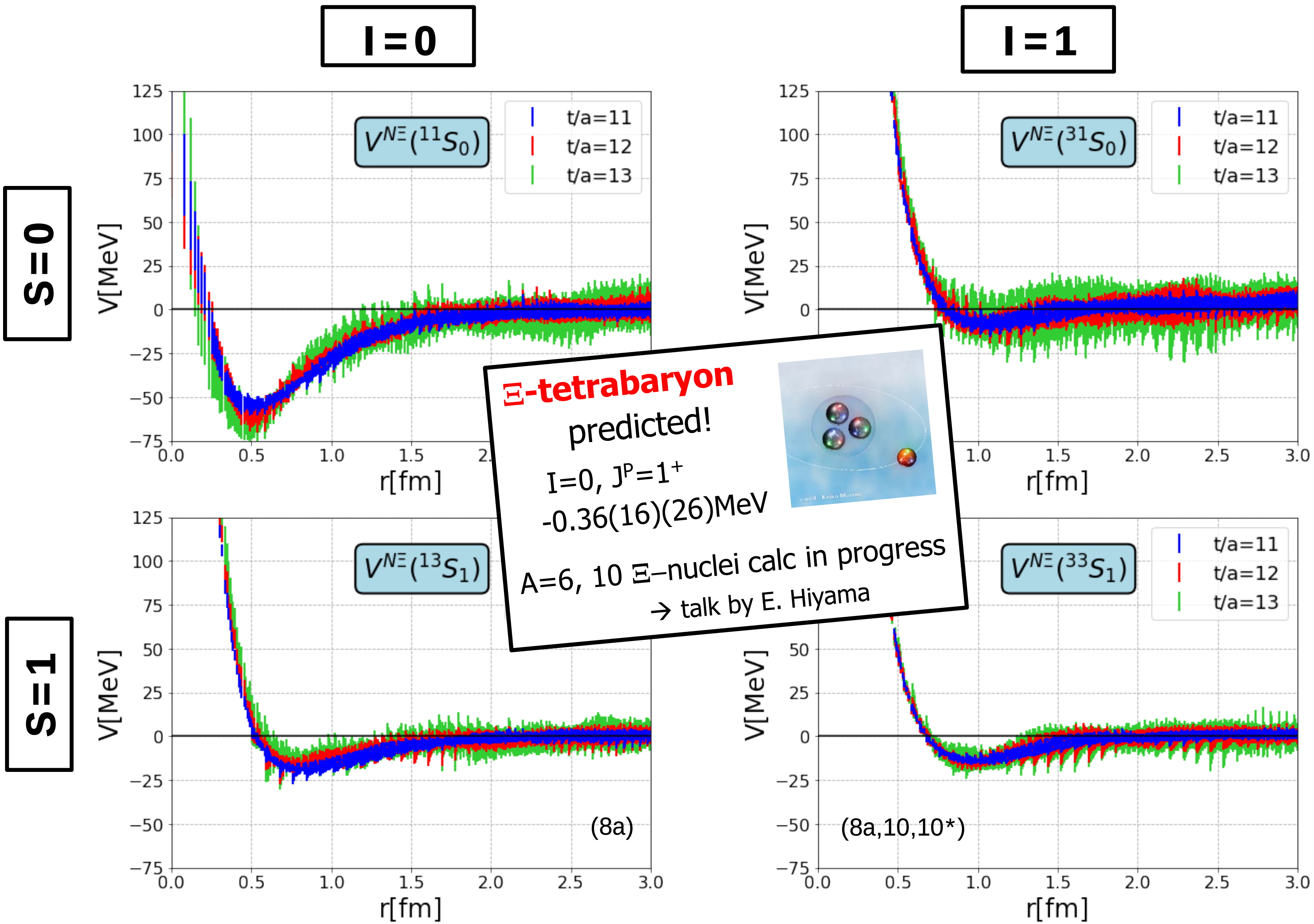


M. Yoshimoto et al., PTEP2021, 073D02

J-PARC E07, E70, more in HEF-EX

Attractive NΞ–int well established
Small NΞ–ΛΛ coupling indicated

Spin-Isospin dependence of NΞ potentials



Ξ-tetrabaryon predicted!

