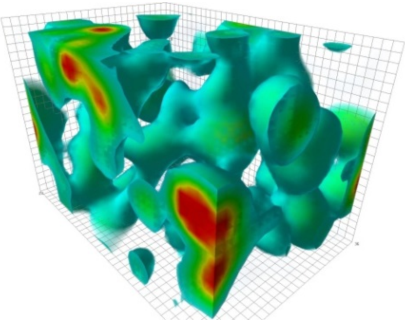
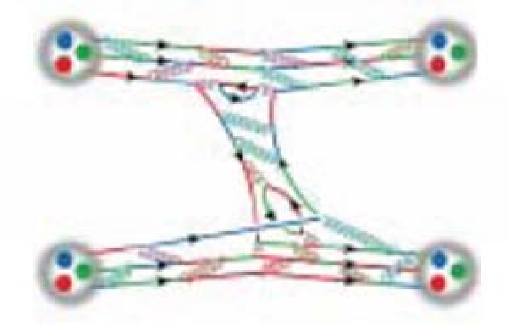
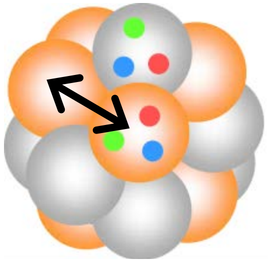
Lattice QCD studies of Hadron interactions from the HAL QCD method

Takumi Doi

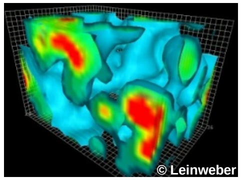
(RIKEN iTHEMS)



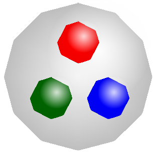




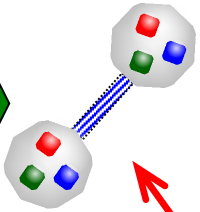
The Odyssey from Quarks to Universe

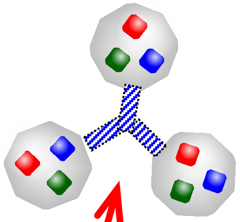


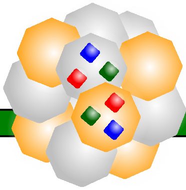
QCD vacuum



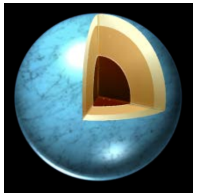
Baryons

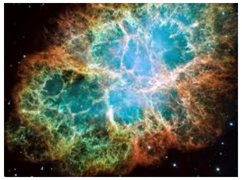






Nuclei





Neutron Stars / Supernovae
Nucleosynthesis

QCD

**1st-principle
Lattice QCD**

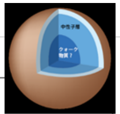
**Hadron
Forces**

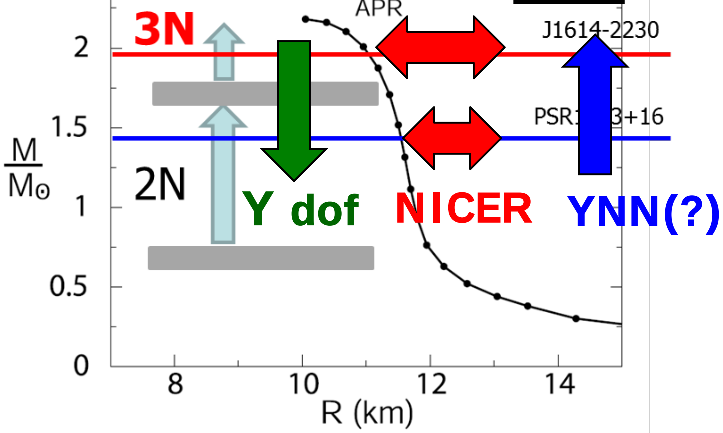
ab-initio nuclear calc.

J-PARC

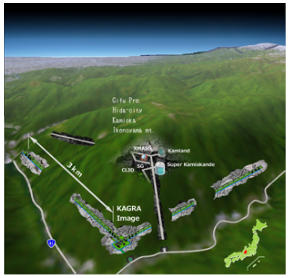
LHC/RHIC

EoS of Dense Matter

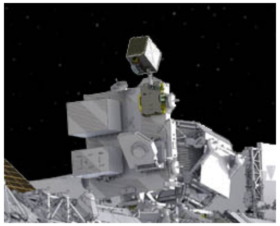




RIBF/FRIB



aLIGO/KAGRA



NICER

Nuclear/Hyperon Forces ➔ Charmed/Bottomed Forces

light ~ a few MeV ~100 MeV ~300 MeV ~1.3 GeV ~4.2 GeV **heavy**

up,down quarks

strange quark

Λ_{QCD}

charm quark

bottom quark

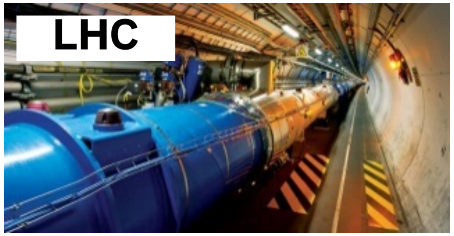
top

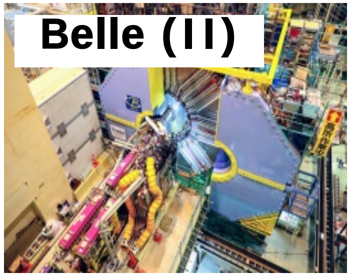
chiral symmetry

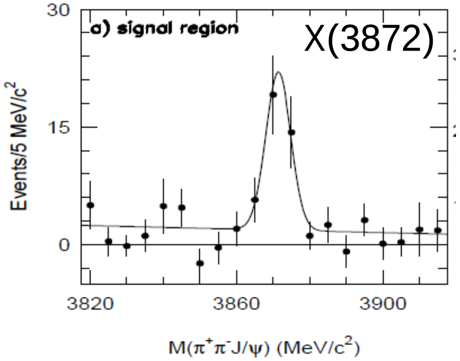
heavy quark symmetry

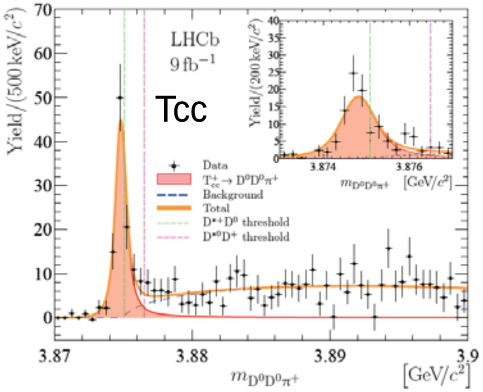
Heavy quarks: New doorway to the mysteries of QCD

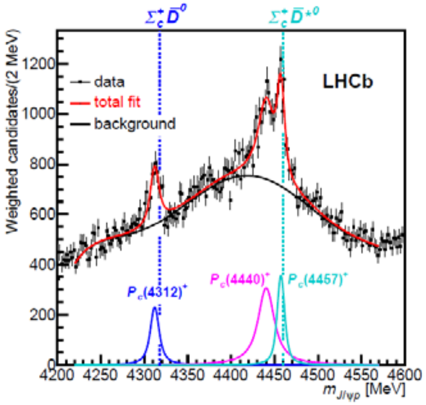
Many new exotic particles being reported!











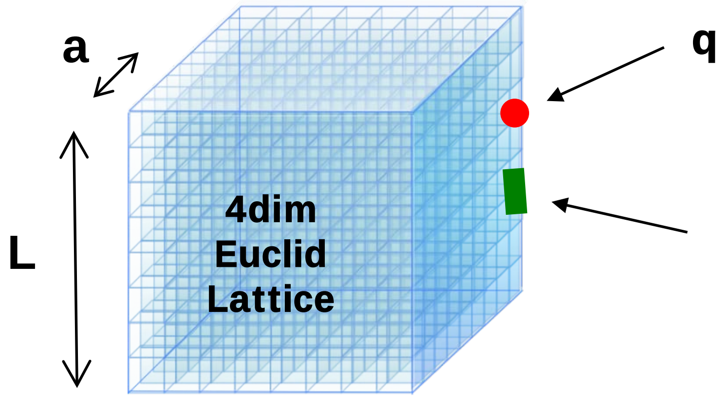
Hadron interactions crucial to understand these “signals” !

e.g., Zc(3900) from HAL LQCD → threshold cusp

Y. Ikeda et al. (HAL), PRL117(2016)242001

Lattice QCD
First-principle calculation of QCD

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



quarks on sites

$$q(x)$$

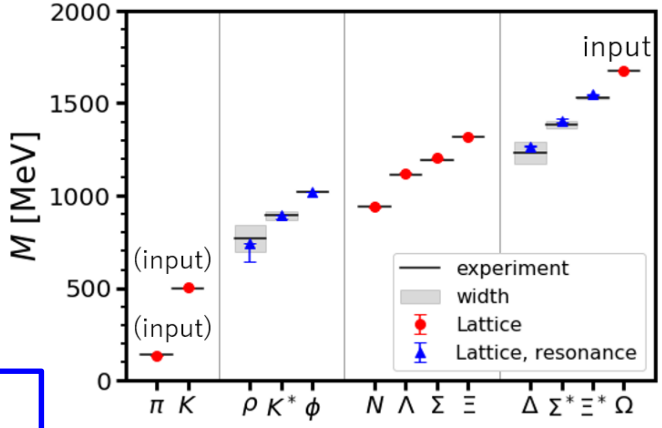
gluons on links

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

K.G. Wilson
(1974)

- Regularized system (finite a and L)
- Gauge-invariance manifest
- Fully-Nonperturbative
- DoF ~ $10^{9\text{-}10}$ ➔ Monte-Carlo w/ Euclid time
  - Numerical calc by supercomputers

Single hadron spectrum well reproduced
→ Next big challenge: ***Interactions between hadrons***



HAL Coll., PRD in press
arXiv:2406.16665

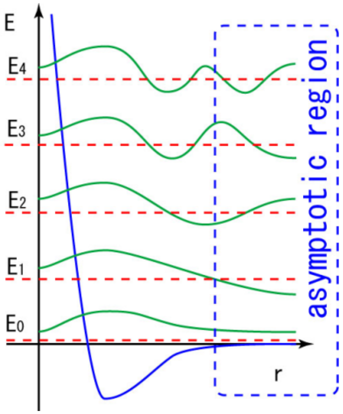
[HAL QCD method]

- “Potential” defined through phase shifts (S-matrix)

- Nambu-Bethe-Salpeter (NBS) wave function

$$\boxed{\psi(\vec{r}) = \langle 0 | H_1(\vec{x}+\vec{r}) H_2(\vec{x}) | H_1(k) H_2(-k); W \rangle}$$

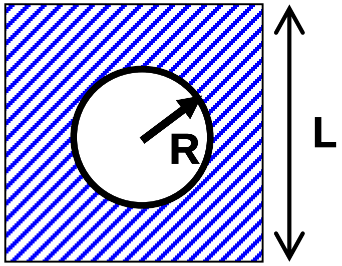
$$(\nabla^2 + k^2)\psi(\vec{r}) = 0, \qquad r > R \qquad\qquad W = 2\sqrt{m^2+k^2}$$



  - Wave function ←→ phase shifts

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

(below inelastic threshold)



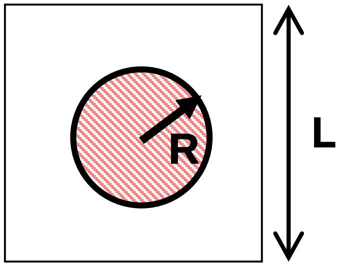
Extended to multi-particle systems

M.Luscher, NPB354(1991)531
C.-J.Lin et al., NPB619(2001)467
CP-PACS Coll., PRD71(2005)094504
Ishizuka, Pos LAT2009 (2009) 119
Aoki-Hatsuda-Ishii PTP123(2010)89
S.Aoki et al., PRD88(2013)014036

“Potential” as a representation of S-matrix

- 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’): <u>NOT</u> an observable, but well defined
    - U(r,r’): E-independent, while non-local in general
      - “Proof of Existence”: Explicit form can be given as

$$U(\boldsymbol{r}, \boldsymbol{r}') = \frac{1}{m} \sum_{n,n'}^{n_{\rm th}} (\nabla_{\boldsymbol{r}}^2 + k_n^2)\psi_n(\boldsymbol{r}) \mathcal{N}_{nn'}^{-1} \psi_{n'}^*(\boldsymbol{r}') \qquad \mathcal{N}_{nn'} = \int d\boldsymbol{r}\, \psi_n^*(\boldsymbol{r})\psi_{n'}(\boldsymbol{r})$$

      - Non-locality ➔ derivative expansion

Okubo-Marshak(1958)

$$U(\vec{r}, \vec{r}') = \left[\underset{\textbf{LO}}{V_C(r)} + \underset{\textbf{LO}}{S_{12} V_T(r)} + \underset{\textbf{NLO}}{\vec{L} \cdot \vec{S} V_{LS}(r)} + \underset{\textbf{NNLO}}{\mathcal{O}(\nabla^2)} \right] \delta(\vec{r} - \vec{r}')$$

Aoki-Hatsuda-Ishii PTP123(2010)89

Check on convergence: Murano+ PTP125(‘11), Iritani+ PRD99(‘19)

Time-dependent HAL method

N.Ishii et al. (HAL QCD Coll.) PLB712(2012)437

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

*They are **not contaminations**, **but signals***

Original (t-indep) HAL method

$$G_{NN}(\vec{r},t) = \langle 0|N(\vec{r},t)N(\vec{0},t)\overline{\mathcal{J}_{\rm src}(t_0)}|0\rangle$$

$$R(\boldsymbol{r},t) \equiv G_{NN}(\boldsymbol{r},t)/G_N(t)^2 = \sum A_{W_i}\psi_{W_i}(\boldsymbol{r})e^{-(W_i-2m)t}$$

← Many states contribute

$$\int d\boldsymbol{r}' U(\boldsymbol{r},\boldsymbol{r}')\underline{\psi_{W_0}(\boldsymbol{r}')} = (\underline{E_{W_0}} - H_0)\underline{\psi_{W_0}(\boldsymbol{r})}$$

$$\int d\boldsymbol{r}' U(\boldsymbol{r},\boldsymbol{r}')\underline{\psi_{W_1}(\boldsymbol{r}')} = (\underline{E_{W_1}} - H_0)\underline{\psi_{W_1}(\boldsymbol{r})}$$

. . .

Coupled Channel formalism
↔ above inelastic threshold

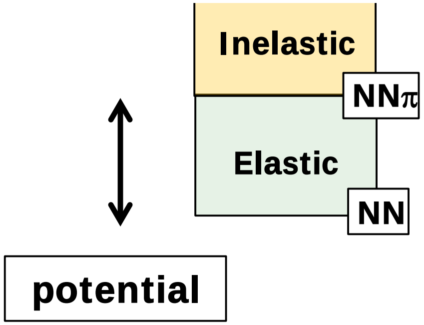
New t-dep HAL method

All equations can be combined as

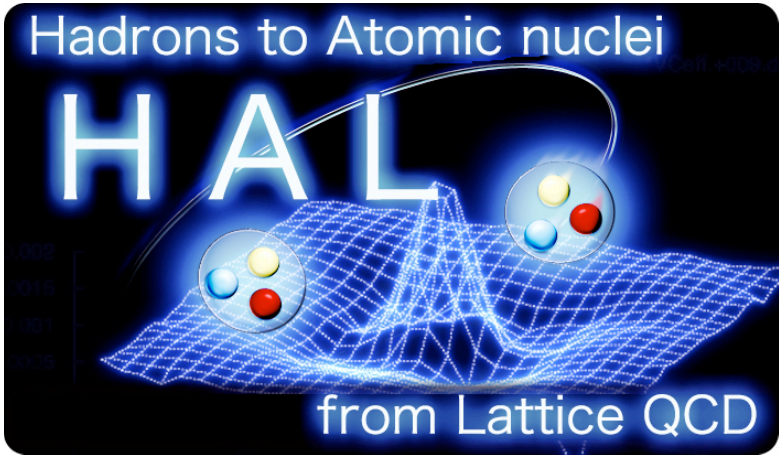
$$\int d\boldsymbol{r}' U(\boldsymbol{r},\boldsymbol{r}')\underline{R(\boldsymbol{r}',t)} = \underline{(-\frac{\partial}{\partial t} + \frac{1}{4m}\frac{\partial^2}{\partial t^2}} - H_0)\underline{R(\boldsymbol{r},t)}$$

~~G.S. saturation~~ → "Elastic state" saturation

[Exponential Improvement]



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



S. Aoki, T. M. Doi, E. Itou (Kyoto U.)
T. Aoyama (ISSP)
T. Doi, T. Hatsuda, Y. Lyu, W. A. Yamada, L. Wang, L. Zhang (RIKEN)
F. Etminan (U. of Birjand)
Y. Ikeda, N. Ishii, P. Junnarkar, H. Nemura, K. Sasaki (Osaka U.)
T. Inoue (Nihon U.)
K. Murakami (Science Tokyo)
K. Murase (Tokyo Metropolitan U.)
T. Sugiura (Rissho U.)
H. Tong (U. of Bonn)

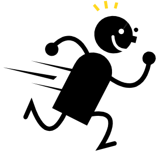
「20XX年宇宙の旅」

from Quarks to Universe

+
I. Kanamori (RIKEN)
K.-I. Ishikawa (Hiroshima U.)
and many more

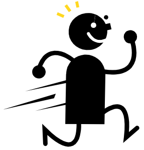
Challenge toward LQCD w/ physical mass

~2012



➔lighter u,d-quark masses
(=lighter pion mass Mπ)

~2018

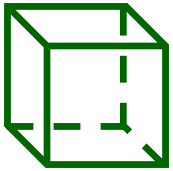


We were here

➔ more challenging

Phys. point

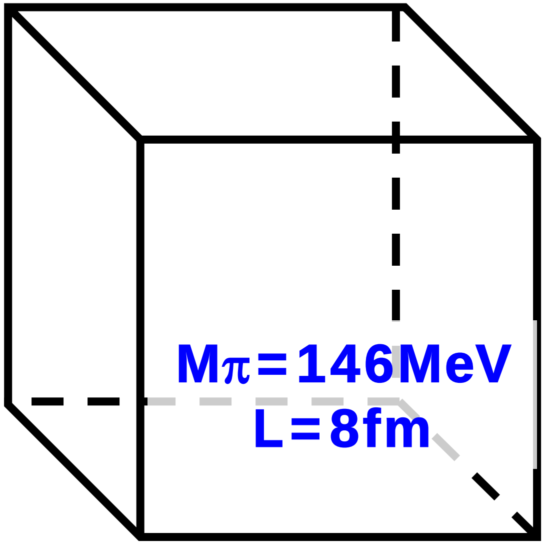
Mπ=400MeV
L=3fm



Theoretical development
+
New supercomputer

Simulation w/
Unrealistic mass

K-computer (11PFlops)

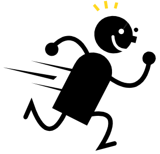


Mπ=146MeV
L=8fm

Simulation w/
~Near physical mass

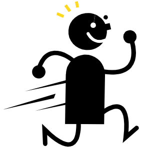
Challenge toward LQCD w/ physical mass

~2012



➔lighter u,d-quark masses
(=lighter pion mass M_π)

~2018

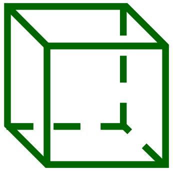


We were here

➔ more challenging

Phys. point

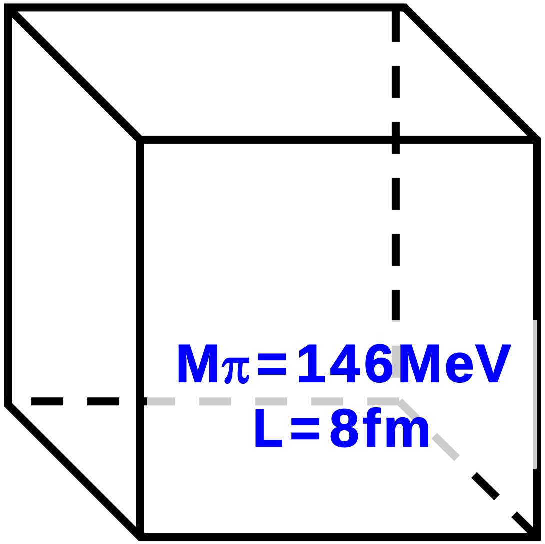
M_π=400MeV
L=3fm



Theoretical development
+
New supercomputer

Simulation w/
Unrealistic mass

Fugaku (440PFlops)



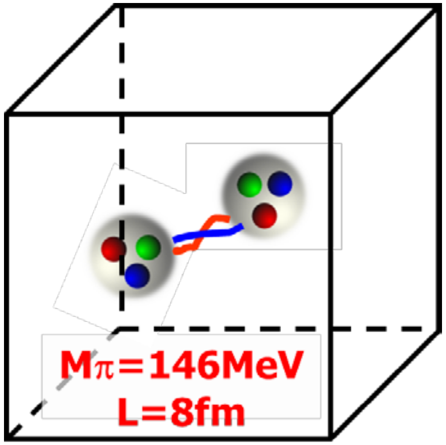
M_π=146MeV
L=8fm

Simulation w/
~Near physical mass

LQCD calc near the physical point

- **Nf = 2 + 1 gauge configs**
  - clover fermion + Iwasaki gauge w/ stout smearing
  - V=$(8.1\text{fm})^4$, a=0.085fm (1/a = 2.3 GeV)
  - **m_π = 146 MeV, m_K = 525 MeV**
  - #traj ~= 2000 generated

