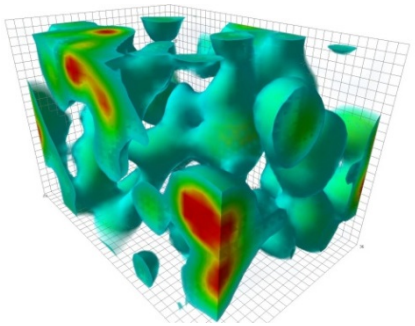
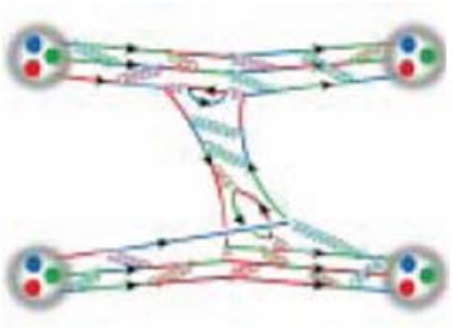
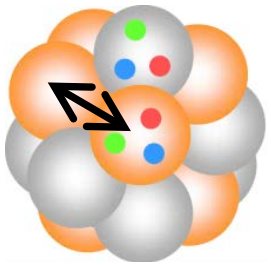
Hadron interactions from Lattice QCD

Takumi Doi

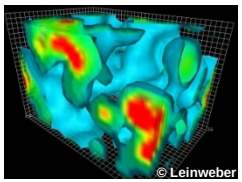
(RIKEN iTHEMS)

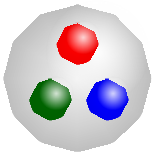


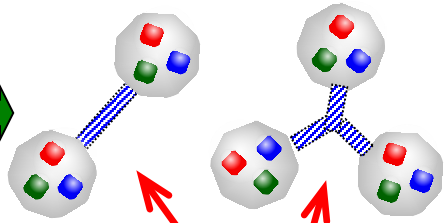


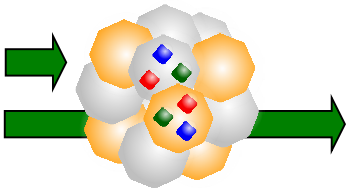


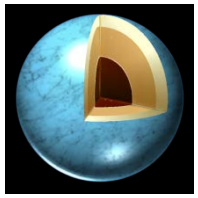
The Odyssey from Quarks to Universe

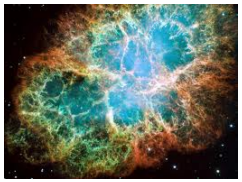












QCD vacuum Baryons Nuclei Neutron Stars / Supernovae Nucleosynthesis

QCD

1st-principle Lattice QCD

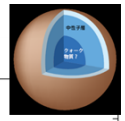
Hadron Forces

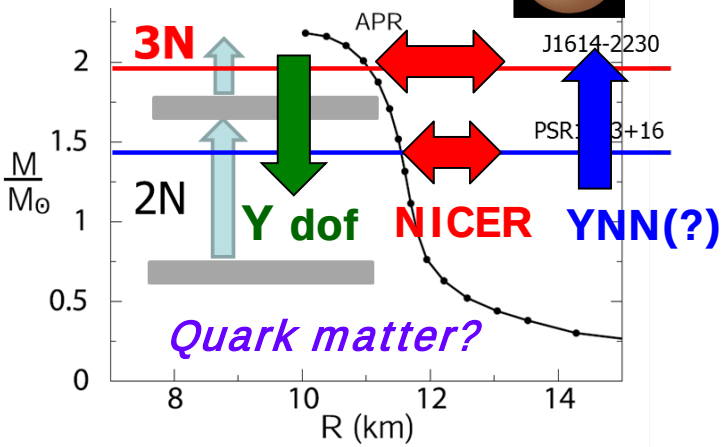
ab-initio nuclear calc.