I=0, $J^P=1^+$

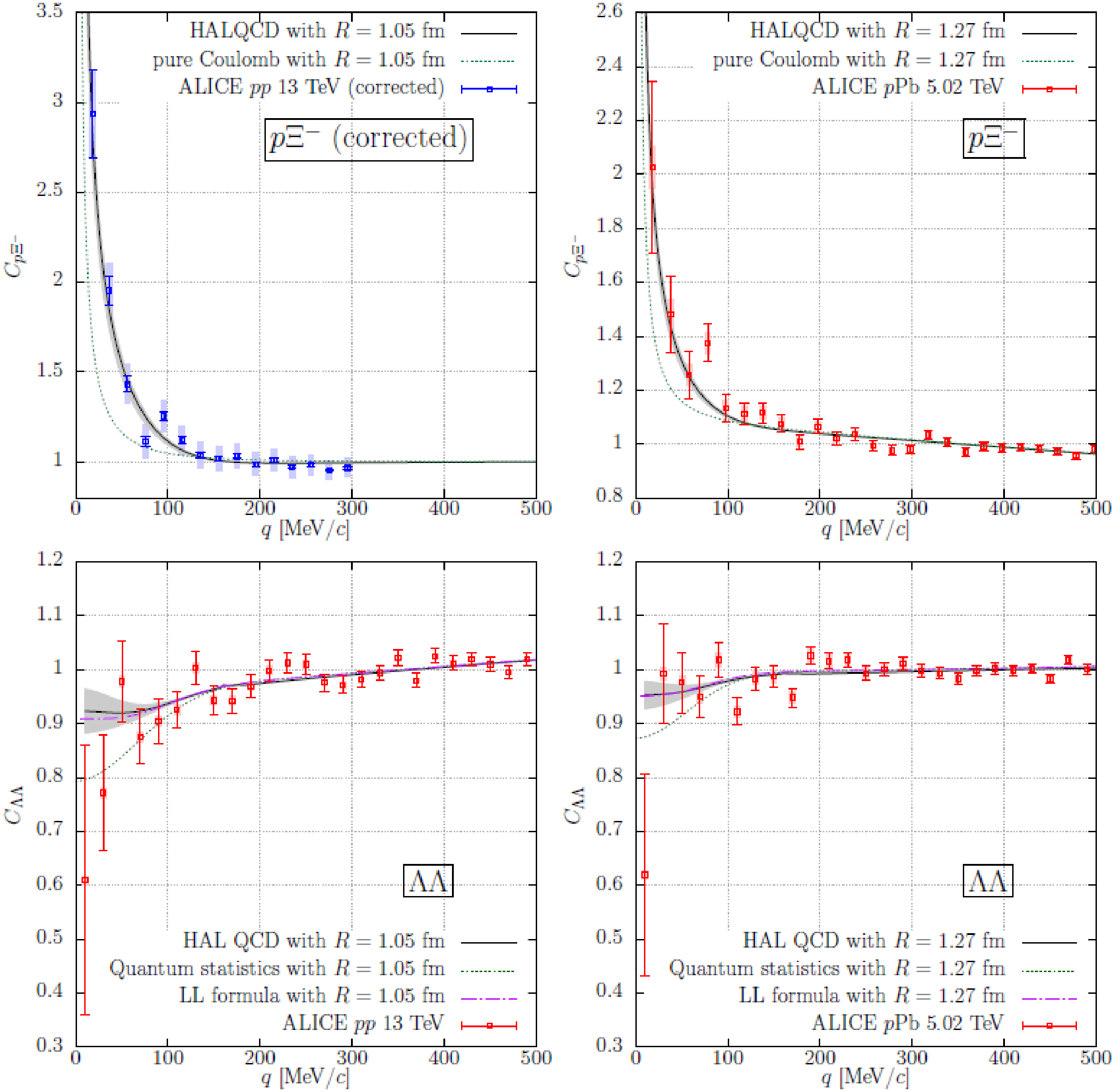
-0.36(16)(26)MeV

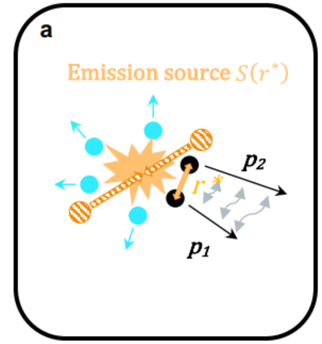
A=6, 10 Ξ–nuclei calc in progress

→ talk by E. Hiyama

K. Sasaki et al., (HAL Coll.), NPA998(2020)12137

Femtoscopy from nucleus collisions





(Fig from ALICE)

⇐ **$p\Xi^-$**

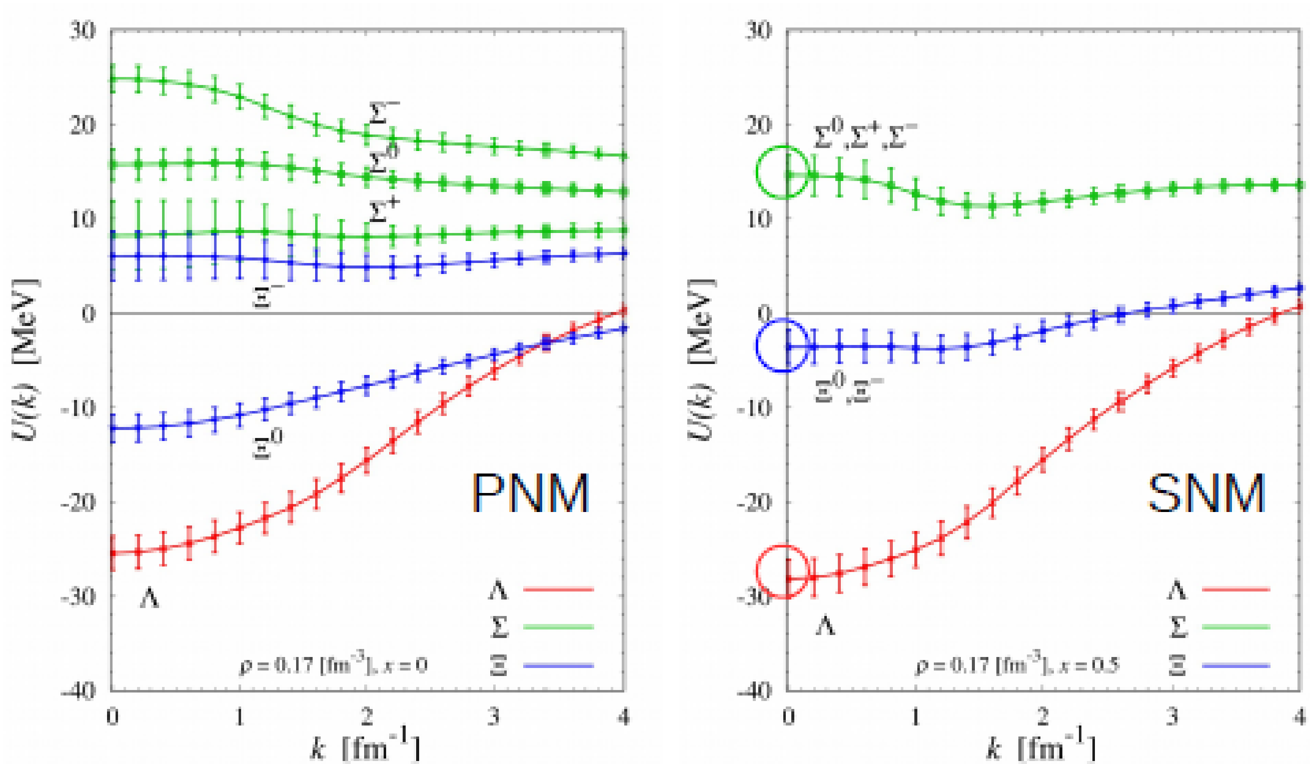
LQCD prediction confirmed by experiment!