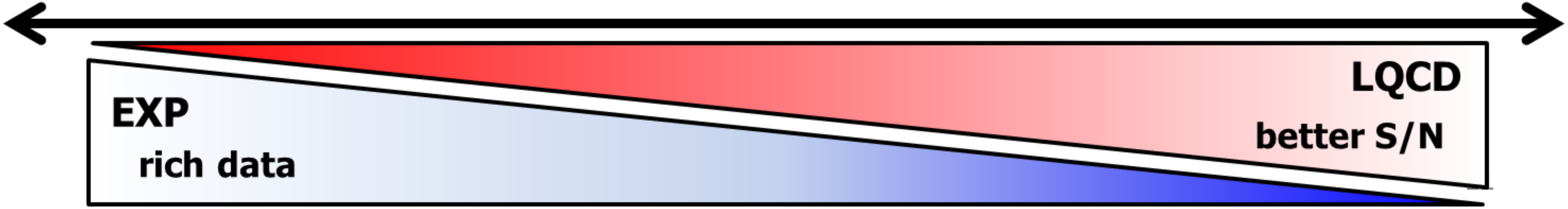
PACS Coll., PoS LAT2015, 075



  - (Quenched) Charm quark w/ RHQ action

Y. Namekawa (PACS), PoS LAT2016, 125

- Nuclear/Hyperon forces + Charmed forces to be predicted
  - Central/tensor forces in S, D-waves



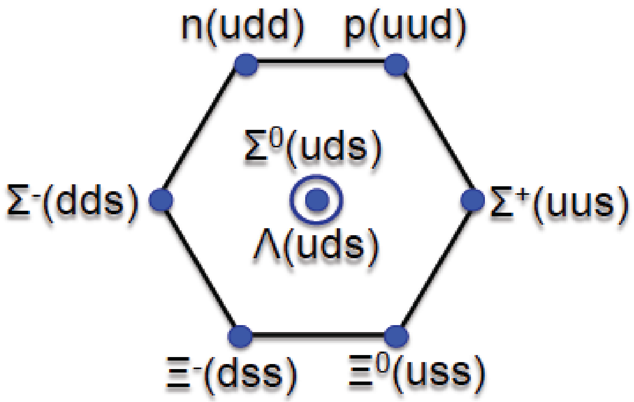
S=0	S=−1	S=−2	S=−3	S=−4	S=−5	S=−6
NN	NΛ, NΣ	ΛΛ, ΛΣ, ΣΣ, NΞ	ΛΞ, ΣΞ, NΩ	ΞΞ	ΞΩ	ΩΩ

EXP
rich data

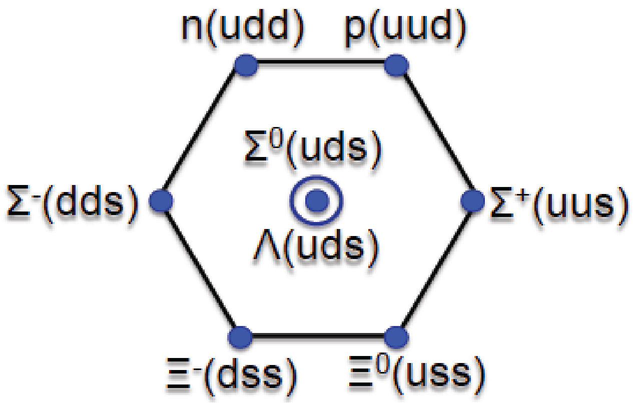
LQCD
better S/N

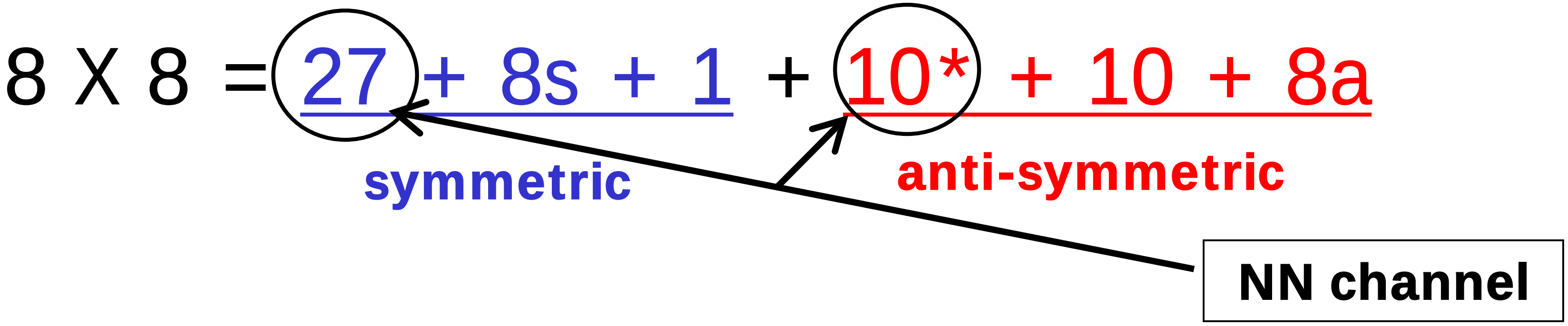
Baryon-Baryon Interactions

Birds-eye View
classification w/ flavor SU(3)-irrep base



X





$$8 \text{ X } 8 = \underbrace{27 + 8s + 1}_{\text{symmetric}} + \underbrace{10^* + 10 + 8a}_{\text{anti-symmetric}}$$

NN channel

c.f. Exact SU(3) limit LQCD calc @ heavy masses

T.Inoue et al. (HAL.), PTP124(2010)591

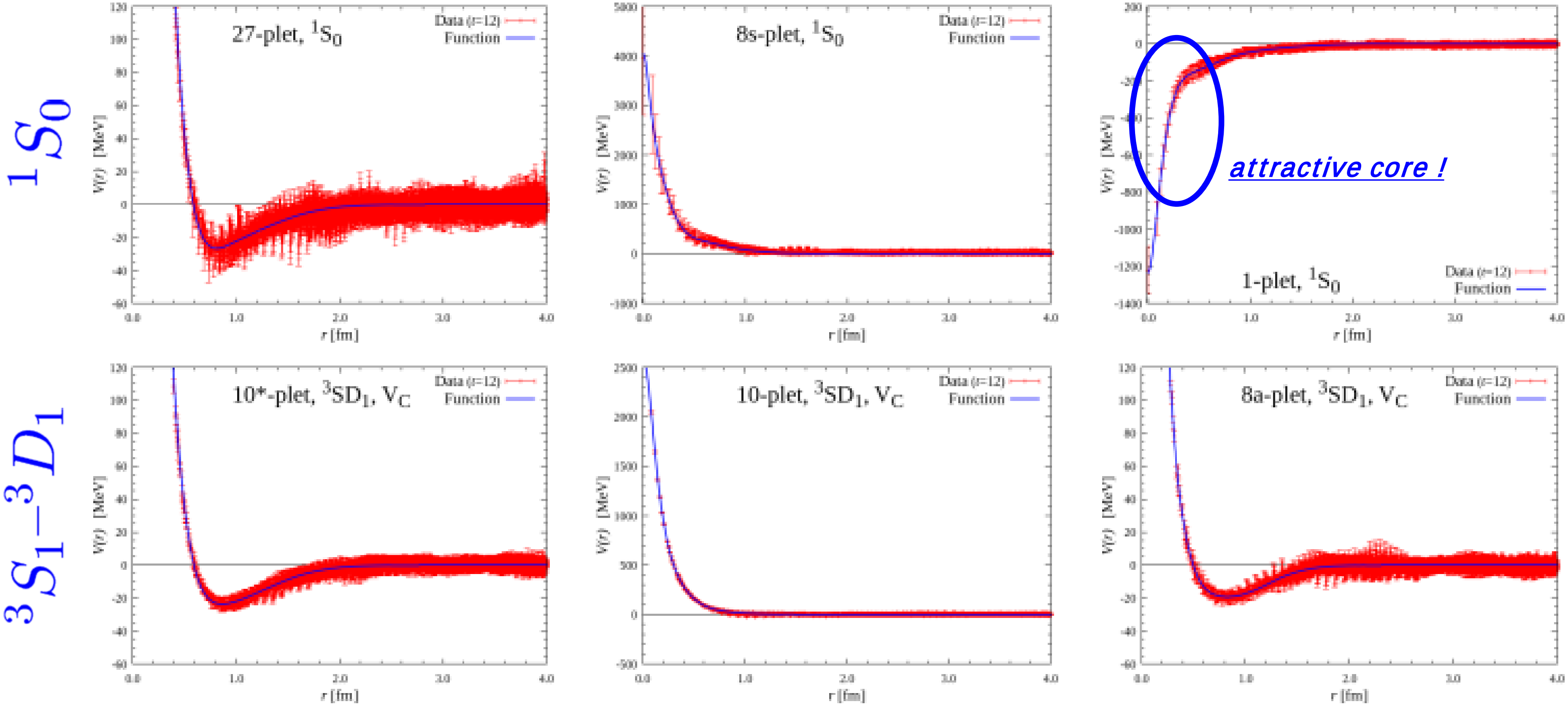
T.Inoue et al. (HAL.), NPA881(2012)28

Diagonal Potentials in SU(3)f-irrep base in S=-2

(only) S= -2 can access all irreps

off-diag pot relatively small

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



attractive core !

27,10*:
NN-type

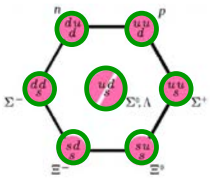
8s,10:
strong repulsive core

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

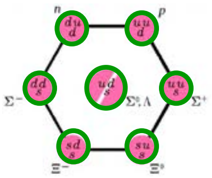
Quark Pauli repulsion + OGE for short range

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

Candidates of di-baryons



X



$$8 \times 8 = \boxed{27} + 8s + \boxed{1} + \boxed{10^*} + 10 + 8a$$

dineutron, ΞΞ etc.
(J=0)

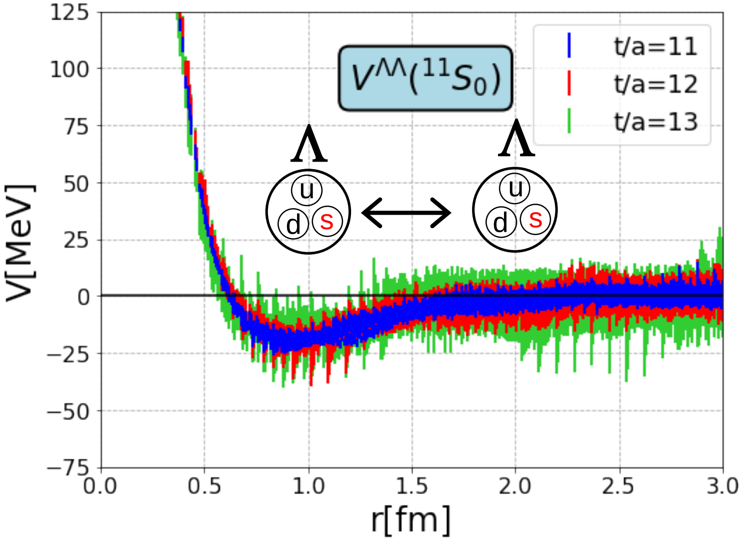
H-dibaryon
(J=0)

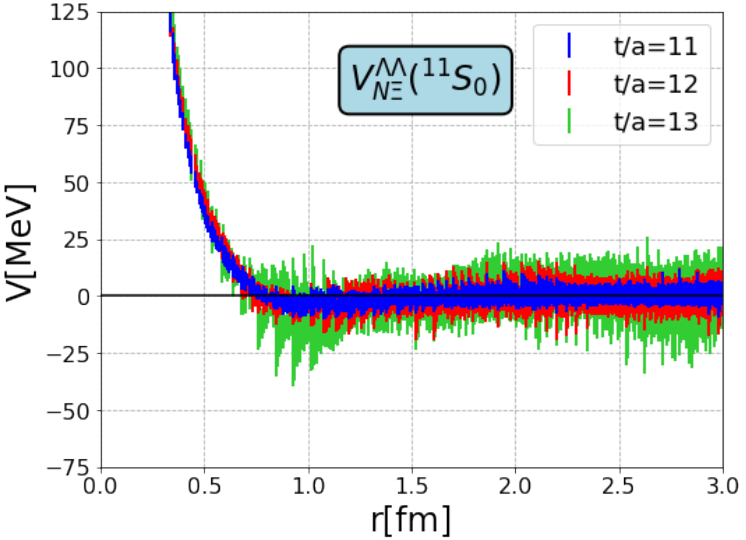
Deuteron
(J=1)

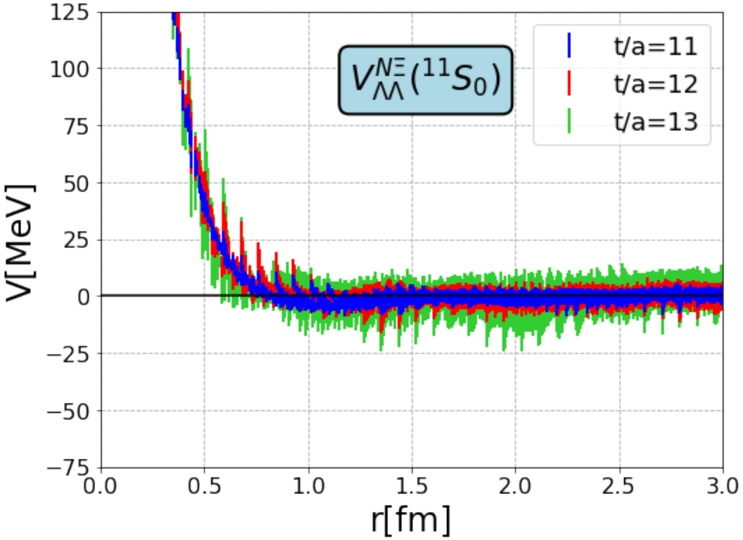
There may also exist S= -2 hypernuclei
relevant to these strong attractions

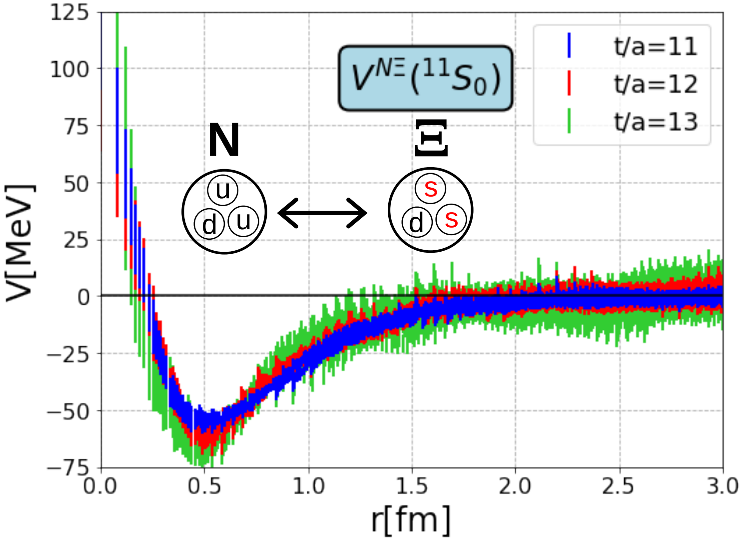
➔Detailed study w/ SU(3) breaking effects
(particle-base)

ΛΛ, NΞ (effective) 2x2 coupled channel analysis





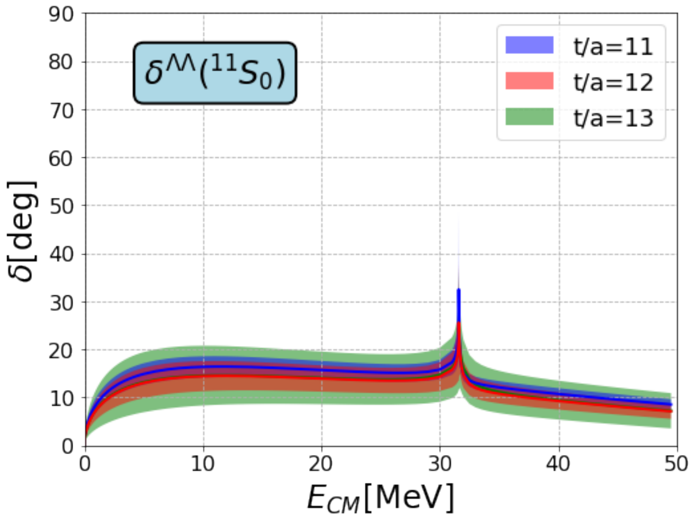




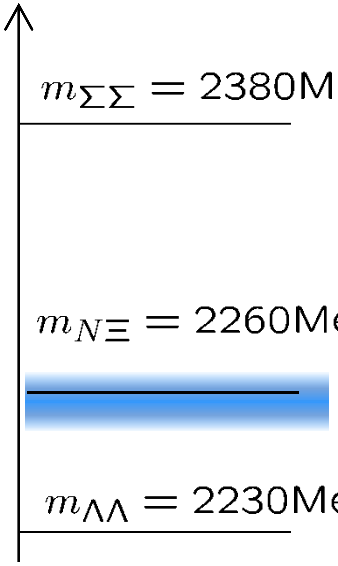
NΞ ($^{11}S_0$) channel is attractive
NΞ–ΛΛ coupling is small

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

ΛΛ, NΞ (effective) 2x2 coupled channel analysis



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



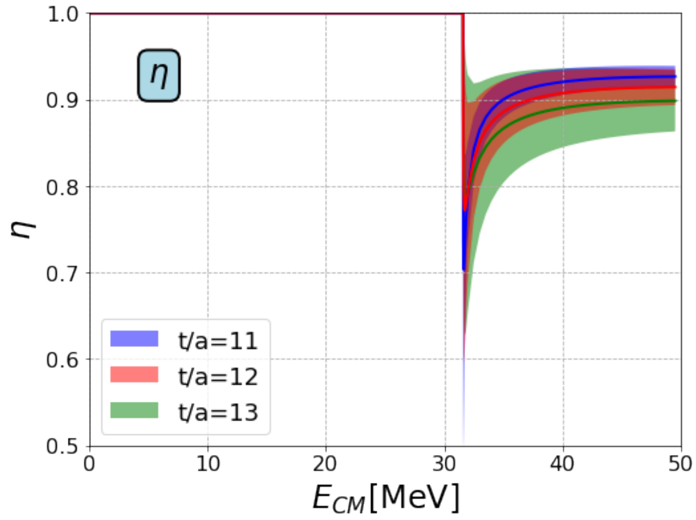
$m_{\Sigma\Sigma} = 2380\text{MeV}$

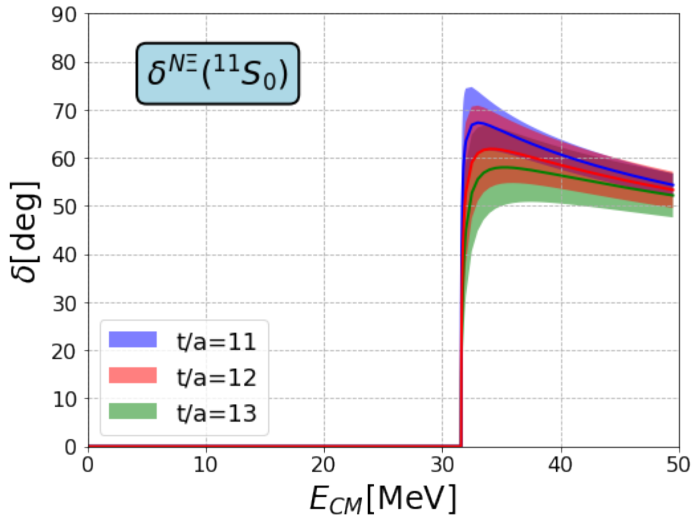
$m_{N\Xi} = 2260\text{MeV}$

$m_{\Lambda\Lambda} = 2230\text{MeV}$

NΞ ~ unitary limit
remnant of "H-dibaryon"

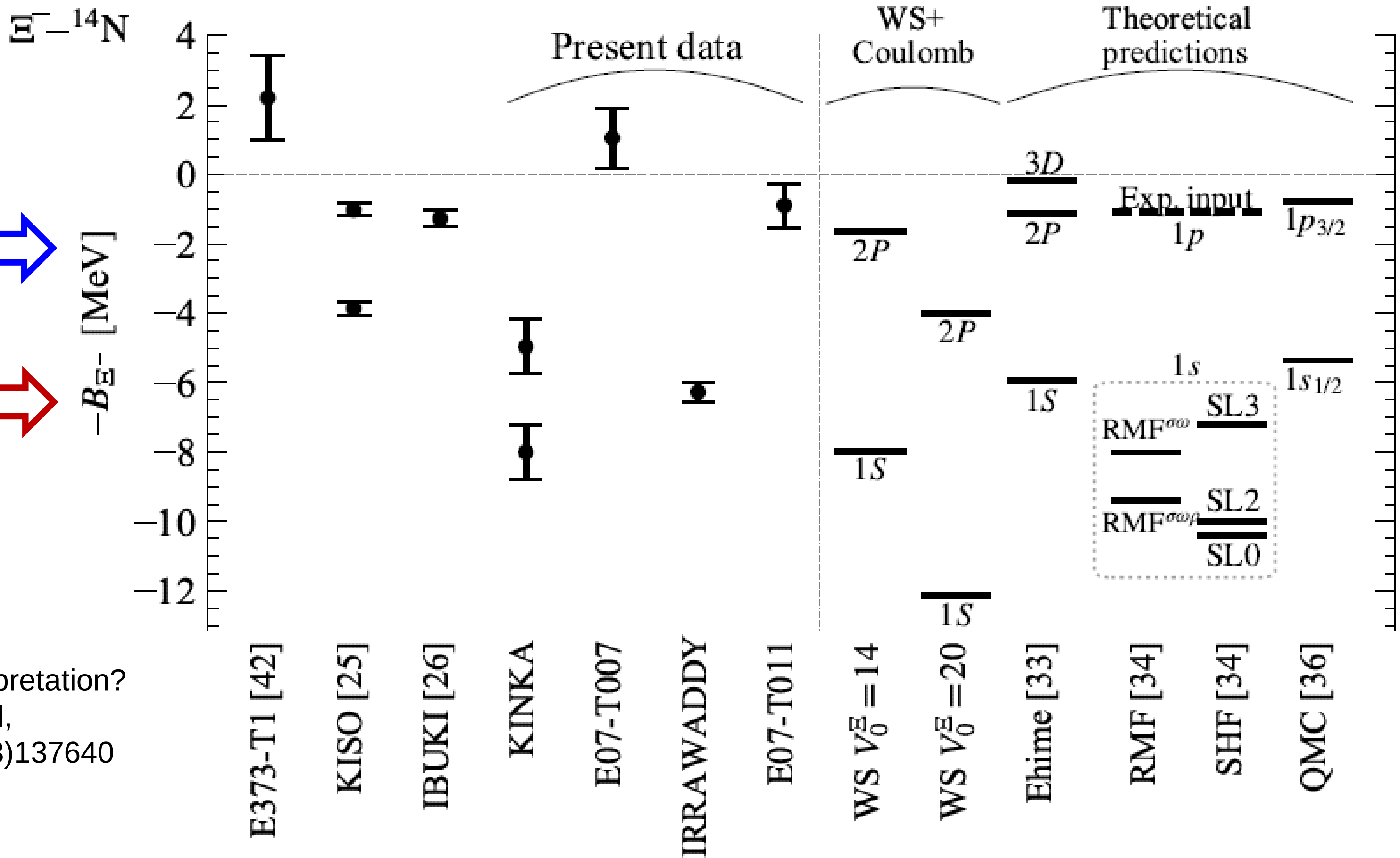
J-PARC E42 (Ahn)





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

Recent experimental progress on Ξ–Hypernuclei



Excited state?