J-PARC

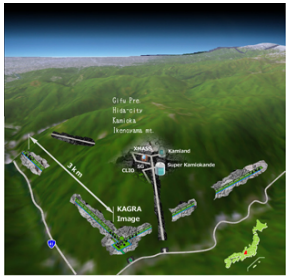
LHC/RHIC

EoS of Dense Matter

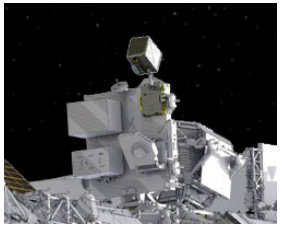




RIBF/FRIB



aLIGO/KAGRA



NICER

Nuclear/Hyperon Forces ➔ Charmed Forces

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

top

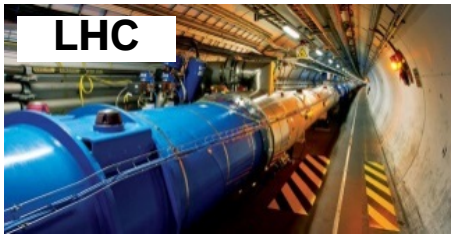
up,down quarks | strange quark | Λ_{QCD} | charm quark | bottom quark

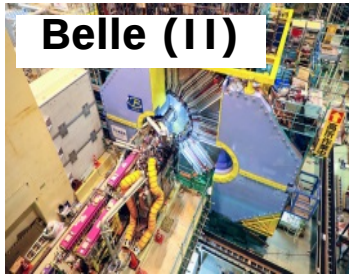
chiral symmetry

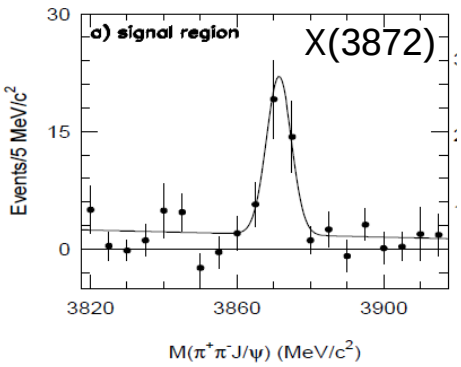
heavy quark symmetry

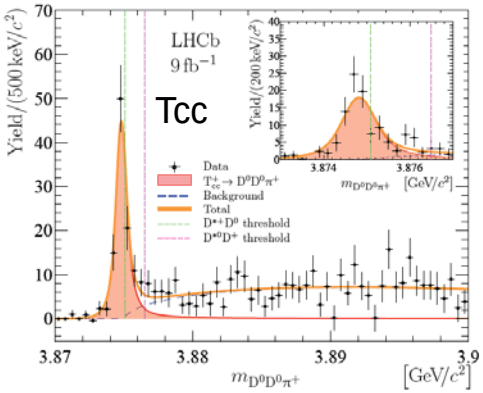
Heavy quarks: New doorway to the mysteries of QCD

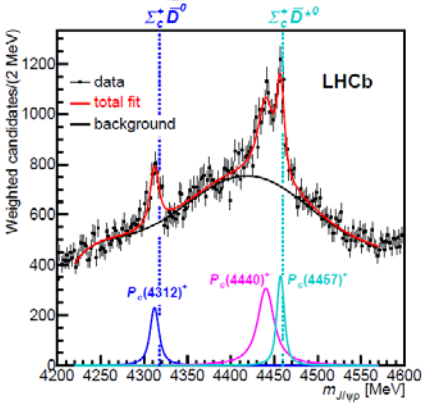
Many new exotic particles being reported!











Hadron interactions crucial to understand these “signals” !