⇐ **$\Lambda\Lambda$**

Y. Kamiya et al., PRC105(2022)014915

See also ALICE Coll., PLB797(2019)134822, PRL123(2019)112002, Nature 588(2020)232

“Super-super heavy nuclei”: Dense matter from LQCD
Hyperon single-particle potential



$@\rho = 0.17\,[\mathrm{fm}^{-3}]$

Preliminary

T. Inoue (HAL Coll.)
PoS INPC2016, 277

- obtained by using *YN*,*YY* S-wave forces form QCD.
- Results are compatible with experimental suggestion.

$$U_\Lambda^{\mathrm{Exp}}(0) \simeq -30, \quad U_\Xi(0)^{\mathrm{Exp}} \simeq -10\,?, \quad U_\Sigma^{\mathrm{Exp}}(0) \geq +20\,? \quad [\mathrm{MeV}]$$

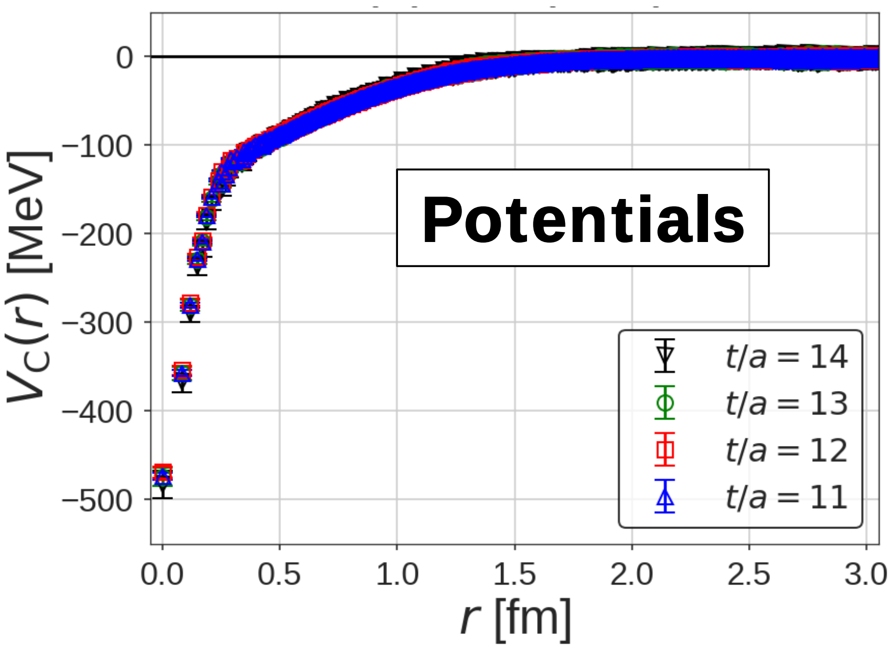
attraction — attraction small — repulsion

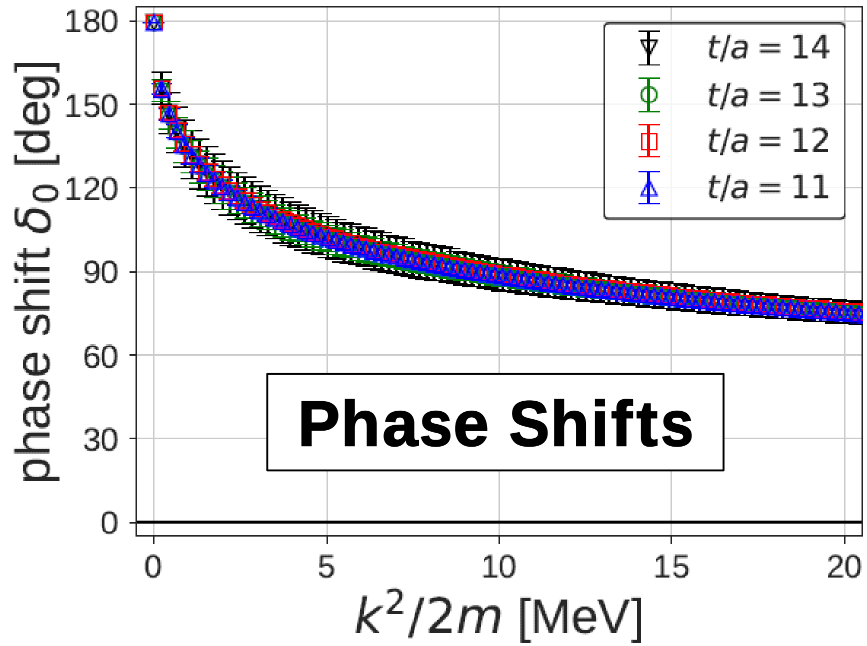
49

(YN/YY pot from SU(3)f-irrep diag used)

[T. Inoue]

NΩ system ($^5S_2$)