Ground state?

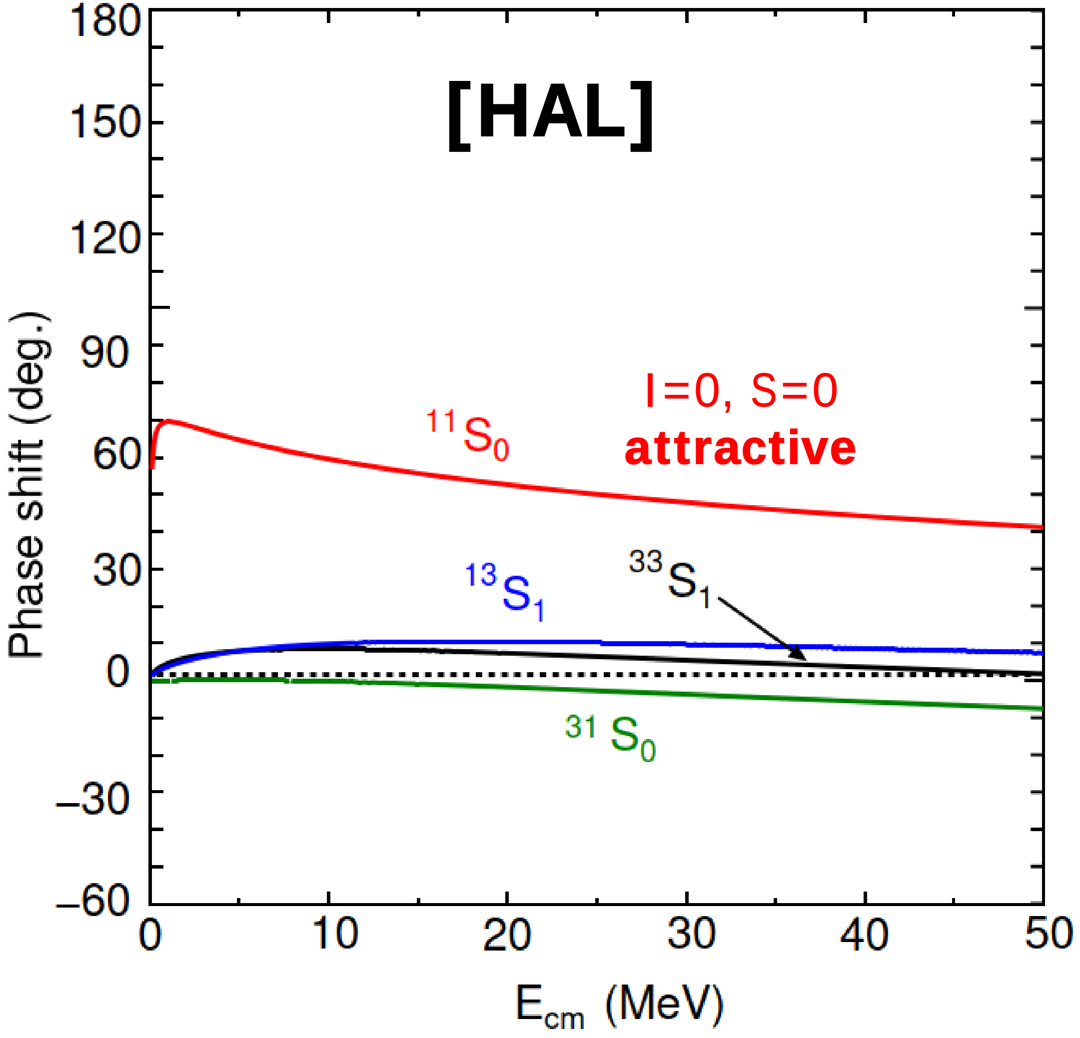
Another interpretation?
Friedman-Gal,
PLB837(2023)137640

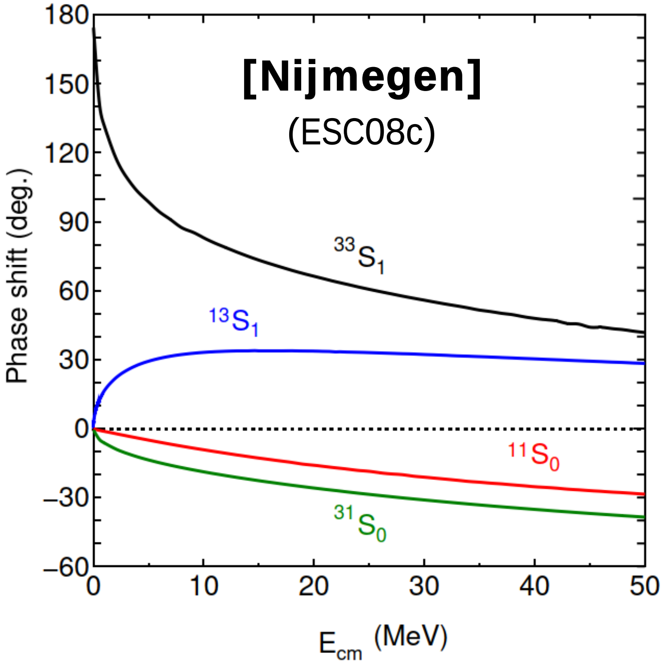
M. Yoshimoto et al.,
PTEP2021, 073D02

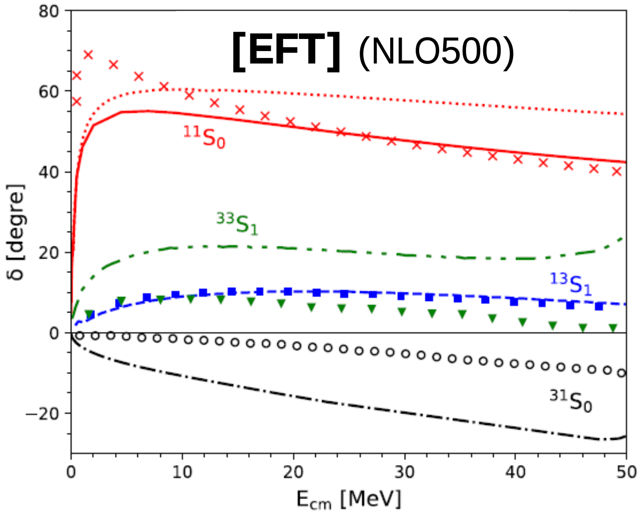
J-PARC E07, E70,
more in HEF-EX

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

NΞ scattering phase shifts and spin-isospin dep







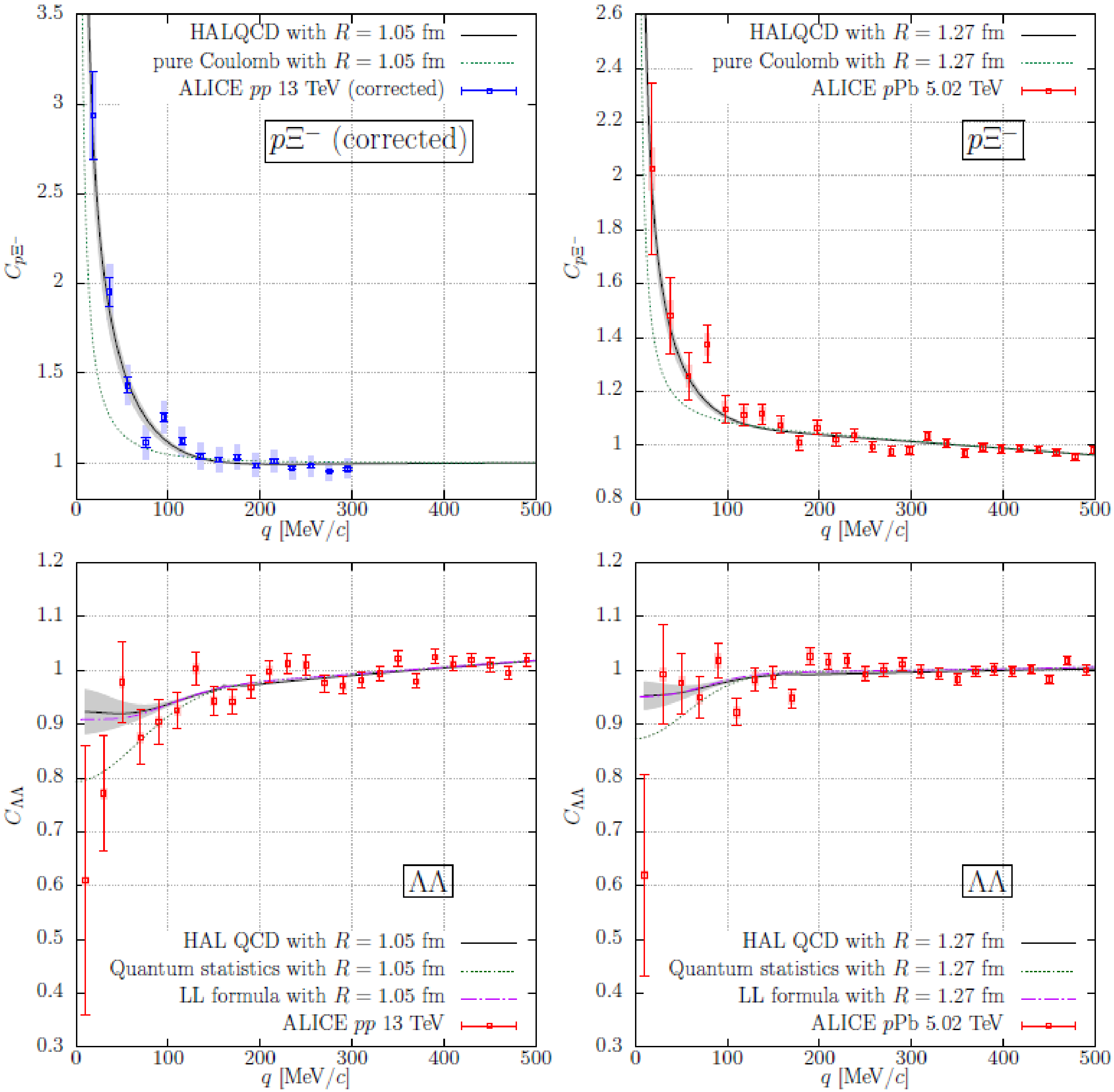
EFT (lines), HAL (points)

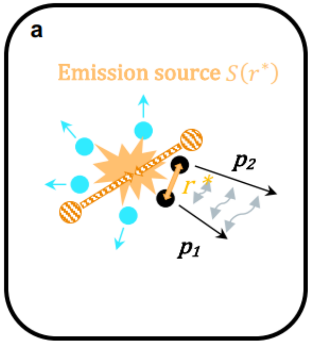
K. Sasaki et al., (HAL Coll.), NPA998(2020)12137

E. Hiyama et al., PRL124(2020)092501

H. Le et al., EPJA57(2021)12

Femtoscopy from nucleus collisions





(Fig from ALICE)

⇦ **$p\Xi^-$**

LQCD prediction confirmed by experiment!

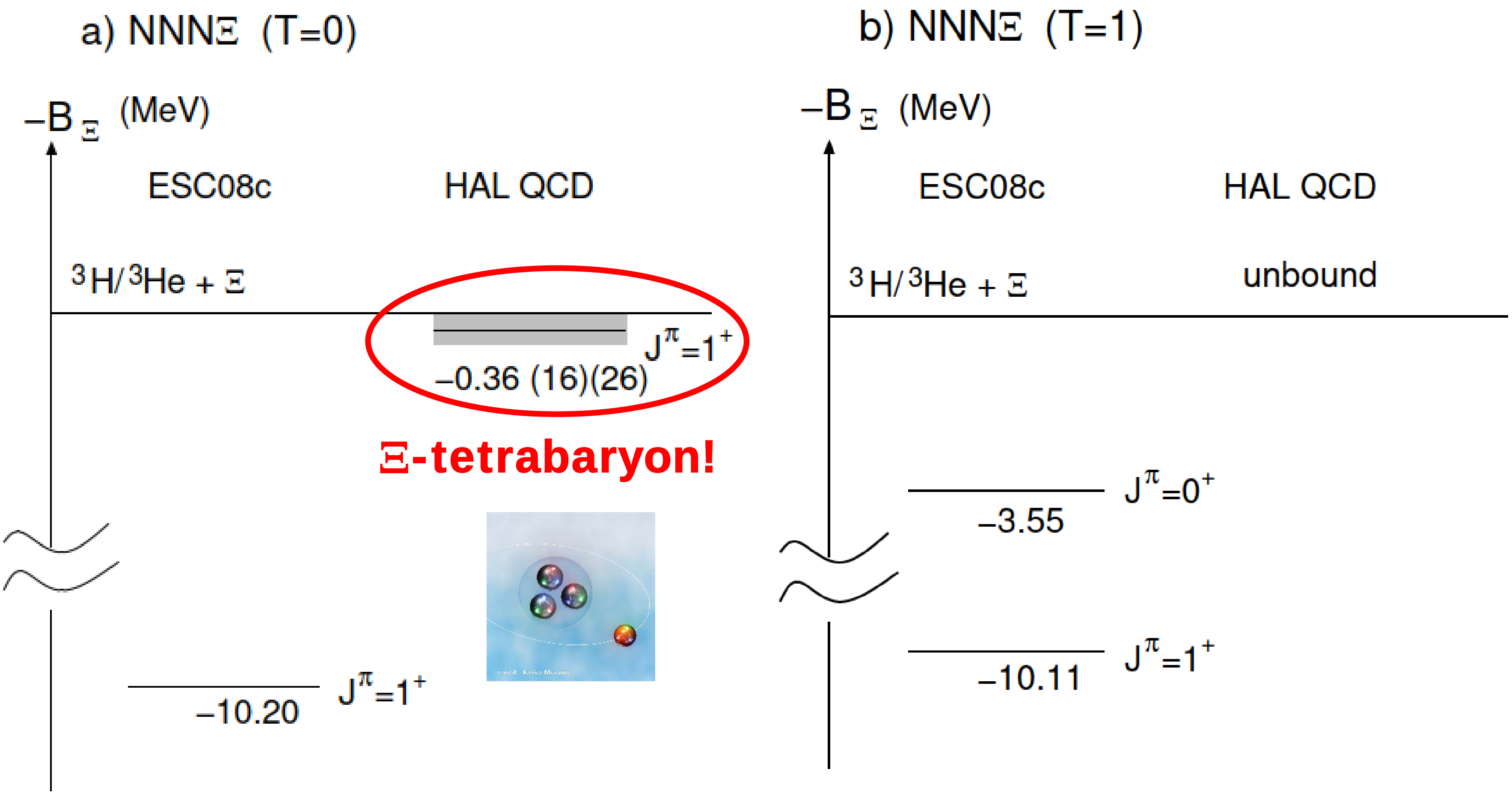
⇦ **$\Lambda\Lambda$**

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

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

S= -2 Light Hypernuclei from LQCD

E. Hiyama et al., PRL124(2020)092501



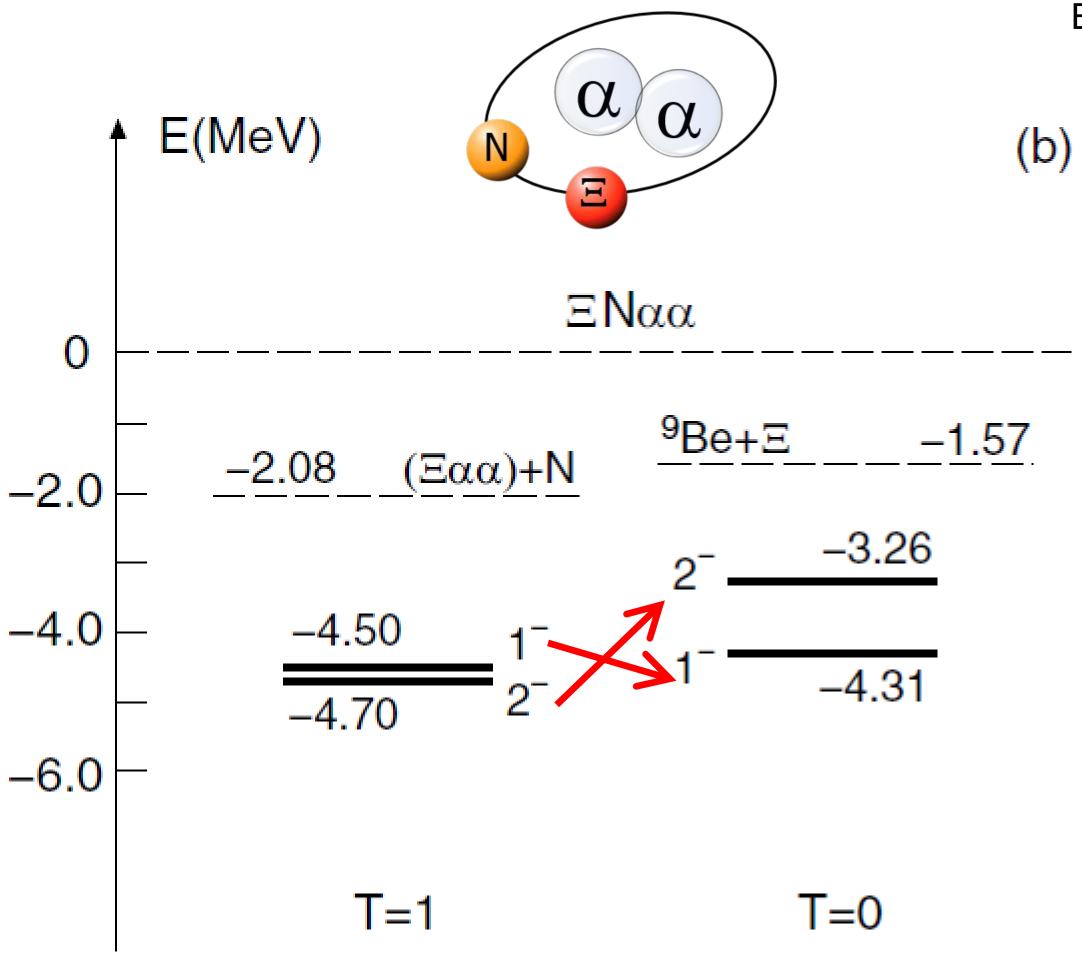
Ξ-tetrabaryon!

LQCD pot after
chiral extrapolation used
(via physical values of $m\pi$, m_K)

c.f. EFT → bound states
(B.E. = 0.6-0.7 MeV)
in T=1, $J^\pi = 1^+, 0^+$
due to stronger $^{33}S_1$

S= -2 (ΞNαα) Hypernuclei from LQCD

E. Hiyama et al., PRC106(2022)064318



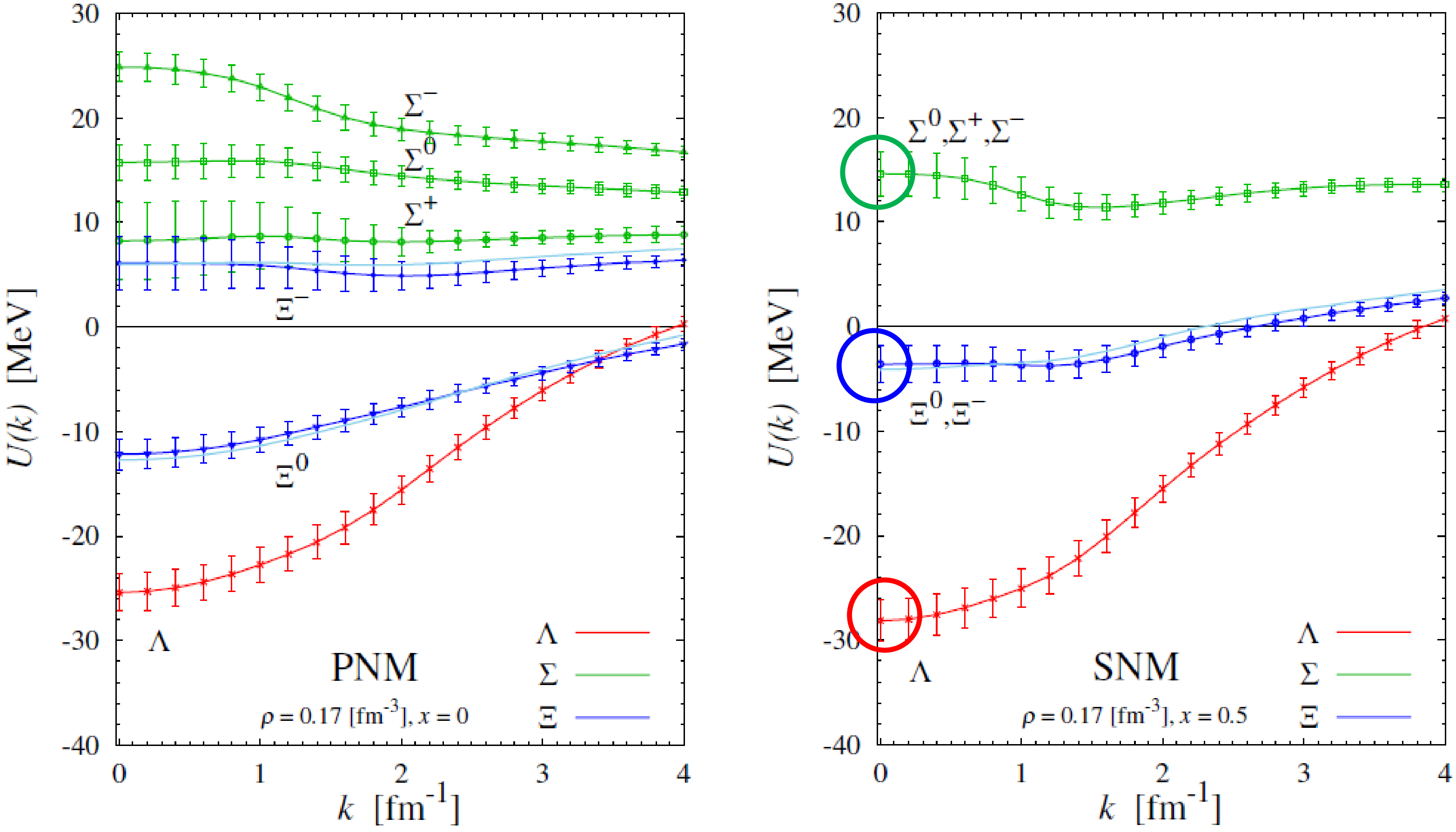
A=10 (ΞNαα) is
found to be bound

Inversion of spin-doublet
between T=1, 0
due to spin-isospin dep of
ΞN potential

A=6 (ΞNα) is
unlikely to be bound

Can be studied by
(K^-, K^+), (K^-, K^0) reaction on ^{10}B

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



- Results are compatible with experimental suggestion.