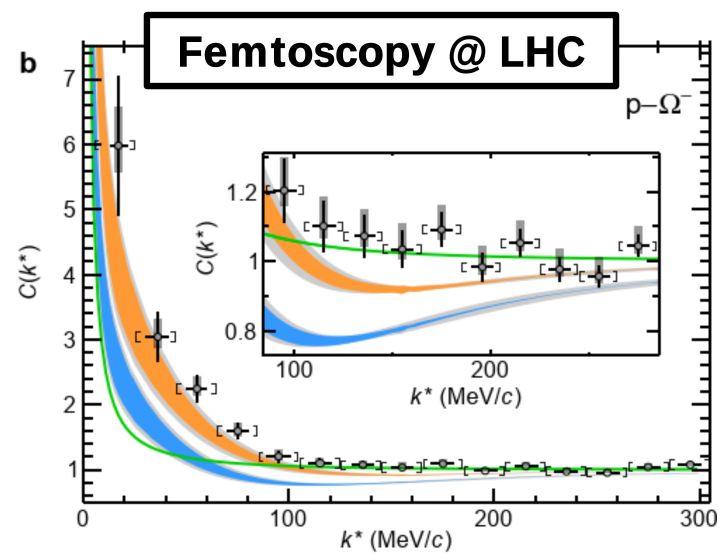


(Quasi) Bound state

[~ Unitary limit]

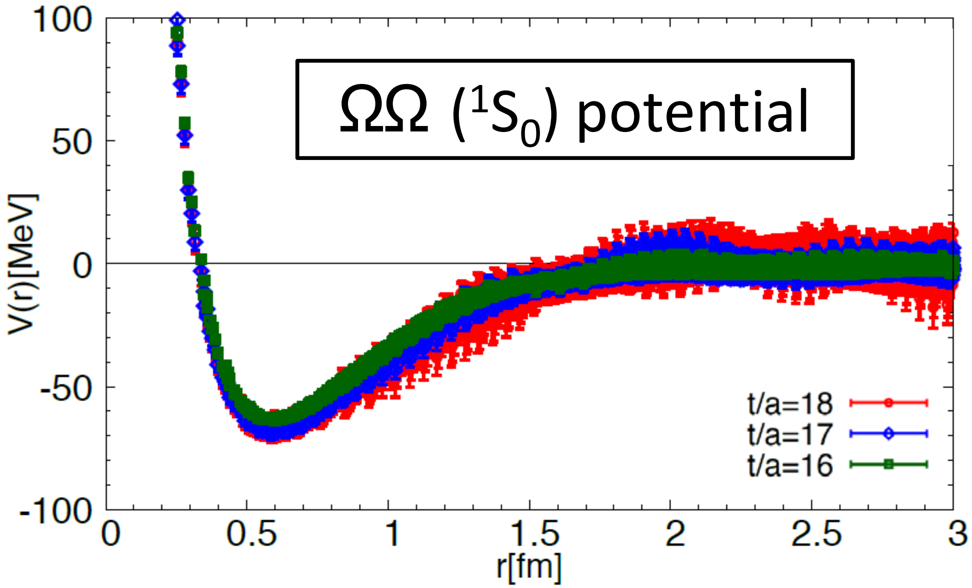
$$B_{N\Omega} = 1.54(0.30)(^{+0.04}_{-0.10})\ \text{MeV}$$
$$B_{p\Omega^-} = 2.46(0.34)(^{+0.04}_{-0.11})\ \text{MeV}$$

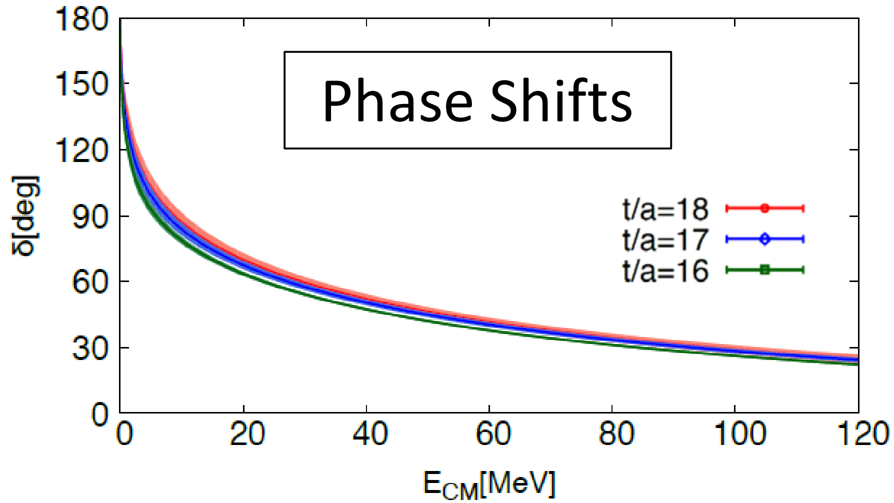
T. Iritani et al. (HAL Coll.), PLB792(2019)284



ALICE Coll., Nature 588 (2020) 232

“Most Strange” Dibaryon : ΩΩ

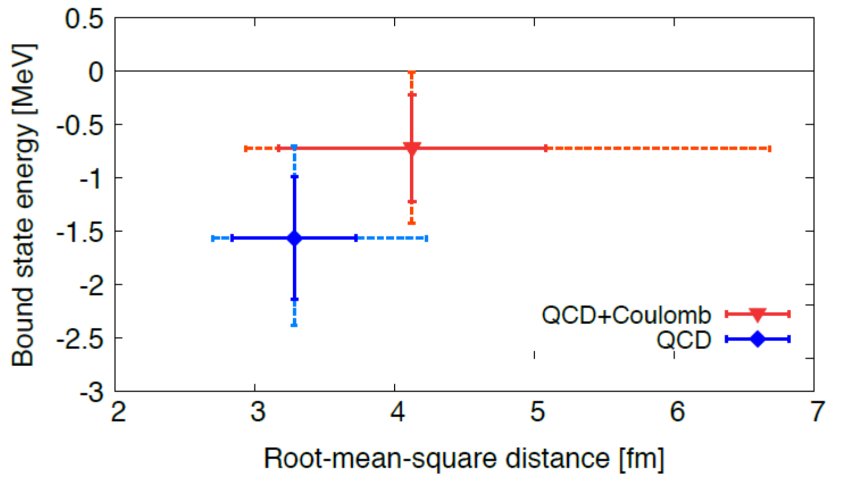




“di-Omega”

[~ Unitary limit]

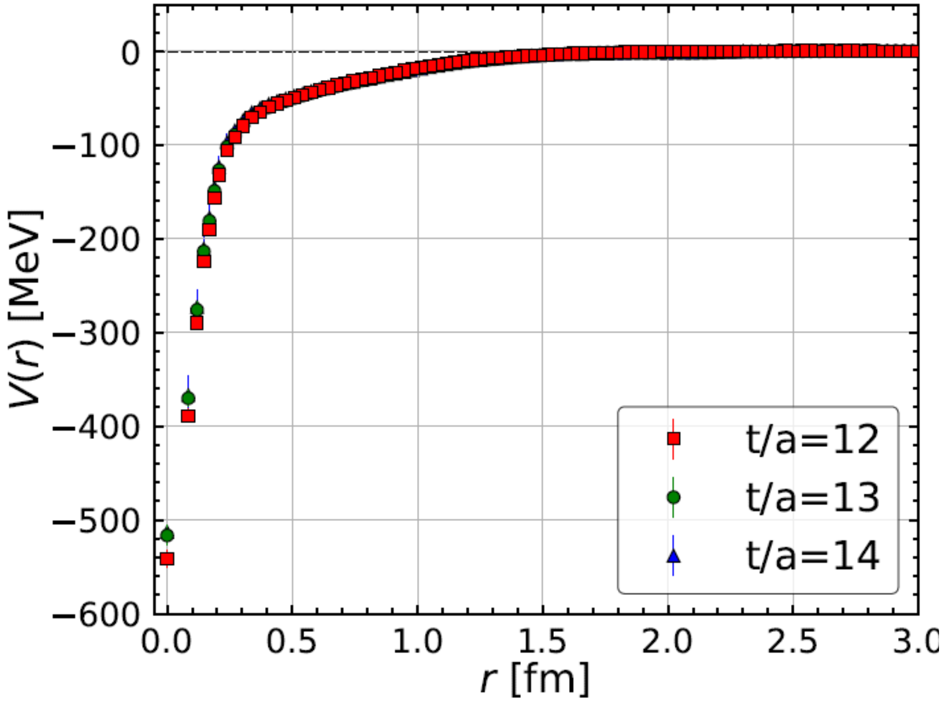
could be searched in LHC RUN3

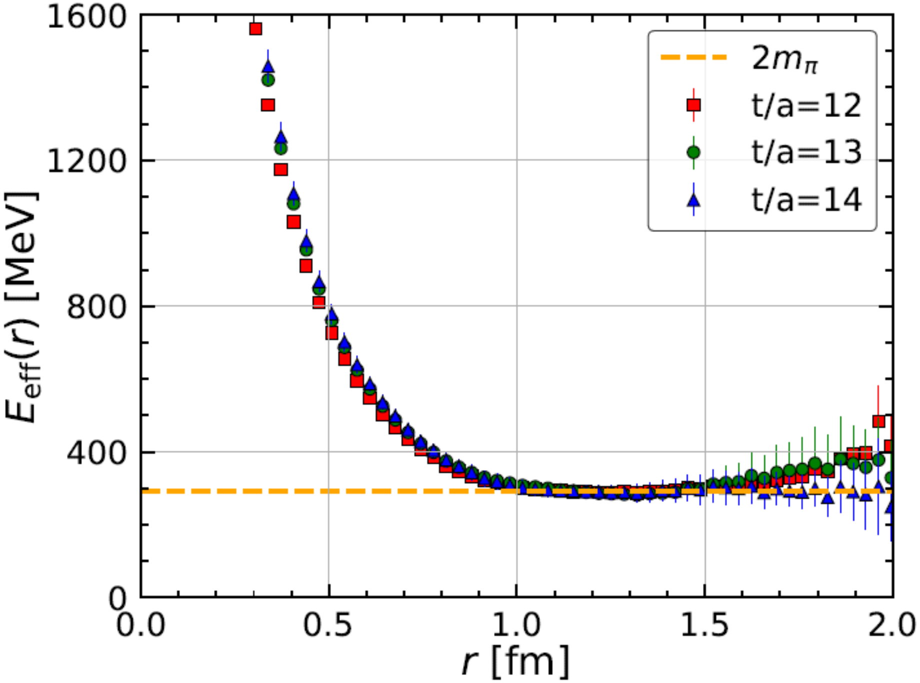


S. Gongyo et al. (HAL Coll.), PRL120(2018)212001

Nϕ system ($^4S_{3/2}$)

Potential ⟹ Tail structure of potential





$$V(r) \xrightarrow{r\to\infty} -\alpha \frac{e^{-2m_\pi r}}{r^2} \quad \Longrightarrow \quad E_{\rm eff}(r) = -\frac{\ln\left[-V(r)r^2/\alpha\right]}{r} \xrightarrow{r\to\infty} 2m_\pi$$