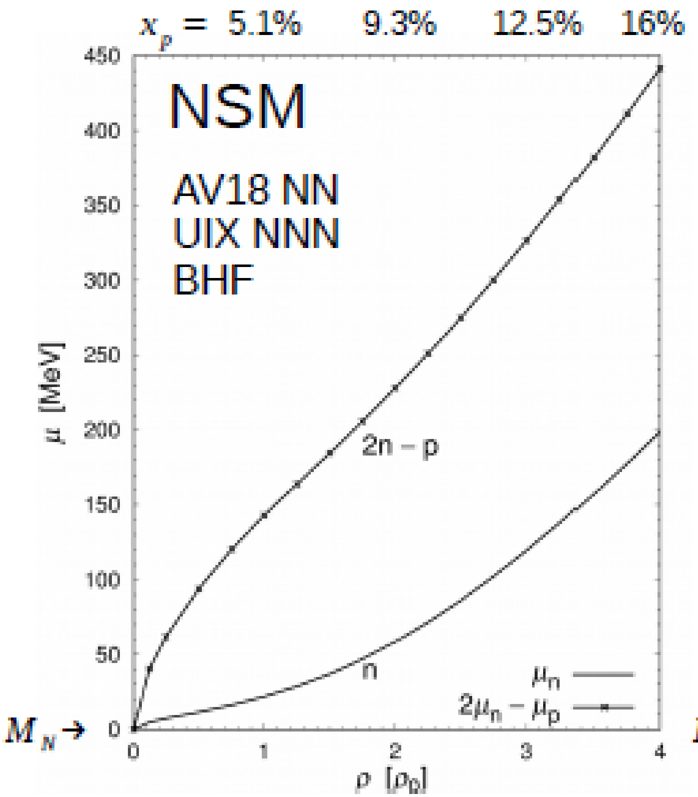
$U_\Lambda^{\rm Exp}(0) \simeq -30$, $U_\Xi(0)^{\rm Exp} \simeq -10$?, $U_\Sigma^{\rm Exp}(0) \geq +20$? [MeV]

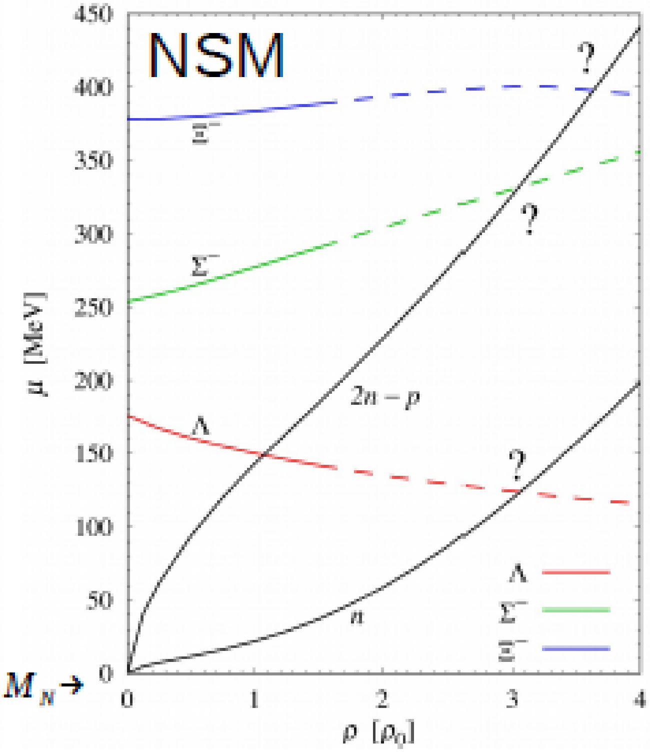
attraction　　attraction small　　repulsion

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

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

Hyperon onset in NSM (just for fun)



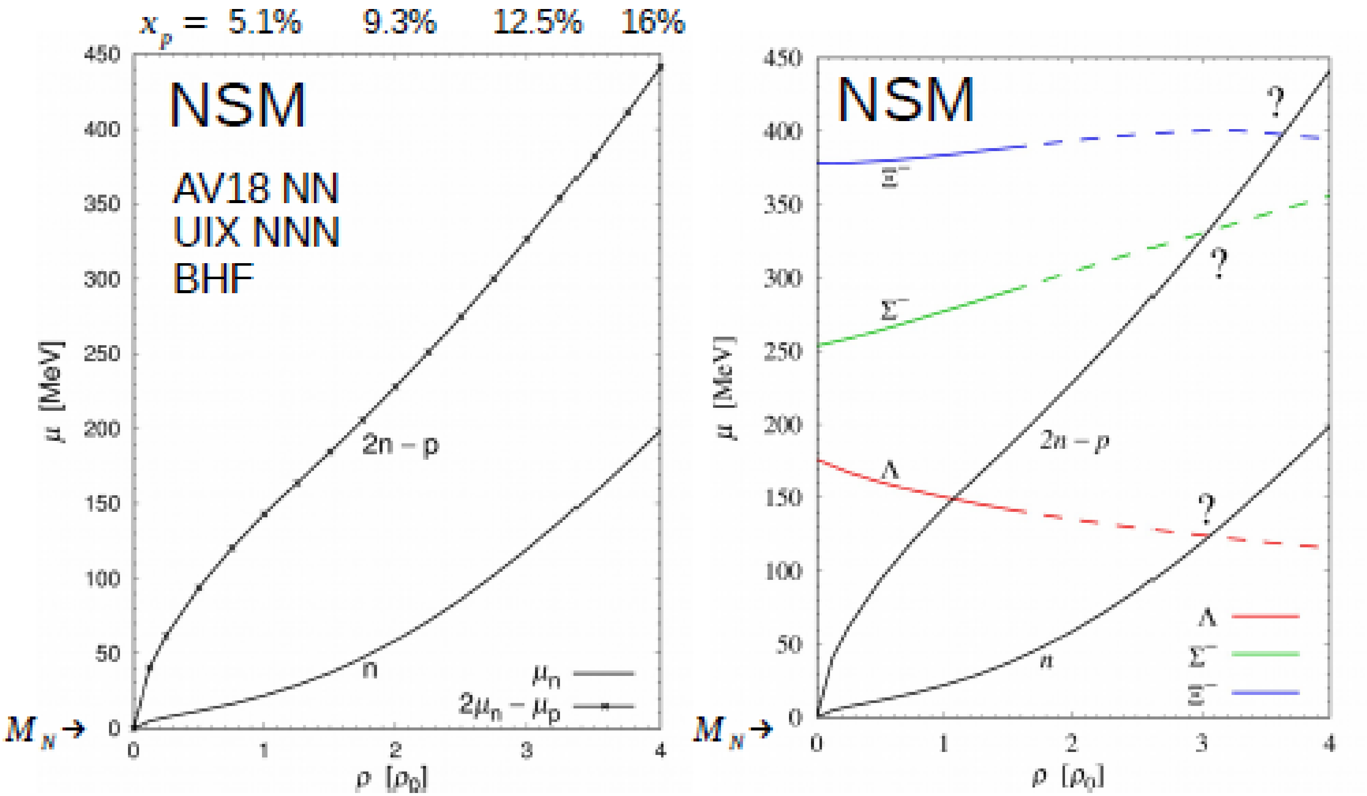


- Result indicate Λ, Σ^-, Ξ^- appear around $\rho = 3.0 - 4.0\ \rho_0$
- However,
  - $YN^{L=1,2...}$ and YNN force could be important at high density.
  - We may need to compare with more sophisticated μ_n, μ_p than BHF.

54

[T. Inoue]

Hyperon onset in NSM (just for fun)



S-wave *YN* only

Preliminary

- Result indicate Λ, Σ^-, Ξ^- appear around $\rho = 3.0 - 4.0\ \rho_0$
- However,
  - $YN^{L=1,2\ldots}$ and YNN force could be imp
  - We may need to compare with more s HF.

[Challenges]
Precision for |S|<=1
3-baryon forces
P-wave/LS forces

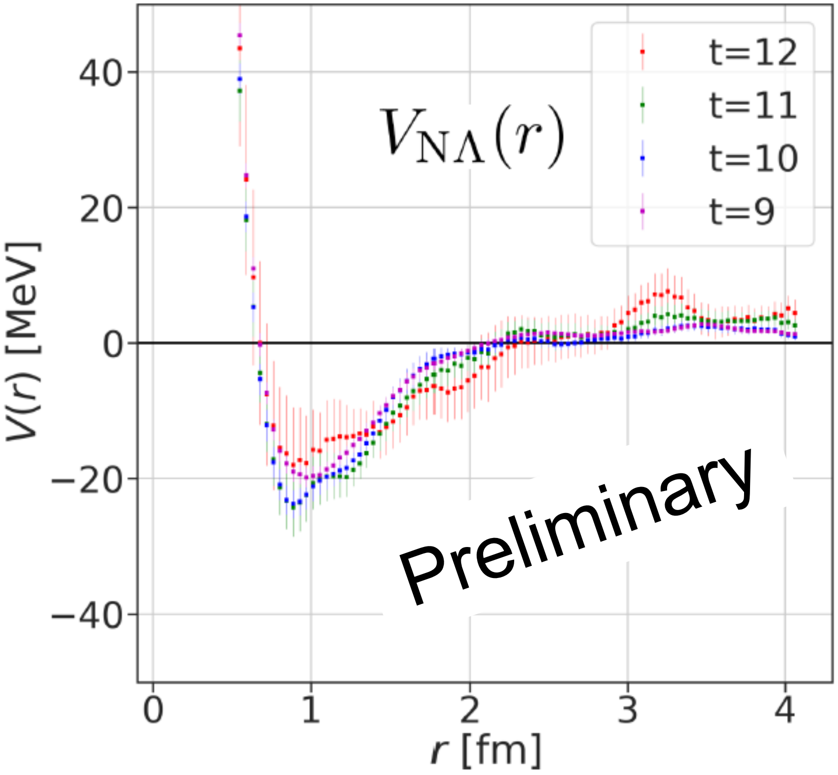
[T. Inoue]

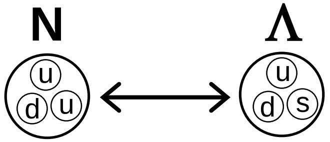
NΛ potentials @ physical point

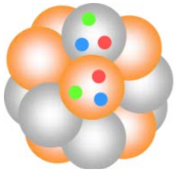
$$\begin{aligned} m_\pi &\neq 146\ \mathrm{MeV} \\ &= 137\mathrm{MeV} \end{aligned}$$

Effective central force in $^1S_0$ channel

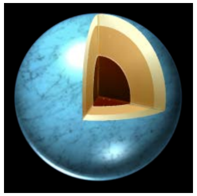
[T. M. Doi]







Properties of Λ hyper-nuclei



Structure of neutron stars

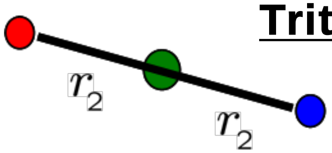
Challenge: Large statistical noises &
contaminations from unwanted (inelastic) states

Possibly Deep Learning is useful to overcome this issue?

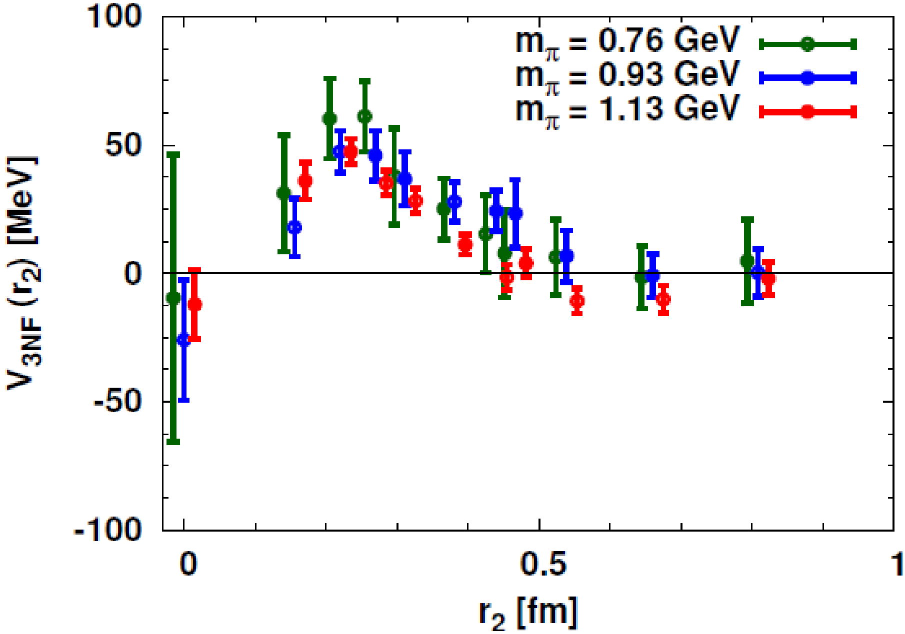
→ related talk by L. Wang (Oct 30)

3N-forces (3NF)

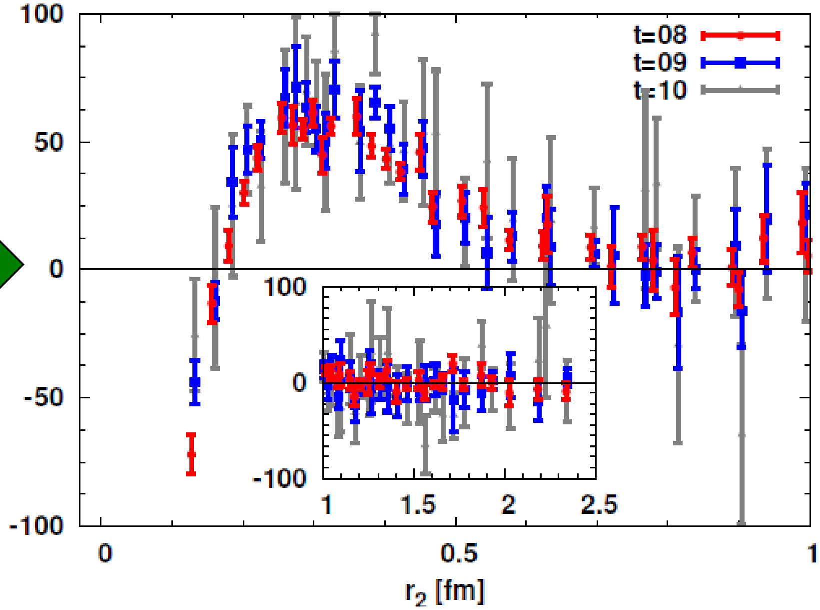
Triton channel



Nf=2, mπ=0.76-1.1 GeV



Nf=2+1, mπ=0.51 GeV

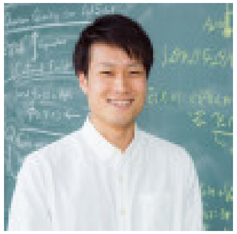


Magnitude of 3NF is similar for all masses
Range of 3NF tend to be enlarged for m(pi)=0.5GeV

Next challenge: **Calc of P-wave 2BF** : better subtraction of 2BF in 3-body systems
YNN (w/o or w/ P-wave 2BF) for structure of neutron stars

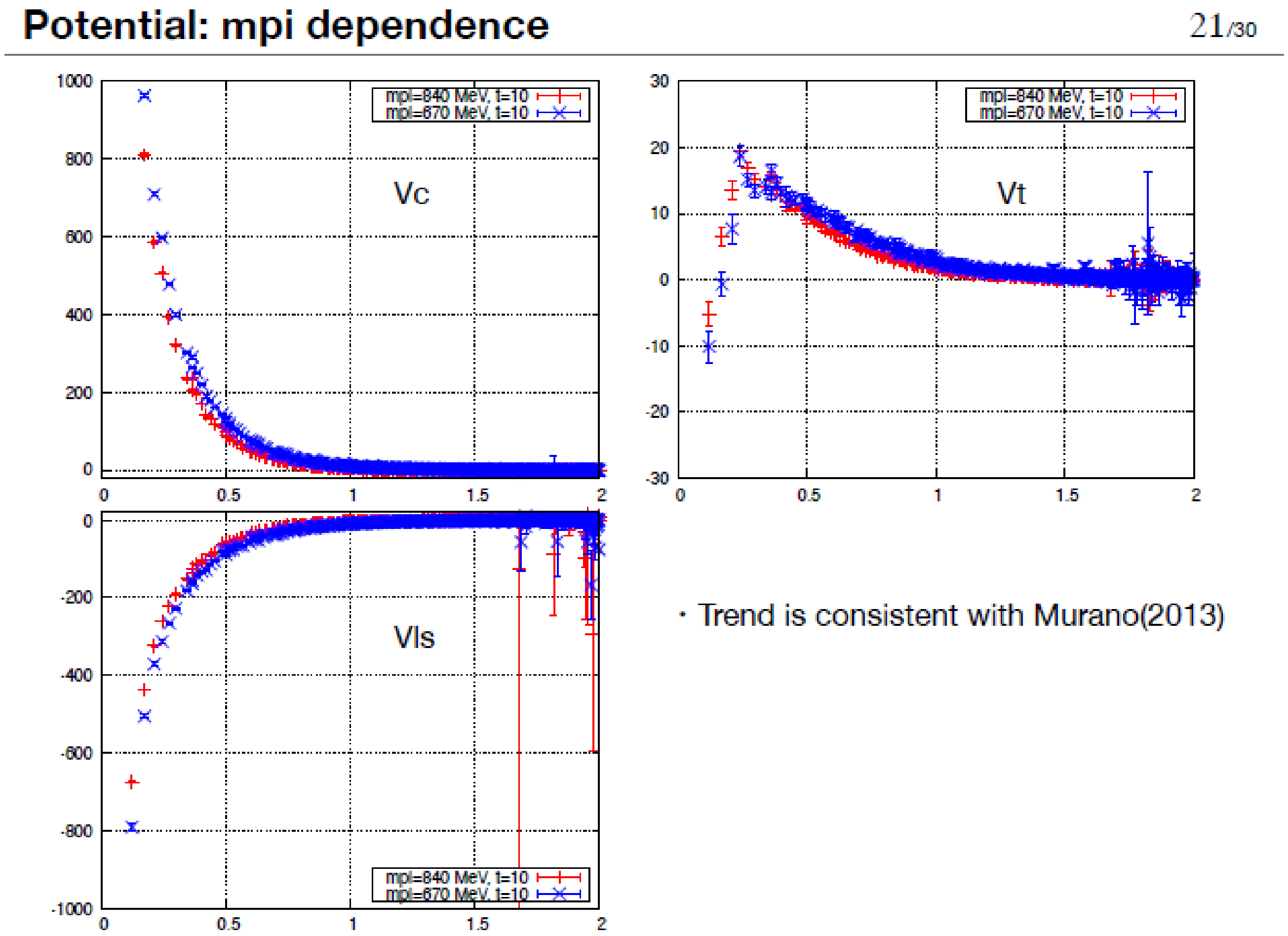
Aoki-Doi Front.Phys.8 (2020) 307

Interactions in P-wave channel



T. Sugiura

- NN interaction in P-wave @ SU(3), m(PS)=670, 840 MeV
- fLapH method for efficient calc

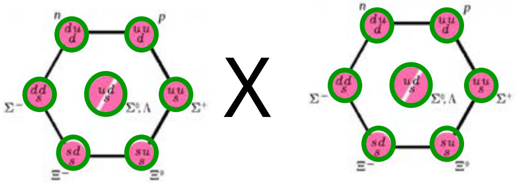


Potential: mpi dependence

21/30

- Trend is consistent with Murano(2013)

Candidates of di-baryons

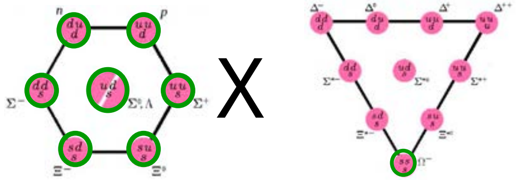


$$8 \times 8 = \boxed{27} + 8s + \boxed{1} + \boxed{10^*} + 10 + 8s$$

dineutron, ΞΞ etc.
(J=0)

H-dibaryon
(J=0)

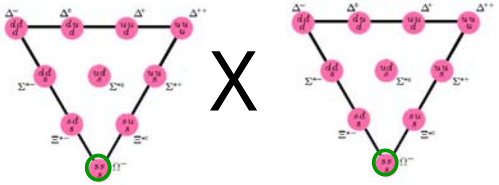
Deuteron
(J=1)



$$8 \times 10 = 35 + \boxed{8} + 10 + 27$$

NΩ (J=2)