Potential is attractive at all distances

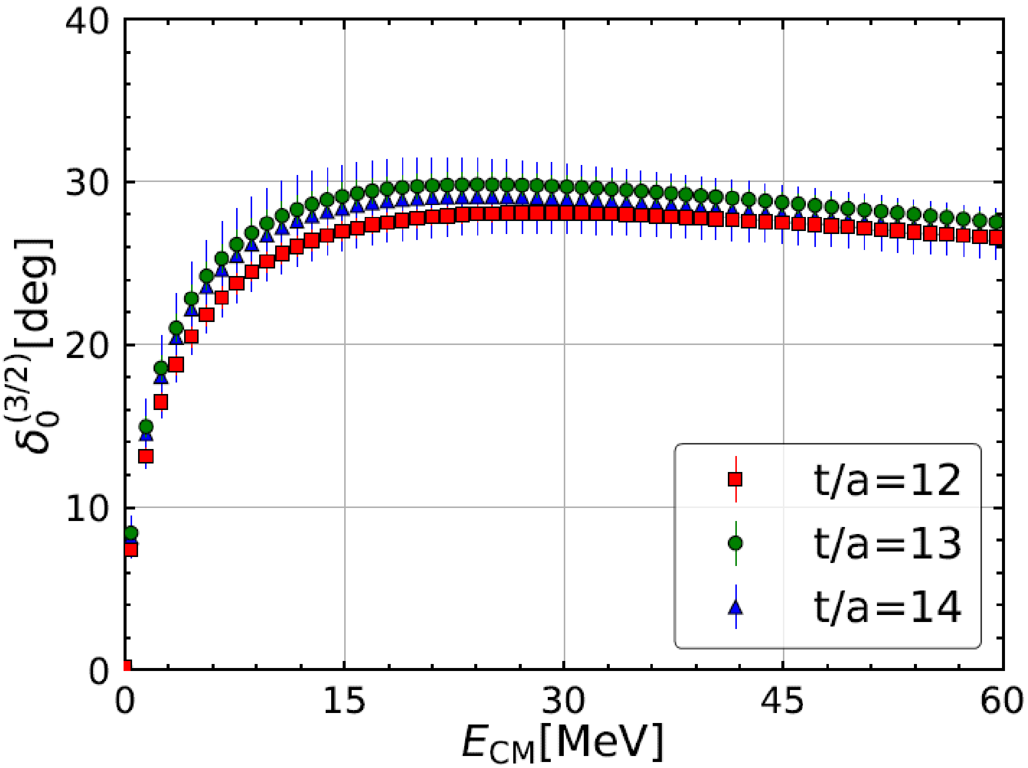
Tail is consistent w/ two-pion exchange (TPE) !

Y. Lyu et al., arXiv:2205.10544

c.f. H. Fujii and D. Kharzeev, Phys. Rev. D 60, 114039 (1999)
J. Castella and G. Krein, Phys. Rev. D 98, 014029 (2018)

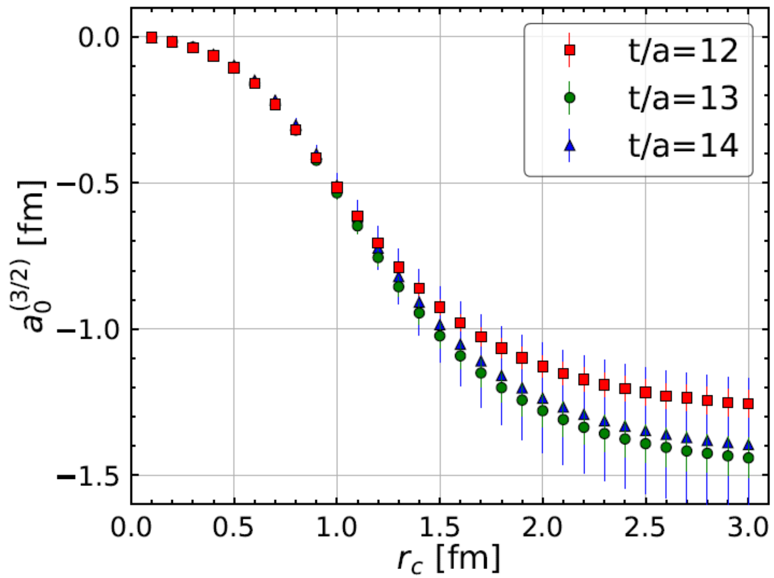
Nϕ system ($^4S_{3/2}$)

Phase shifts



Scattering length from

$$V(r;r_c) = \theta(r_c - r)V(r)$$



➔ Dominated by TPE tail

$$a_0^{(3/2)} = -1.43(23)(^{+36}_{-06}) \text{ fm}, \; r_{\text{eff}}^{(3/2)} = 2.36(10)(^{+02}_{-48}) \text{ fm}$$

Y. Lyu et al., arXiv:2205.10544

Future prospects: physical point simulation!

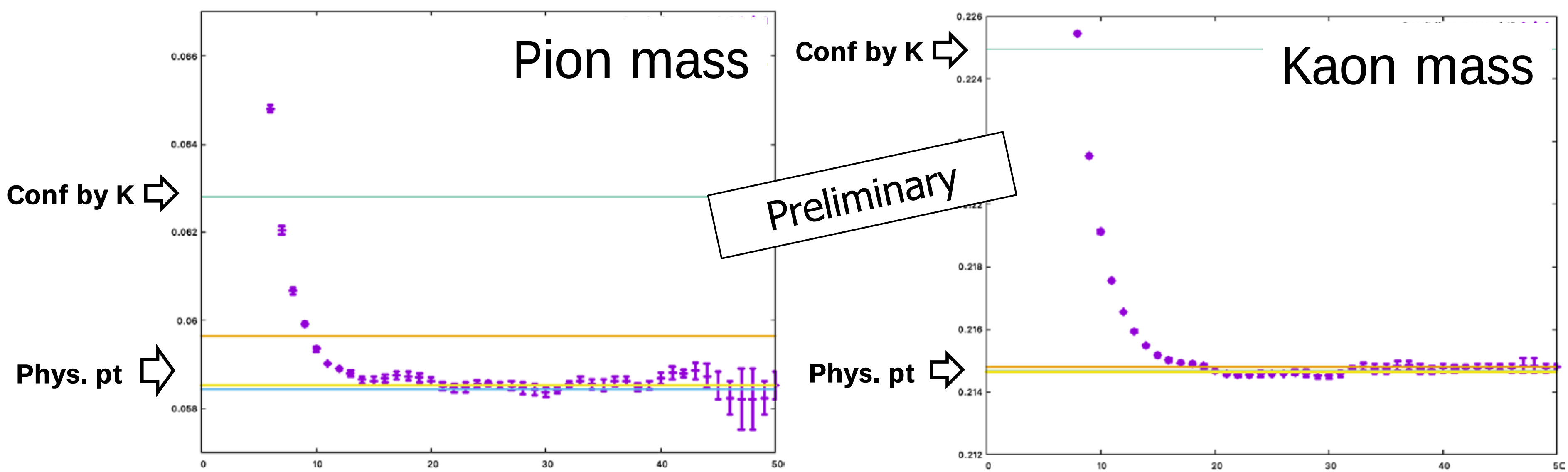
Fugaku (富岳) supercomputer

Successor of K-computer
Fastest in the world @ 2020-22

Codesign of hardware/software
(LQCD was one of 9 targets)