Goldman et al. (‘87)
Oka (‘88)



$$10 \times 10 = \boxed{28} + 27 + \boxed{10^*} + 35$$

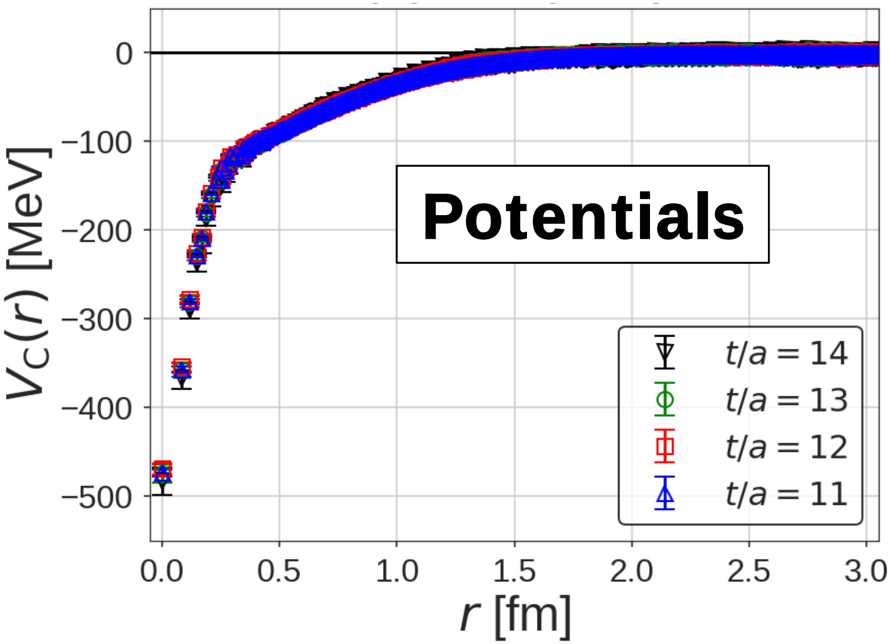
ΩΩ (J=0)

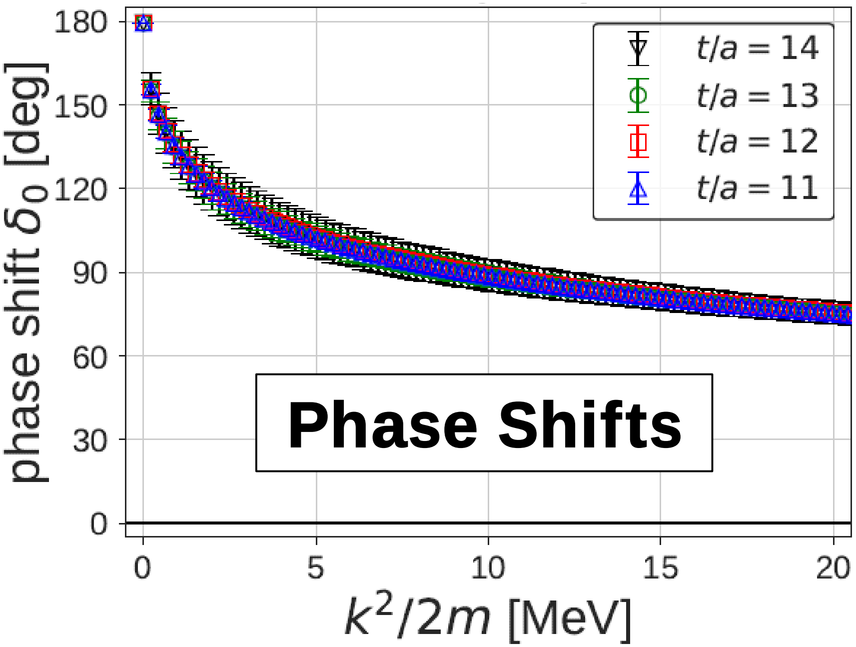
ΔΔ (J=3)

Zhang et al. (‘97)

Dyson-Xuong (‘64)
Kamae-Fujita (‘77)
Oka-Yazaki (‘80)

NΩ system ($^5S_2$)

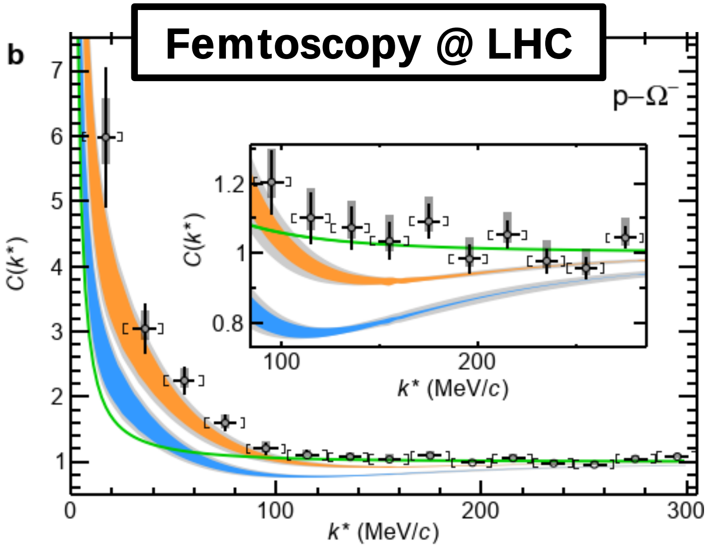




(Quasi) Bound state

[~ Unitary limit]

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

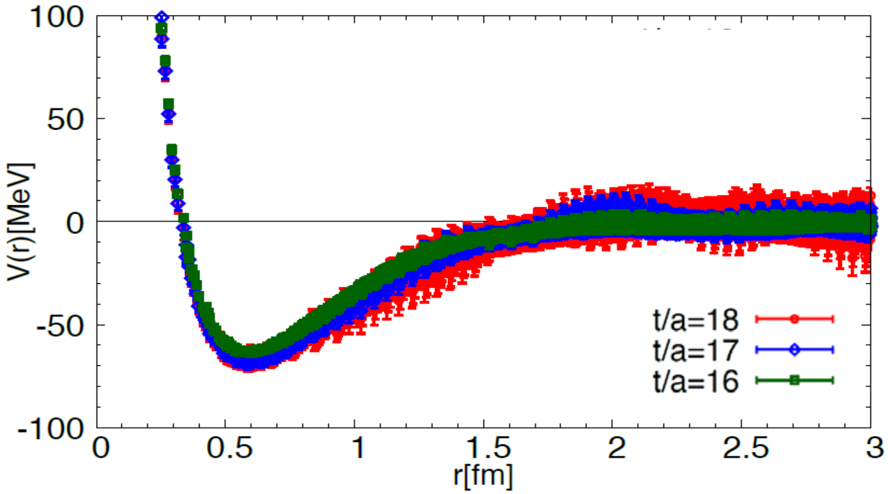


T. Iritani et al. (HAL Coll.), PLB792(2019)284

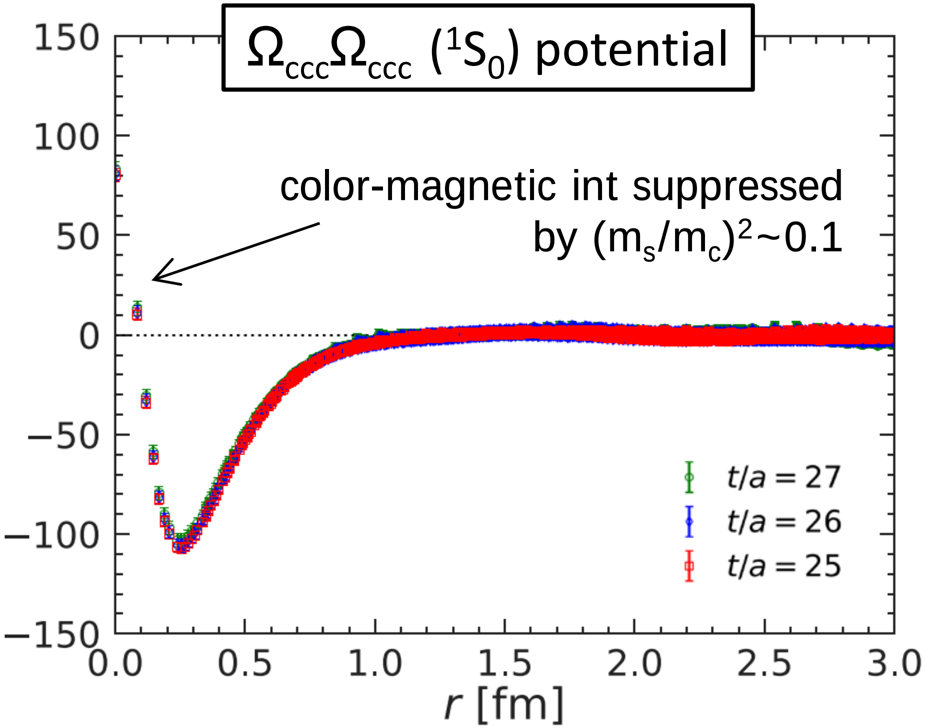
ALICE Coll., Nature 588 (2020) 232

Most Strange/charming Dibaryons : ΩΩ, $\Omega_{ccc}\Omega_{ccc}$

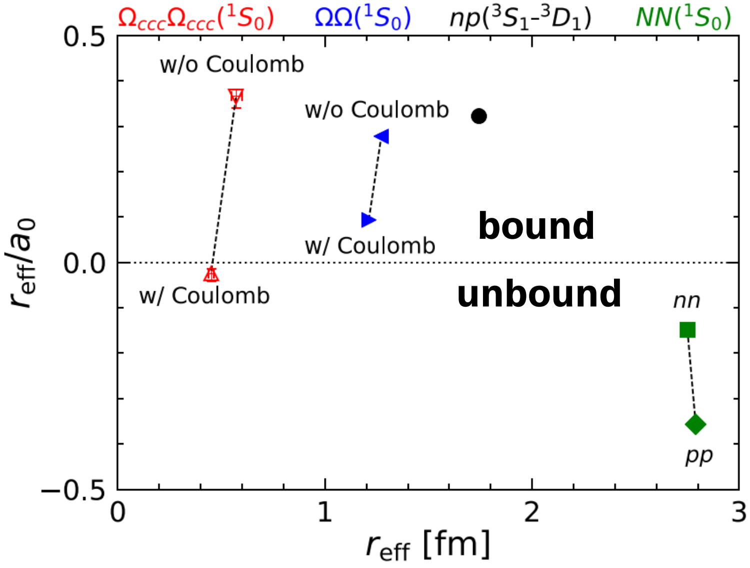
ΩΩ ($^1S_0$) potential



$\Omega_{ccc}\Omega_{ccc}$ ($^1S_0$) potential



color-magnetic int suppressed by $(m_s/m_c)^2$~0.1



di-Omegas near unitarity

ΩΩ could be searched in LHC RUN3

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

Y. Lyu, H. Tong et al., PRL127(2021)072003

Meson-Meson and Meson-Baryon Interactions

Related talks by

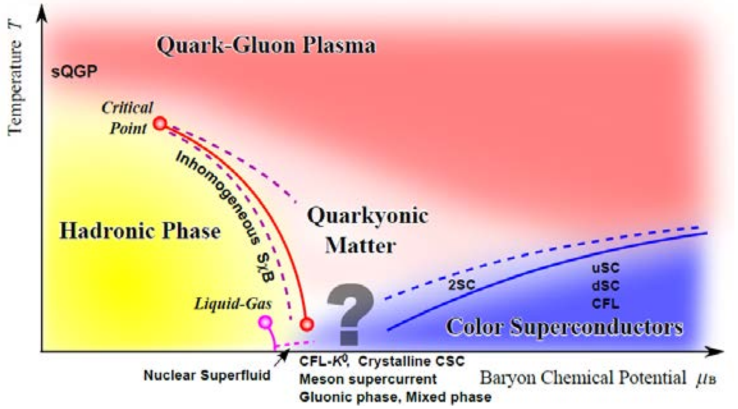
Y. Lyu (Oct 18) : D-Dbar* for T_{cc}
K. Murakami (Oct 28) : Kbar-N for $\Lambda(1405)$
W. A. Yamada (Oct 29) : Dbar-N for Penta(?)

Nϕ system

Medium effects on hadron properties

←→ partial restoration
of chiral symmetry

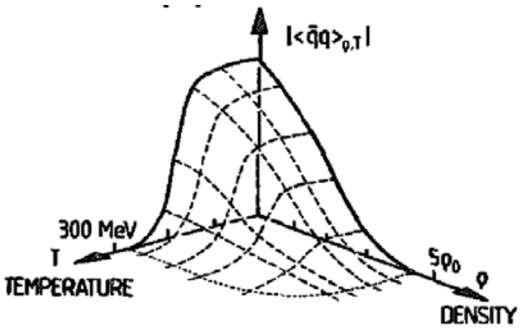
Hayano-Hatsuda, ReV. Mod. Phys. 82 (2010) 2949



Fukushima-Hatsuda, RPP74(2011)014001

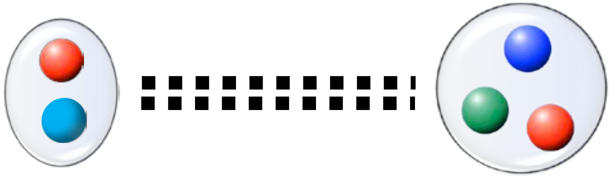
ϕ-meson is one of the ideal probes

Brown-Rho, RRL66(1991)2720
Hatsuda-Lee, PRC46(1992)R34
Gubler-Weise, NPA954(2016)125)



Weise, NPA553(1993)59

How color-dipole interacts w/ other hadrons?

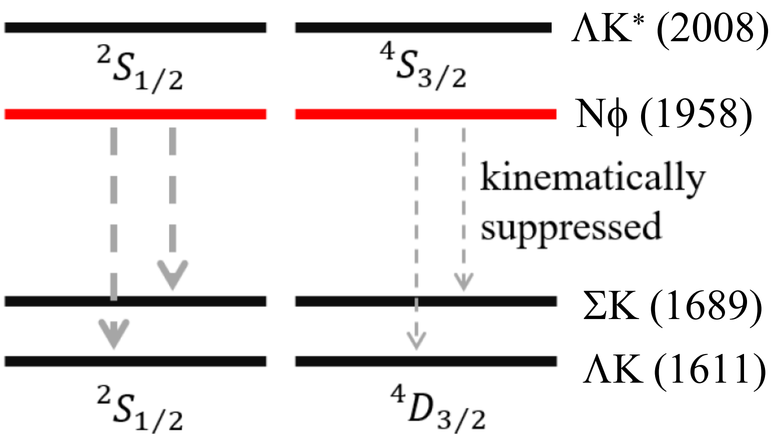


2-pion-exchange?

Dipole-Dipole int: H. Fujii and D. Kharzeev, PRD60(1999)114039
Dipole-Nucleon int: J. Castella and G. Krein, PRD98(2018)014029

$N\phi$ system

[PDG]



$N\phi$ interaction from LQCD

ΛK, ΣK thresholds are open

Coupled channel calc expensive

J=3/2 : ΛK, ΣK suppressed by D-wave

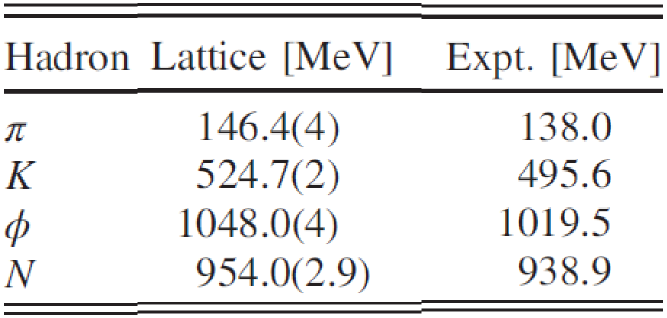
J=1/2 : ΛK, ΣK S-wave mixing, no suppression

(3-body decay modes,
ϕ–decay modes neglected)

(ωN, ρN also neglected by OZI)

→ **We calculate $N\phi$ (J=3/2) w/ single-channel approximation**

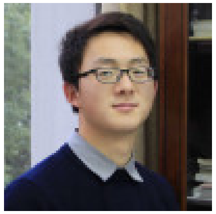
Y. Lyu et al., PRD106(2022)074507



Hadron	Lattice [MeV]	Expt. [MeV]
π	146.4(4)	138.0
K	524.7(2)	495.6
ϕ	1048.0(4)	1019.5
N	954.0(2.9)	938.9

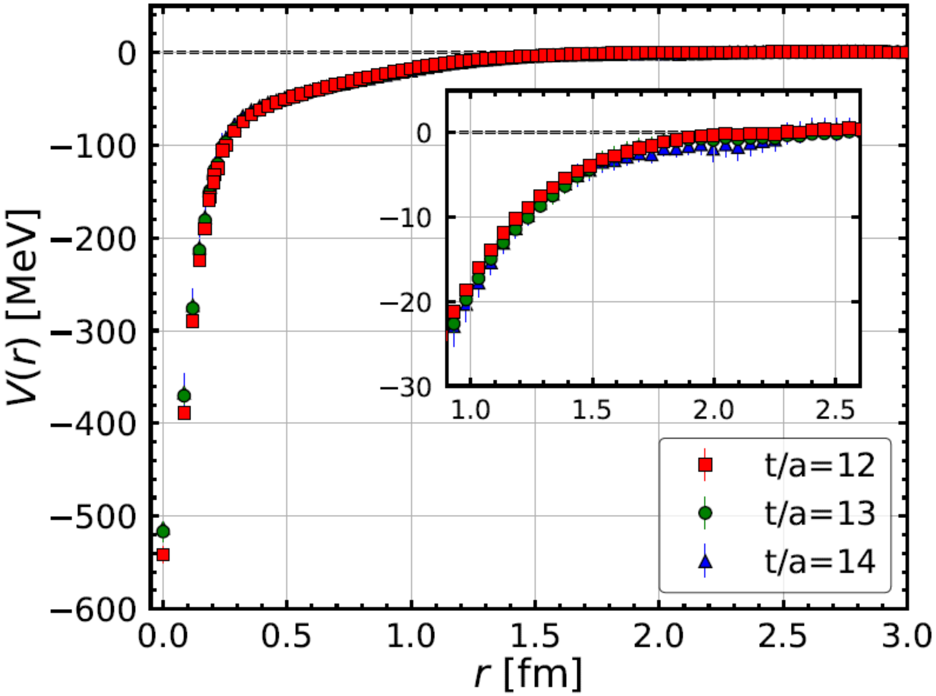
s-sbar annihilation neglected
ϕ → K-Kbar forbidden at this mass
ϕ→ 3π found to be negligible

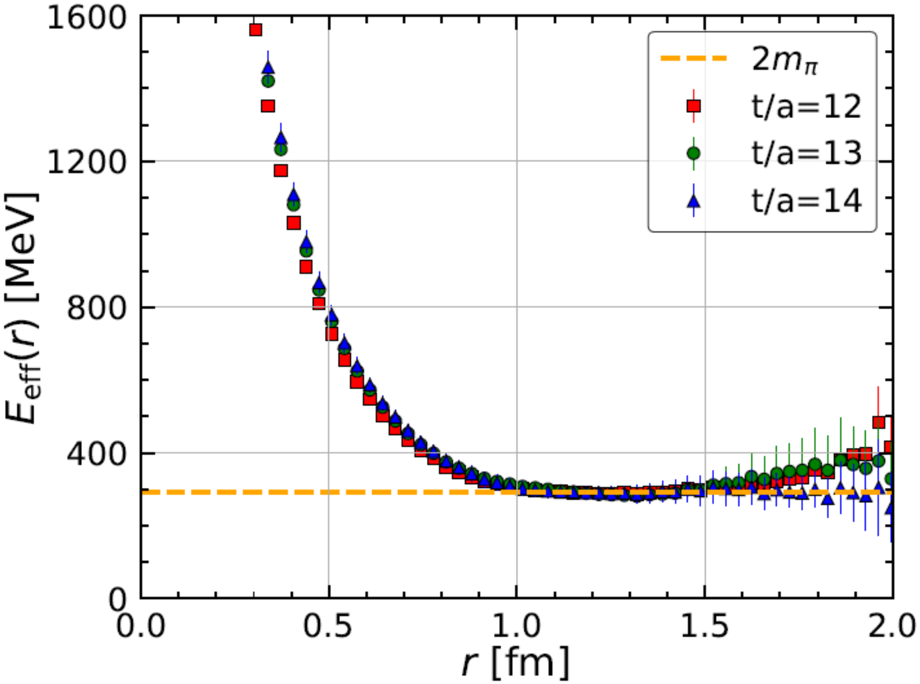
Nϕ system ($^4S_{3/2}$)



Y. Lyu

Potential ⇒ Tail structure of potential





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

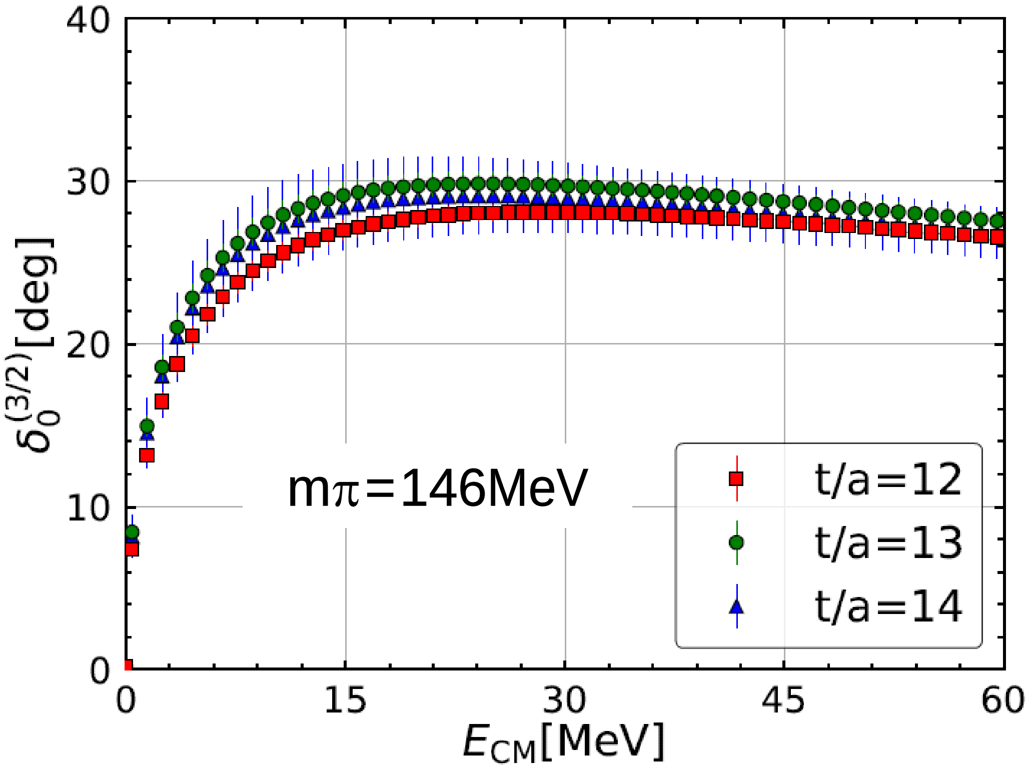
Potential is attractive at all distances