440 PFlops!

Our Efficiency = ~17% (w/ naïve double prec count)



[E. Itou+]

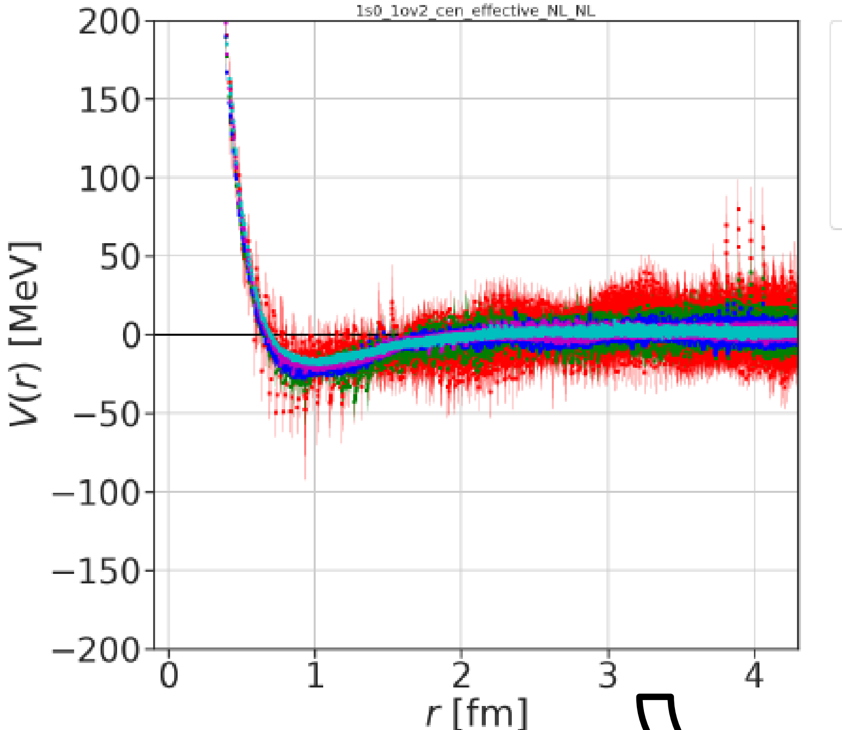
We are on the physical point!

S/N improvement by partial wave decomposition

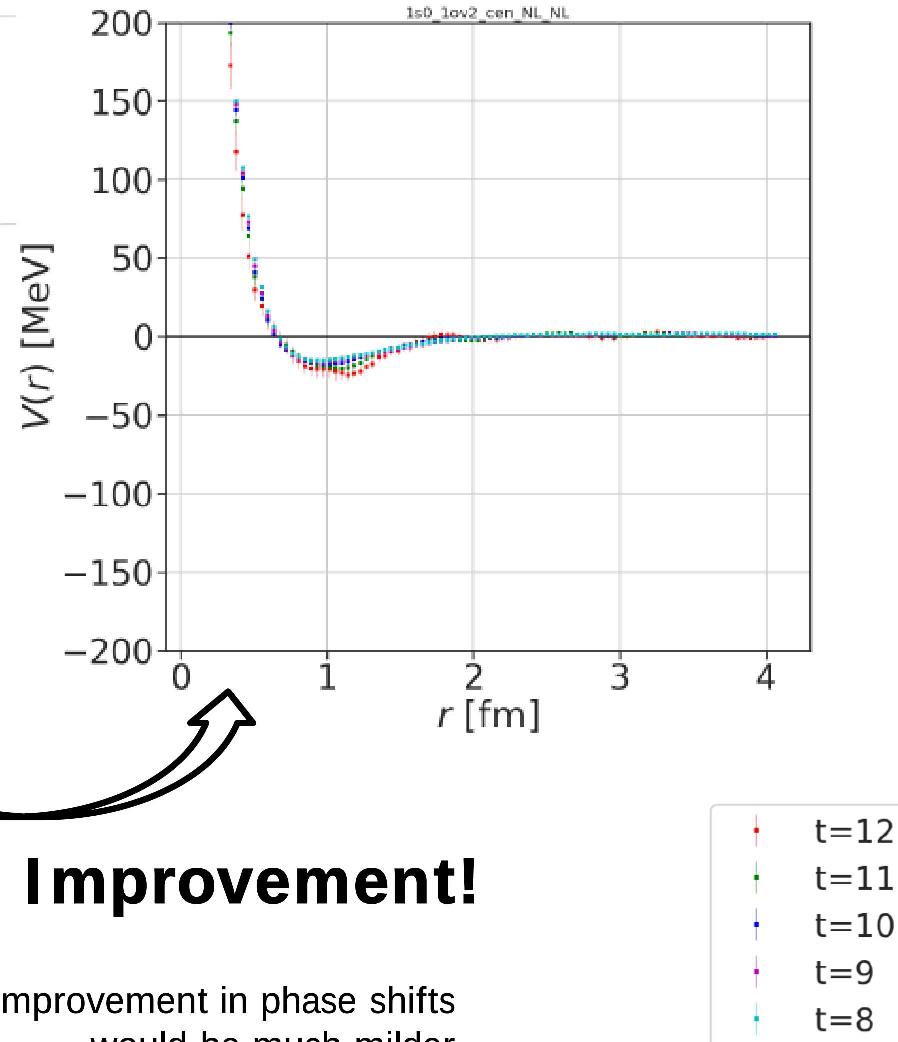
Effective NΛ ($^1S_0$) central potential

T. Miyamoto et al. (HAL Coll.), PRD101(2020)074514

w/o partial wave decomp.



w/ partial wave decomp.