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

Y. Lyu et al., PRD106(2022)074507

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

Phase shifts of Nϕ ($^4S_{3/2}$)



Fit the potential and solve Schrodinger eq. in infinite V

$$V_{\rm fit}(r) = \sum_{i=1,2} a_i e^{-(r/b_i)^2} + a_3 m_\pi^4 f(r;b_3) \frac{e^{-2m_\pi r}}{r^2}$$

$\uparrow$

EFT by Castella-Krein

Fit w/ mπ = mπ(LQCD)

Semi-quantitative extrapolation by mπ → mπ(phys)

m_π [MeV]	$a_0^{(3/2)}$ [fm]	$r_{\rm eff}^{(3/2)}$ [fm]
146.4	$-1.43(23)_{\rm stat}\left(^{+36}_{-06}\right)_{\rm syst}$	$2.36(10)_{\rm stat}\left(^{+02}_{-48}\right)_{\rm syst}$
138.0	$\simeq -1.25$	$\simeq 2.49$

c.f. ALICE Coll. $a_0^{(\rm spin-ave)} = -0.85(34)(14)$ fm $r_{\rm eff}^{(\rm spin-ave)} = 7.85(1.54)(0.26)$ fm

New avenue for Hadron interactions by Combined analysis of LQCD & femtoscopy

Nϕ J=3/2 ← LQCD calc possible (ΛK, ΣK mixings suppressed by D-wave)

Nϕ J=1/2 ← LQCD challenging (ΛK, ΣK mixings are S-wave)

Nϕ spin average ← ALICE femtoscopy possible
(but spin projection difficult)

➔ By combining LQCD and ALICE femtoscopy,
we can extract Nϕ J=1/2

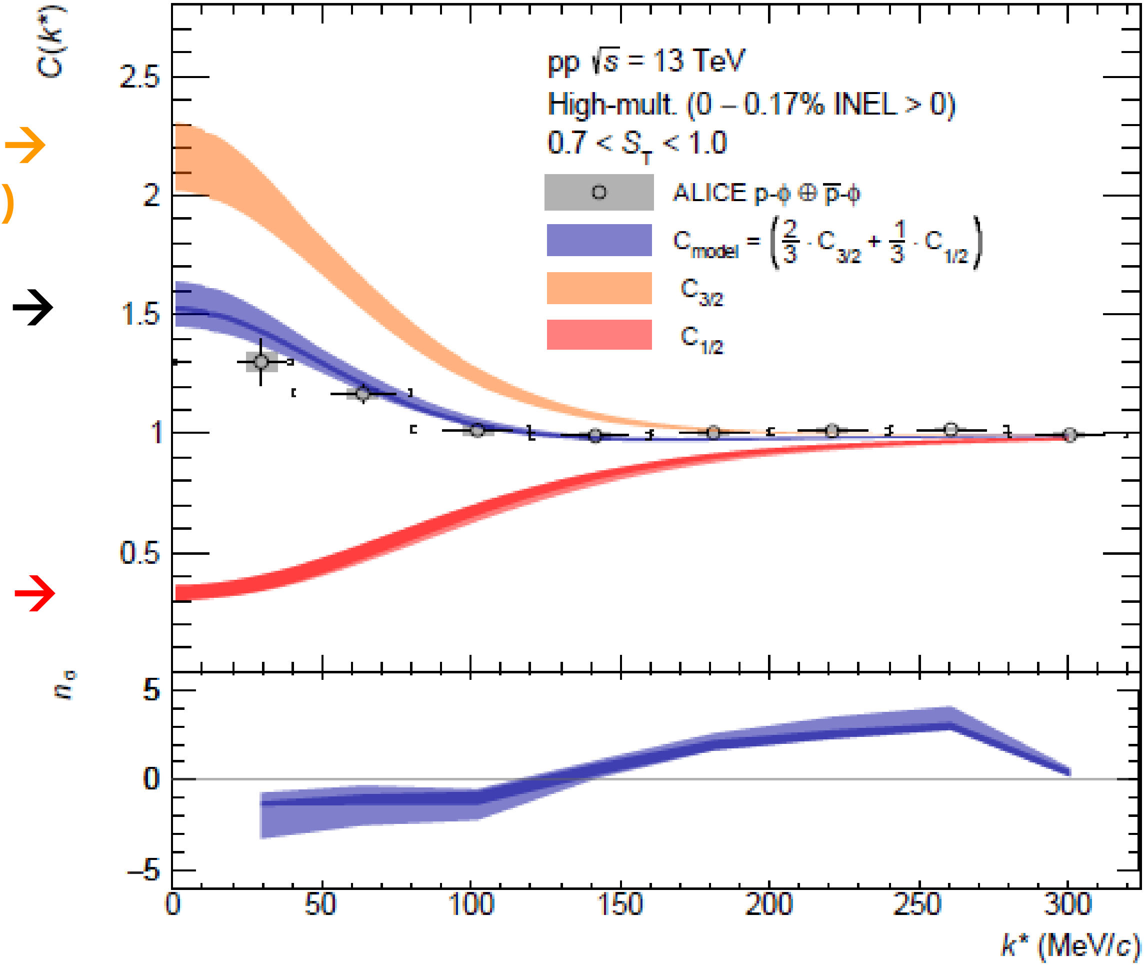
E. Chizzali+, PLB848(2024)138358

Nϕ system ($^2S_{1/2}$) from LQCD + Exp

J=3/2 →
(LQCD)

J=ave →
(Exp)

J=1/2 →
(new!)

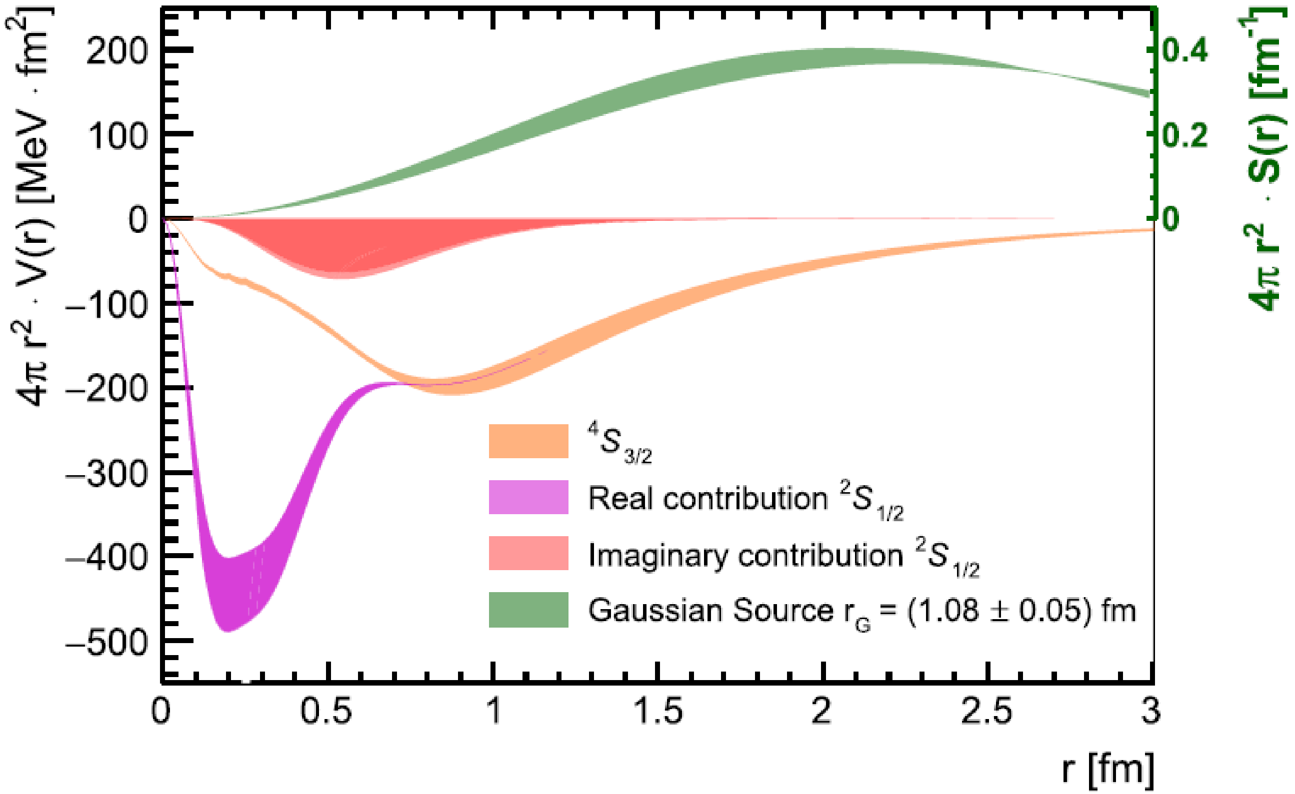


Correlation function measured by ALICE

Fit the femtoscopy data w/ parameters in potential in J=1/2

Nϕ system ($^2S_{1/2}$) from LQCD + Exp

Potential (w/ phase space factor of 4πr²)



Indication of Nϕ bound state in J=1/2

B.E. = 12.8-56.1 MeV

$$\mathrm{Re}\ f_0^{(1/2)} = -1.54^{+0.53}_{-0.53}(\mathrm{stat.})^{+0.16}_{-0.09}(\mathrm{syst.})\ \mathrm{fm},$$

$$\mathrm{Im}\ f_0^{(1/2)} = \ \ 0.00^{+0.35}_{-0.00}(\mathrm{stat.})^{+0.16}_{-0.00}(\mathrm{syst.})\ \mathrm{fm},$$

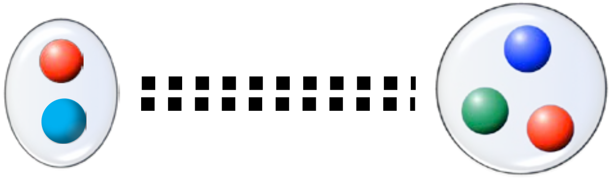
$$\mathrm{Re}\ d_0^{(1/2)} = +0.39^{+0.09}_{-0.09}(\mathrm{stat.})^{+0.02}_{-0.03}(\mathrm{syst.})\ \mathrm{fm},$$

$$\mathrm{Im}\ d_0^{(1/2)} = \ \ 0.00^{+0.00}_{-0.04}(\mathrm{stat.})^{+0.00}_{-0.02}(\mathrm{syst.})\ \mathrm{fm}.$$

Exploring hadron interactions in broader scope w/ charm degrees of freedom

- N-J/ψ, N-η_c (N-$c\bar{c}$) interactions ←→ N-ϕ (N-$s\bar{s}$)

How color-dipole interacts w/ other hadrons?



Dipole-Dipole int: H. Fujii and D. Kharzeev, PRD60(1999)114039
Dipole-Nucleon int: J. Castella and G. Krein, PRD98(2018)014029

- N-Ω_{ccc} interactions ←→ N-ϕ, N-Ω (=N-Ω_{sss})

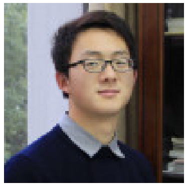
NΩ is quasi bound ← issue of open channels, $\Lambda\Xi$, $\Sigma\Xi$

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

NΩ_{ccc} is ideal system ← NΩ_{ccc} is below $\Lambda_c\Xi_{cc}$, $\Sigma_c\Xi_{cc}$ thresholds

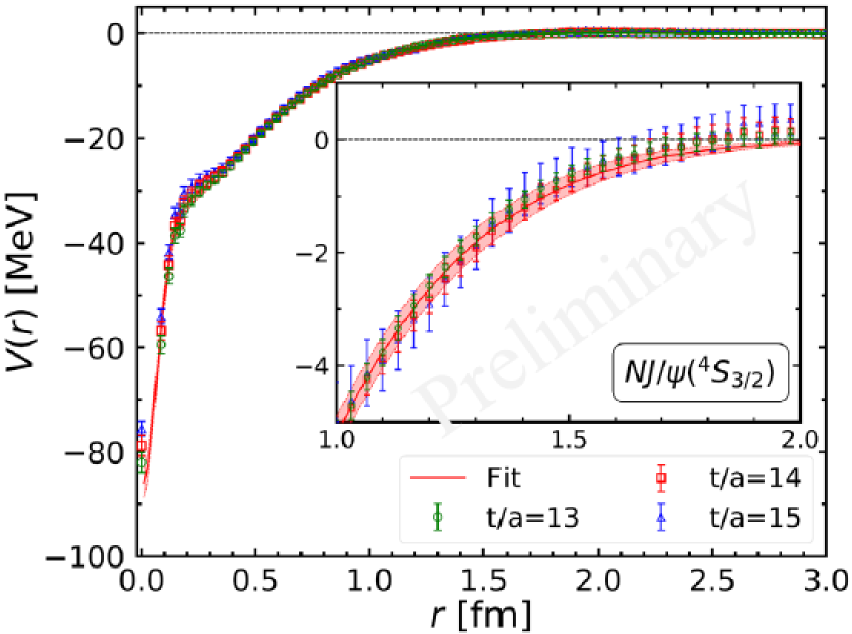
- Ξ_{cc}–Ξ_{cc} interactions ←→ superflavor partner of Tcc

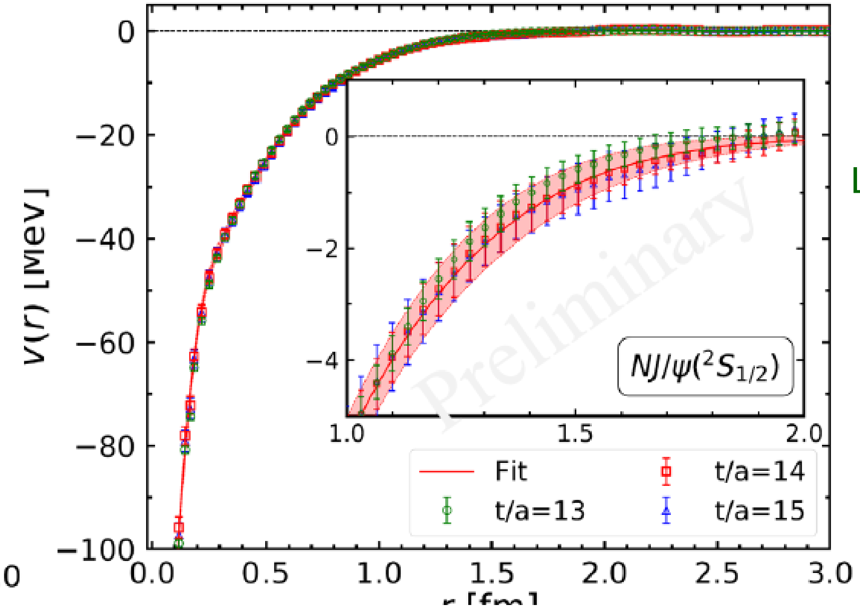
$N-c\bar{c}$ potentials near phys point

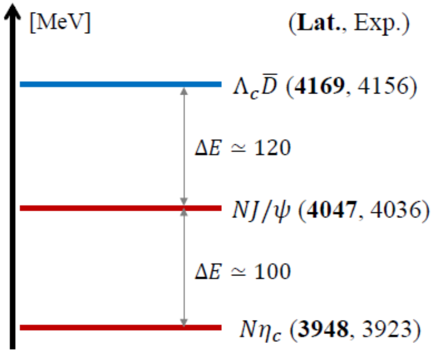


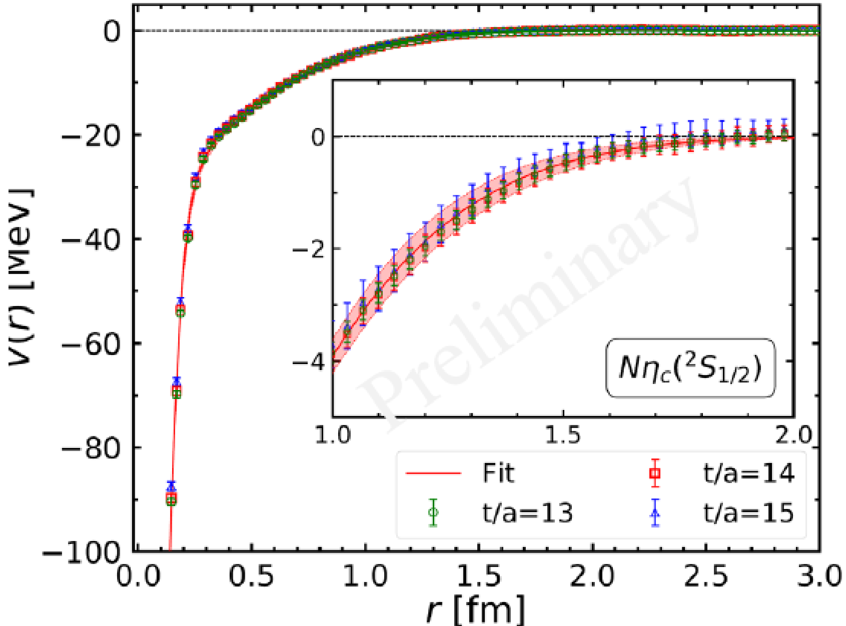
Y. Lyu

Slides from Lattice 2024



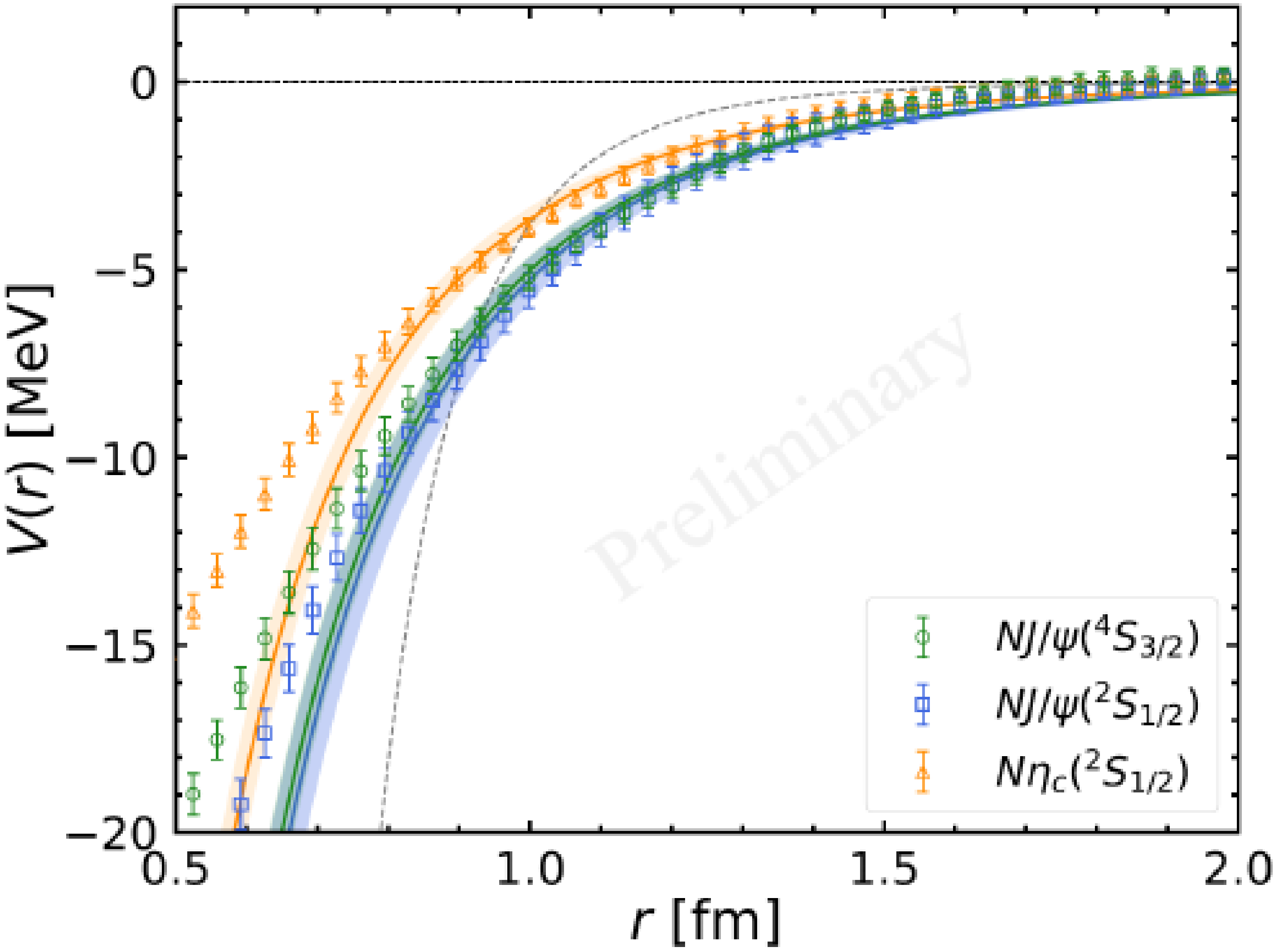






mπ=146MeV (Lat)

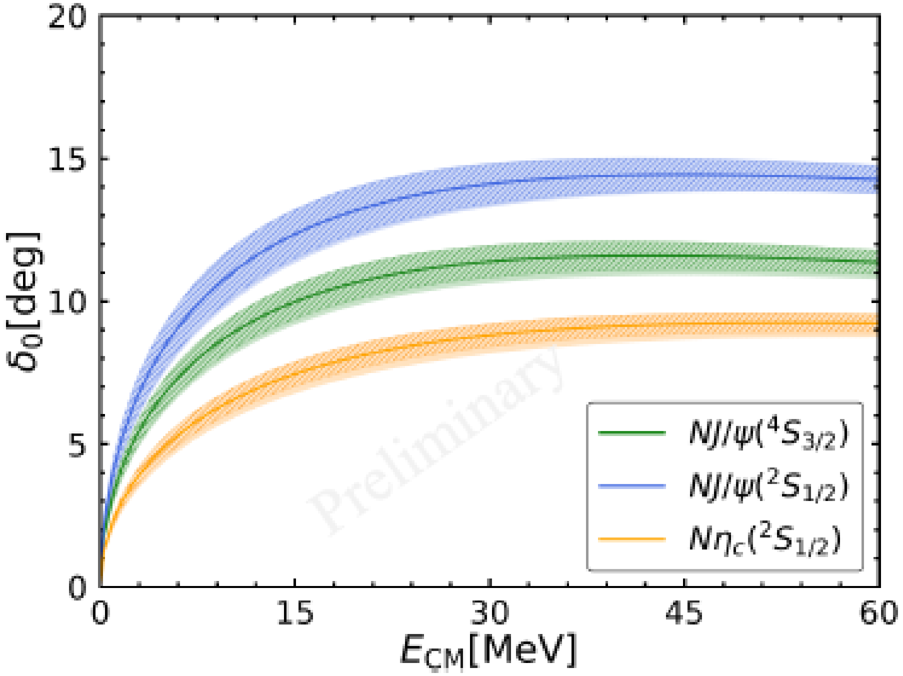
Long-range potentials of $N{-}c\bar{c}$



The long-range potentials are consistent with the two-pion-exchange (TPE)

Physical observables

- Scattering phase shifts



$$\boxed{k\cot\delta_0 = \frac{1}{a_0} + \frac{1}{2}r_{\text{eff}}k^2}$$

channel	a_0 [fm]	r_{eff} [fm]
$NJ/\psi(^4S_{3/2})$	$0.30(2)\left(^{+0}_{-2}\right)$	$3.25(12)\left(^{+6}_{-9}\right)$
$NJ/\psi(^2S_{1/2})$	$0.38(4)\left(^{+0}_{-3}\right)$	$2.66(21)\left(^{+0}_{-10}\right)$
$N\eta_c(^2S_{1/2})$	$0.21(2)\left(^{+0}_{-1}\right)$	$3.65(20)\left(^{+0}_{-6}\right)$

- A direct phenomenological application
  - The J/ψ mass modification in nuclear medium is related to the spin-averaged scattering length of N-J/ψ scattering

A. Hayashigaki, Prog. Theor. Phys. 101 (1999)

$$\boxed{\delta m_{J/\psi} \simeq -\frac{2\pi(m_N + m_{J/\psi})}{m_N m_{J/\psi}} a_{J/\psi}^{\text{spin-av}} \rho_{\text{nm}} = -19(3)\ \text{MeV}}$$

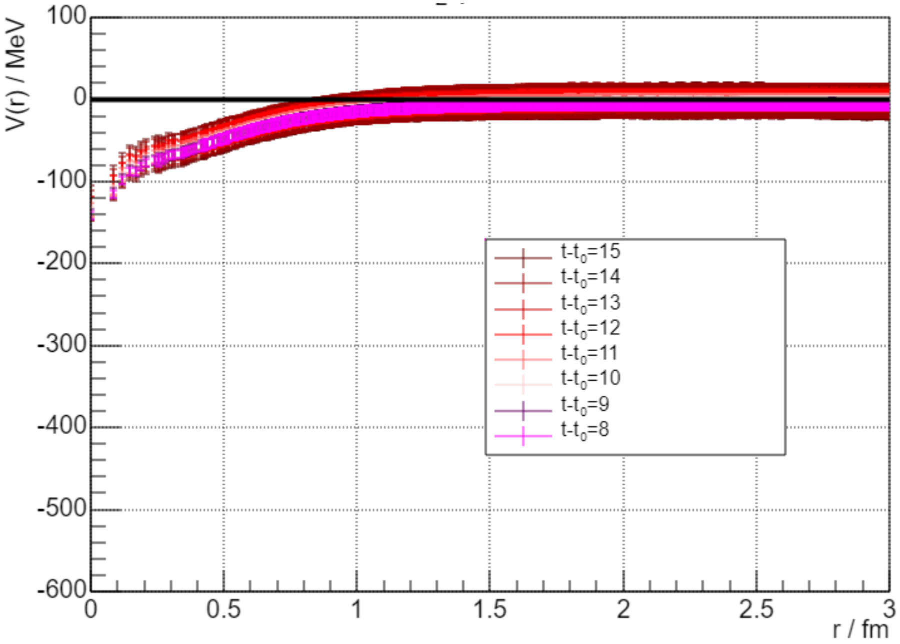
N–Ω_{ccc} interactions on the phys point

L. Zhang

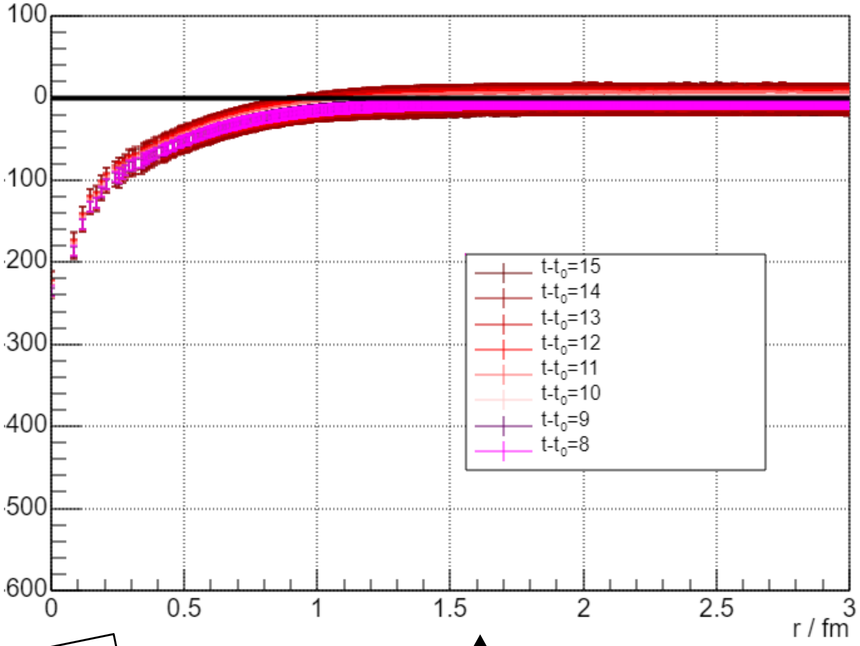
Results for the potentials

$m\pi$=137MeV (Lat)

$^5S_2$



$^3S_1$



Preliminary

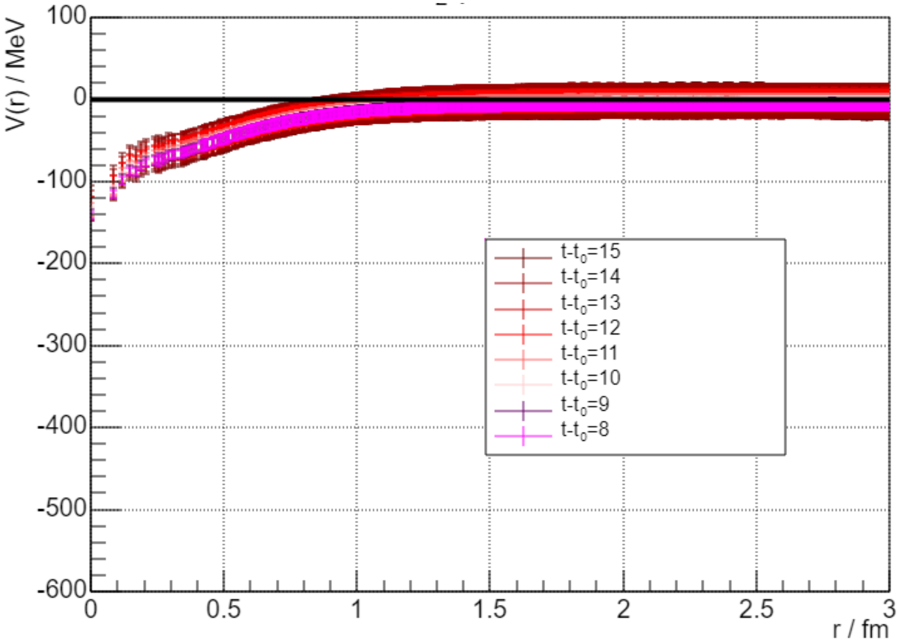
↑

channel difficult to
be accessed by $N\Omega$

TPE or not? To be studied

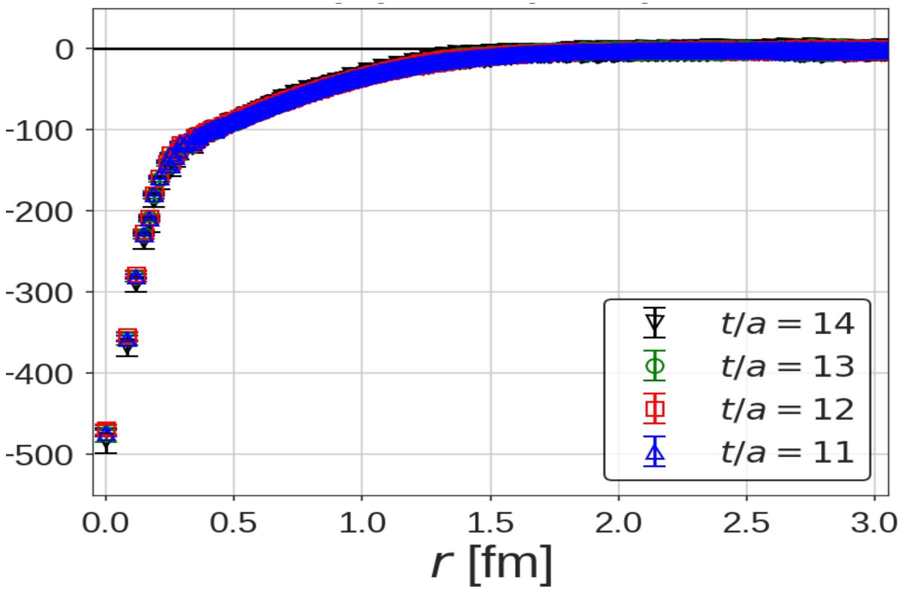
N–Ω_{ccc} vs. N–Ω interactions

NΩ_{ccc} ($^5S_2$)



mπ=137MeV (Lat)

NΩ ($^5S_2$)



mπ=146MeV (Lat)

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

Λ_c–N interactions near the phys point

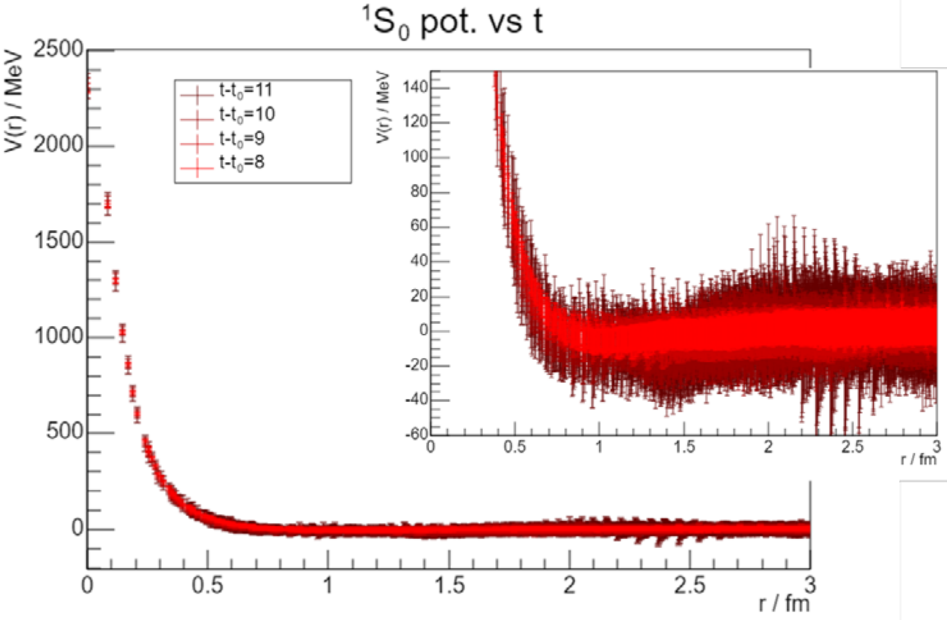
L. Zhang

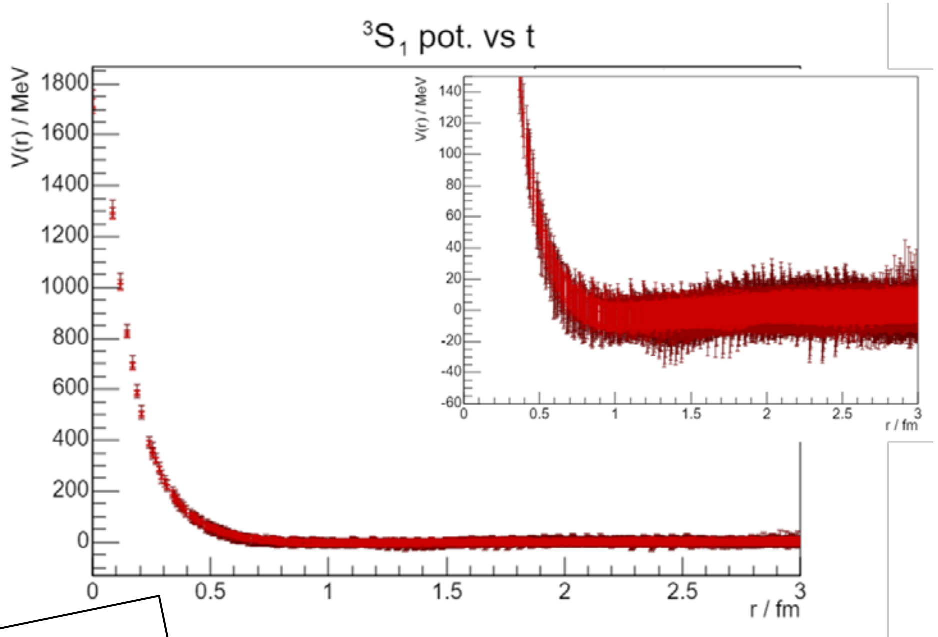
Possibility of Λ_c hypernuclei?

c.f. T. Miyamoto et al., (HAL Coll.) NPA971(2018)113
m(pi)=0.41-0.70 GeV

Impact on EFT

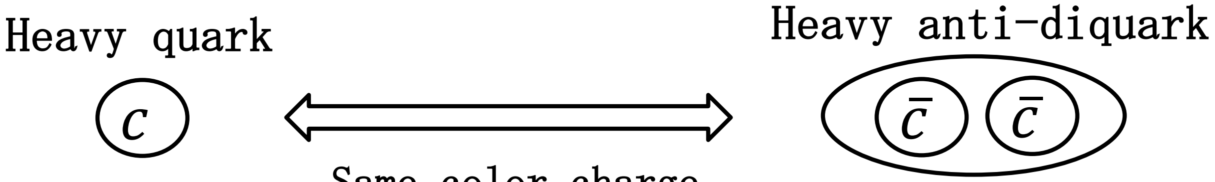
Haidenbauer-Krein (2018, 2021), J. Song et al. (2020)





Preliminary

Superflavor partner of Tcc ?



Georgi-Wise, PLB243(1990)279
Savage-Wise, PLB248(1990)177

Tcc (D-D*) ⟺ Pentaquark state? (Dbar$^{(*)}$-$\Xi_{cc}{}^{(*)}$)

Tcc bar: (cbar u) – (cbar d)

$I(J^P) = 0(1^+)$

(cbar u) – (cc d)

$I(J^P) = 0(1/2^-)$

Asanuma-Yamaguchi-Harada, arXiv:2311.04695

OBEP + superflavor sym → Bound state could exist

⟺ Hexaquark state? (Ξ_{cc}–Ξ_{cc})

(cc u) – (cc d)

$I(J^P) = 0(1^+)$

Physical point simulation of Ξ_{cc}–Ξ_{cc} interactions

- F-conf is used for phys point calc on Fugaku
- Ξ_{cc}–Ξ_{cc} interactions

$I(J^P) = 0(1^+)$ $^3S_1$-$^3D_1$ channel ⇦ Candidate of Tcc partner

$I(J^P) = 1(0^+)$ $^1S_0$ channel

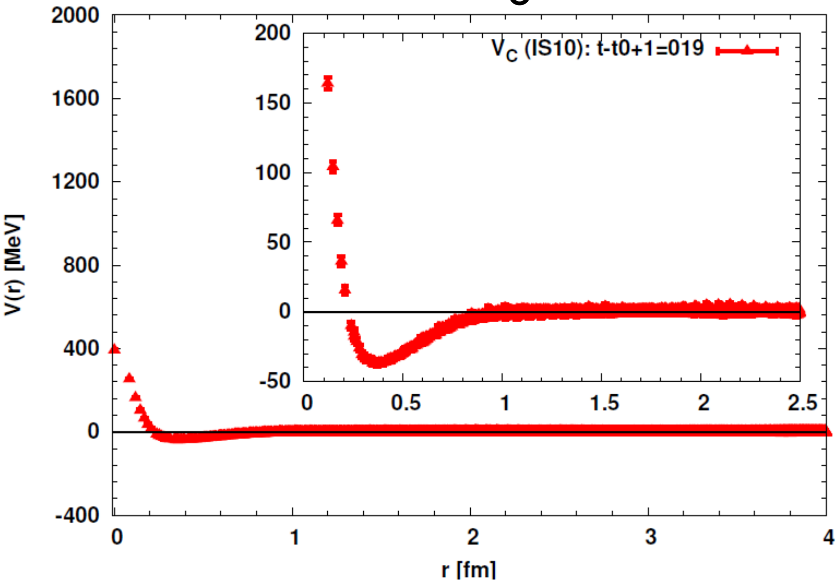
- Ξ_{ss}–Ξ_{ss} (= usual Ξ–Ξ) interactions
  - We can use this system as a "reference" to probe the role of heavy quark

$I(J^P) = 0(1^+)$ $^3S_1$-$^3D_1$ channel ← SU(3)f 10-plet

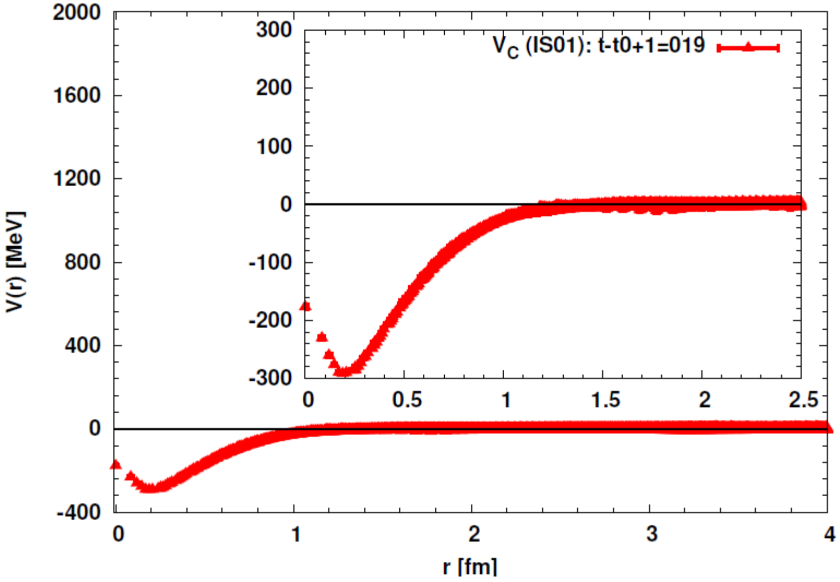
$I(J^P) = 1(0^+)$ $^1S_0$ channel ← SU(3)f 27-plet

Ξ_{cc}–Ξ_{cc} interactions

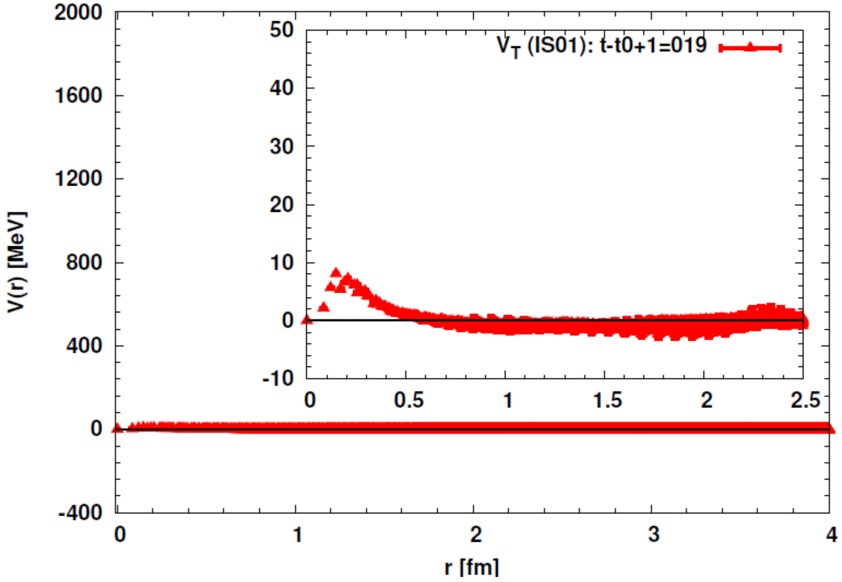
$^1S_0$



$^3S_1$-$^3D_1$



Central



Tensor

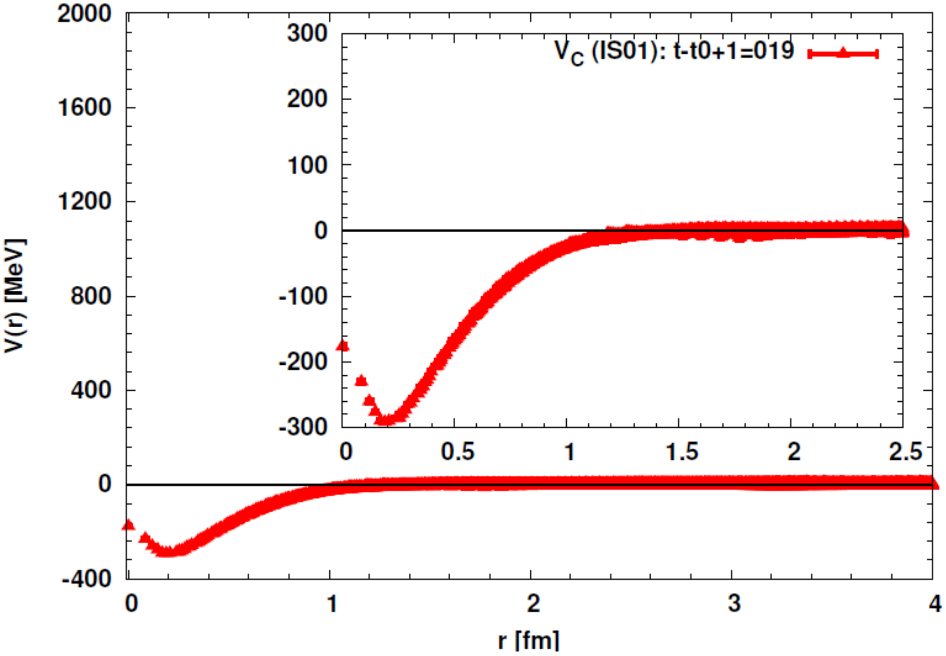
$^1S_0$: Repulsive core
+ attractive pocket