Significant Improvement!

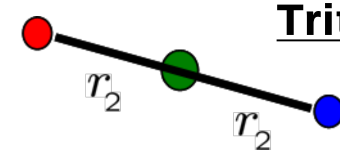
[T. M. Doi]

See also H. Nemura, arXiv:2203.07661
for w/o partial wave decomp

N.B. improvement in phase shifts
would be much milder

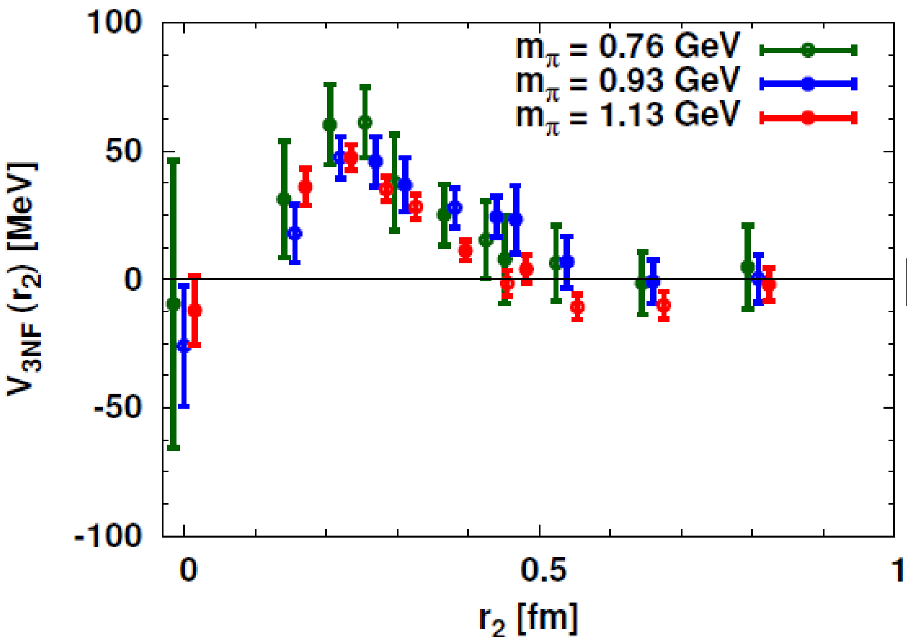
3N-forces (3NF)

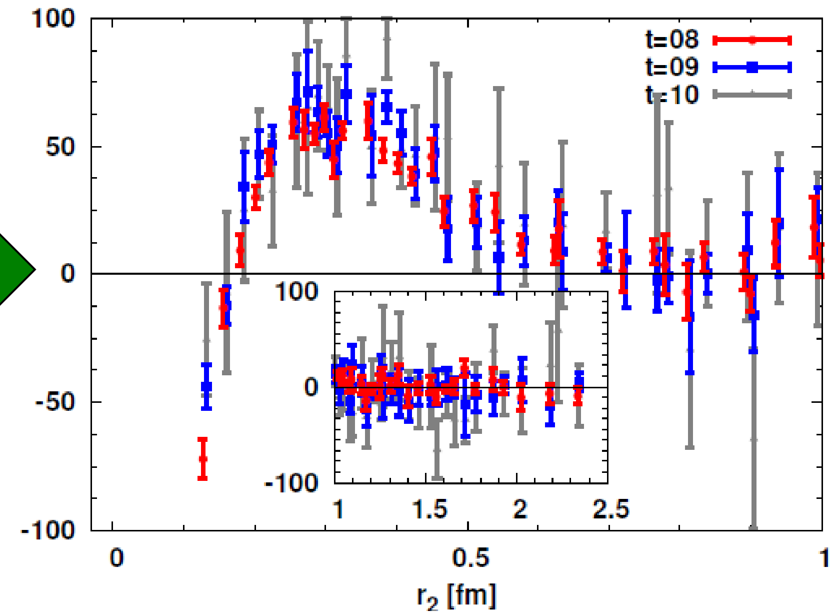
Triton channel



Nf=2, mπ=0.76-1.1 GeV

Nf=2+1, mπ=0.51 GeV





Magnitude of 3NF is similar for all masses
Range of 3NF tend to be enlarged for m(pi)=0.5GeV

Next challenge: **Calc of P-wave 2BF** : better subtraction of 2BF in 3-body systems
YNN (w/o or w/ P-wave 2BF) : gauge conf generation on Fugaku

T.D. et al. (HAL Coll.) PTP127(2012)723
Aoki-Doi Front.Phys.8 (2020) 307

Summary

- Renaissance in particle/nuclear/astro-physics
  - **Observations** of neutron stars (LIGO-Virgo-KAGRA, NICER, …)
  - **Experiments** of hadrons/nuclei → J-PARC, LHC, Belle II, …
  - **Theory** by **LQCD calc of hadron interactions**

- The 1st LQCD for Baryon Interactions near the phys. point
  - Central/Tensor forces for NN/YN/YY in P=(+) channel
  - Dibaryons, Applications to Hypernuclei, EoS

- Prospects
  - **Hadron forces on the physical point by Fugaku supercomputer**
    - **Interactions w/ strangeness** are one of the primary targets, **Interactions w/ charm** also coming
  - Future: P=(-) channel, LS-forces, 3-baryon forces, etc., & EoS
  - Resonances & Exotics