$^3SD_1$: Strong attraction
& weak tensor force

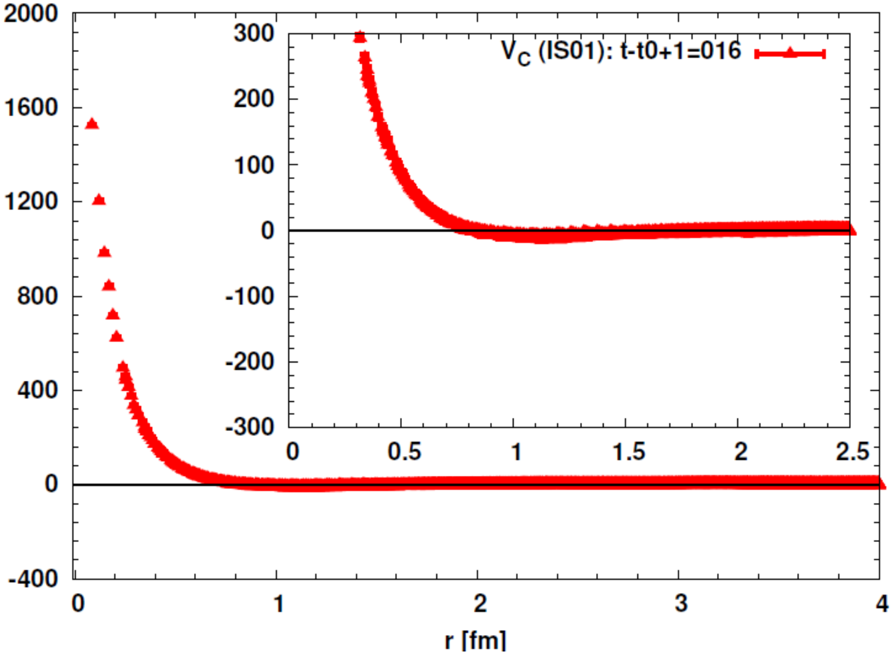
$M(\Xi_{cc})$ = 3642.9(1.4) MeV

Comparison of central potential in $^3SD_1$ channel

Ξ_{cc}–Ξ_{cc}



Ξ_{ss}–Ξ_{ss}

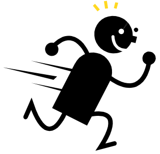


Completely different!

(N.B. There exists open channel, $\Lambda_c\Omega_{ccc}$, below $\Xi_{cc}\Xi_{cc}$ channel)

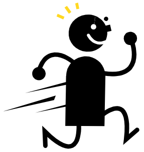
Challenge toward LQCD w/ physical mass

~2012



➔lighter u,d-quark masses
(=lighter pion mass Mπ)

~2018



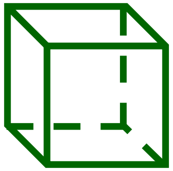
2023 !

We were here

➔ more challenging

Phys. point

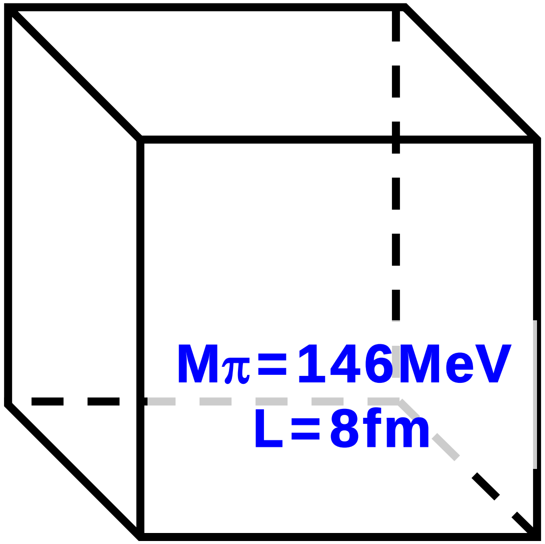
Mπ=400MeV
L=3fm



Theoretical development
+
New supercomputer

Simulation w/
Unrealistic mass

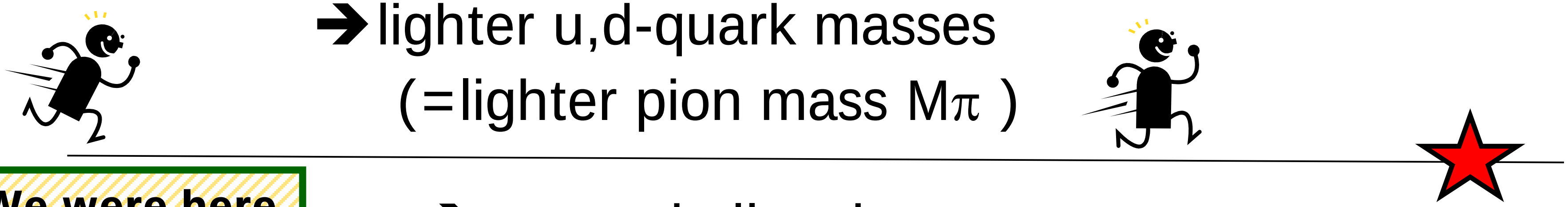
Fugaku (440PFlops)



Mπ=146MeV
L=8fm

Simulation w/
~Near physical mass

Challenge toward LQCD w/ physical mass



~2012

➔lighter u,d-quark masses
(=lighter pion mass M_π)

~2018

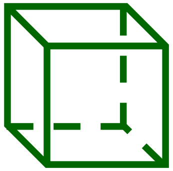
2023 !

We were here

➔ more challenging

Phys. point

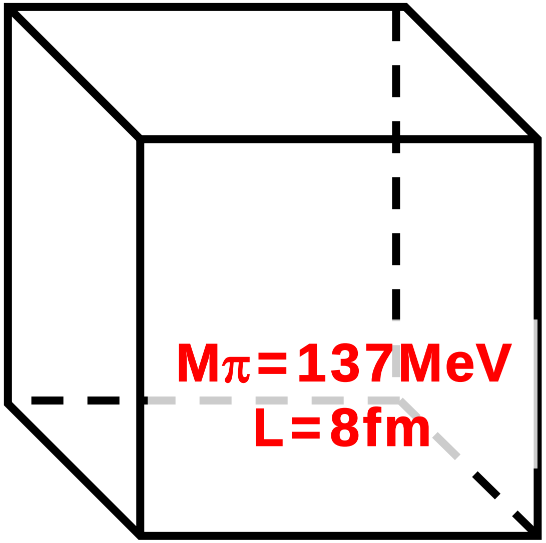
M_π=400MeV
L=3fm



Theoretical development
+
New supercomputer

Simulation w/
Unrealistic mass

Fugaku (440PFlops)

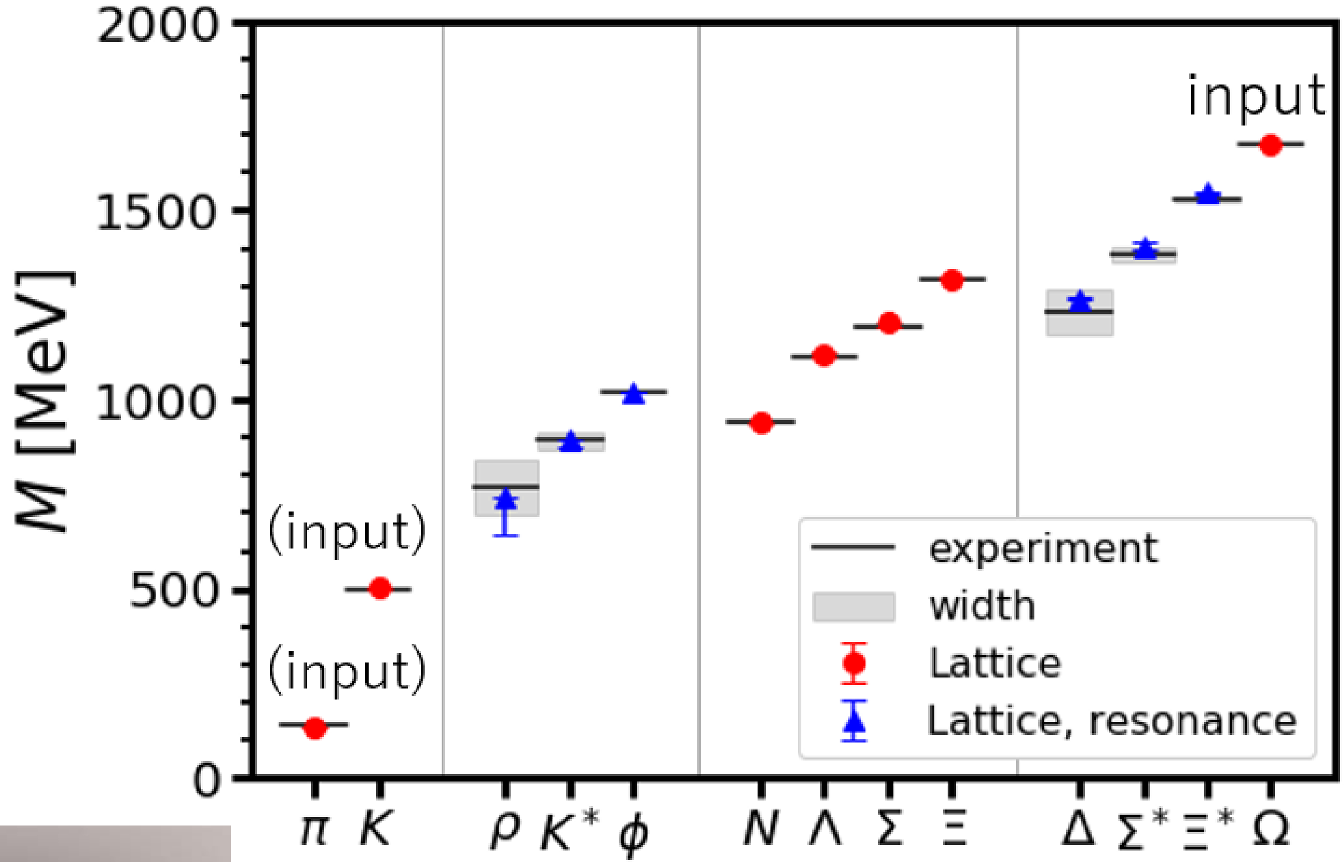


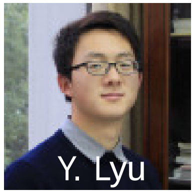
M_π=137MeV
L=8fm

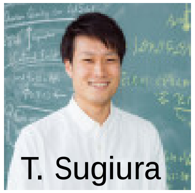
Simulation w/
the physical mass

LQCD simulations at the physical quark masses

(mπ=137MeV)







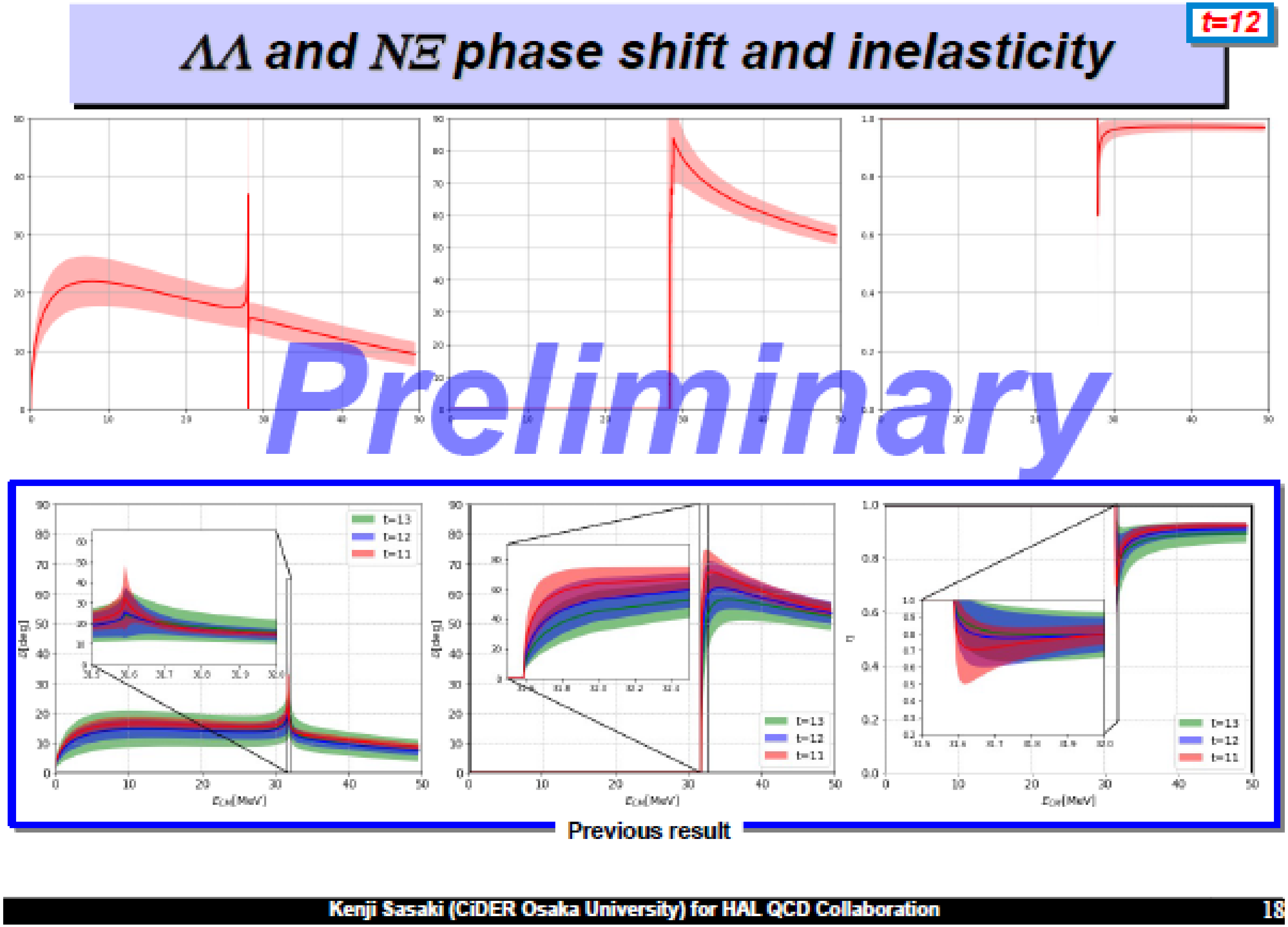
HAL QCD Coll., PRD in press, arXiv:2406.16665

Fugaku (440PFlops)

Calc of Hadron Interactions in progress!

Fate of H-dibaryon on the physical point

($M\pi$=137MeV)



ΛΛ and NΞ phase shift and inelasticity

t=12

Preliminary

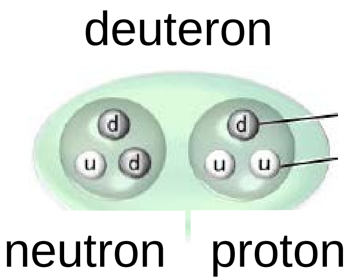
Previous result

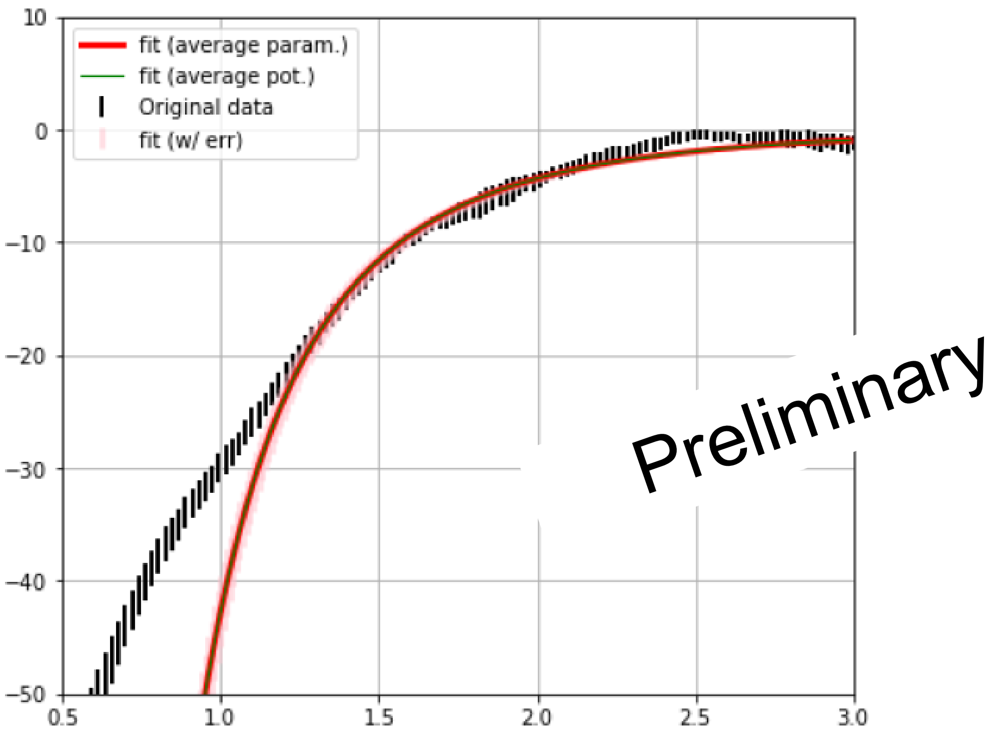
Kenji Sasaki (CiDER Osaka University) for HAL QCD Collaboration 18

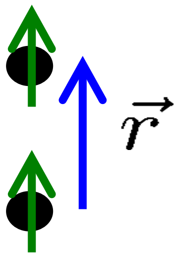
[K. Sasaki]

NN potentials @ physical point

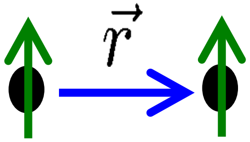
Tensor force: one of the most important potentials
characteristics of Yukawa's pion theory







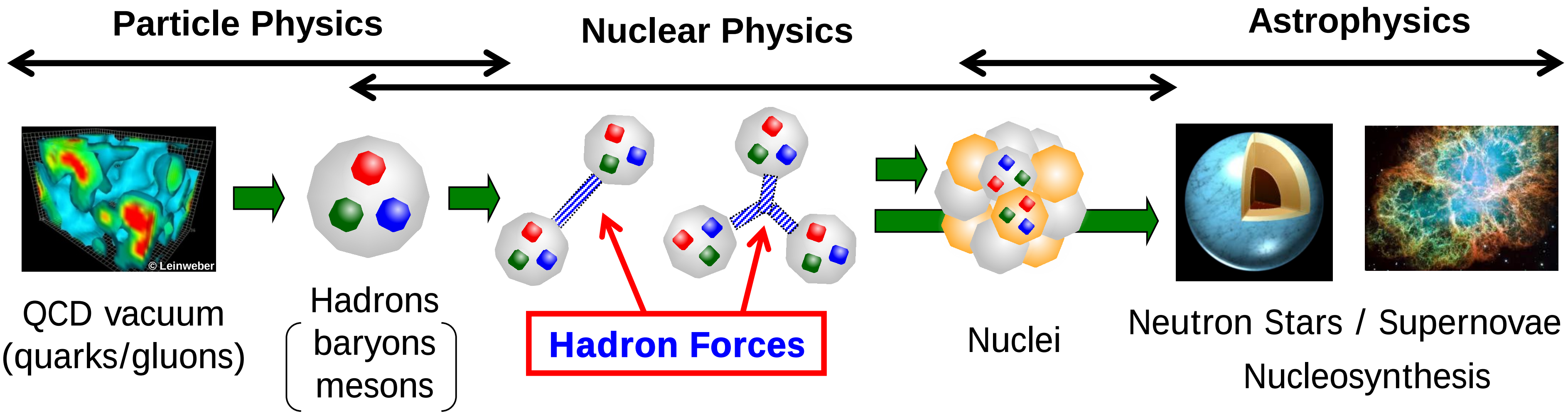
（Attraction）



（Repulsion）

Consistent w/ tail structure of one-pion exchange potential

20XX : A Space Odyssey from Quarks to Nuclei & Universe



Particle Physics

Nuclear Physics

Astrophysics

QCD vacuum
(quarks/gluons)

Hadrons
baryons
mesons

Hadron Forces

Nuclei

Neutron Stars / Supernovae

Nucleosynthesis

$\sim 10^{-14}$ cm

$\sim 10^{-13}$ cm

$\sim 10^{-12}$ cm

$\sim 10^{+6}$ cm (= 10 km)

Nuclear Physics from QCD

New Era is dawning !

J-PARC (HEF-ex)
LHC (ALICE, LHCb)
Belle II
BES III
HIAF
RIBF/FRIB
LIGO/Virgo/KAGRA