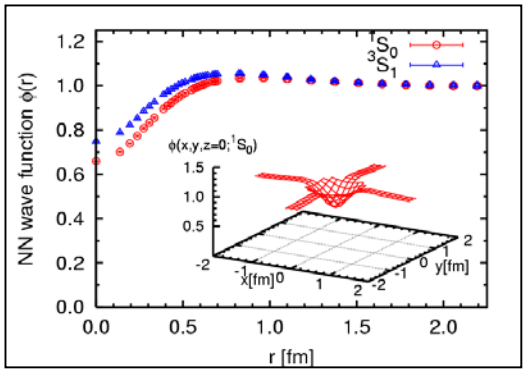
e.g., Zc(3900) from HAL LQCD → threshold cusp

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

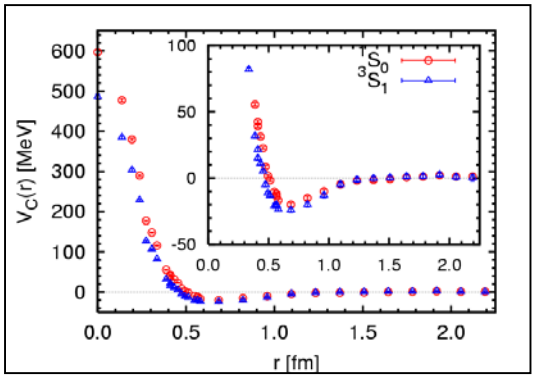
HAL QCD method

Lattice QCD

NBS wave func.



Lat Hadron Force



$$\psi_{\rm NBS}(\vec{r}) = \langle 0|H_1(\vec{r})H_2(\vec{0})|H_1(\vec{k})H_2(-\vec{k}),in\rangle \simeq A_k \sin(kr - l\pi/2 + \delta_l(k))/(kr)$$

$$\left(k^2/m_N - H_0\right)\psi_{\rm NBS}(\vec{r}) = \int d\vec{r}' U(\vec{r},\vec{r}')\psi_{\rm NBS}(\vec{r}')$$

- **Interacting kernel ("potential") from spatial & temporal correlation**
  - Potential → Phase Shifts guaranteed by QFT

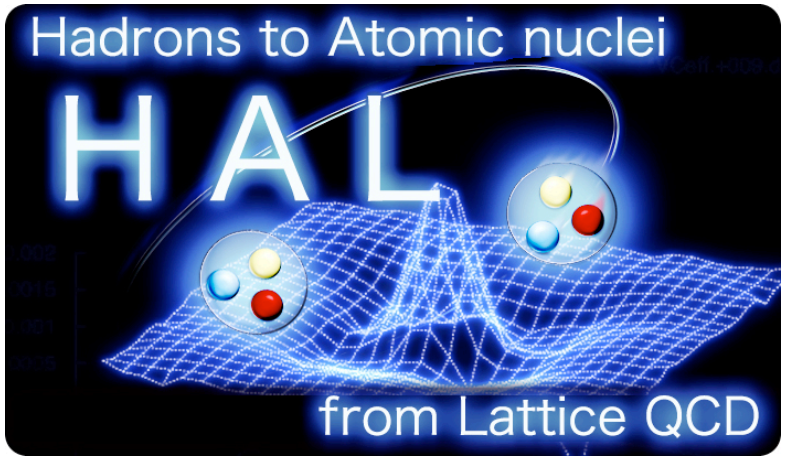
  Aoki-Hatsuda-Ishii PTP123(2010)89
- **Energy-indep potential**

  N.Ishii et al. (HAL Coll.) PLB712(2012)437
  - "Signal" from (elastic) excited states → Ground state saturation NOT required
- **Coupled Channel formalism**

  S. Aoki et al. (HAL Coll.) Proc.Jpn.Acad.B87(2011)509
  - Physics above inelastic threshold → Essential for Hyperon-forces, Exotics
- **Extension to N-body systems (N>=3)**

  S. Aoki et al. (HAL Coll.) PRD88(2013)014036
  (non-rela approx.)

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



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

「20XX年宇宙の旅」

from Quarks to Universe

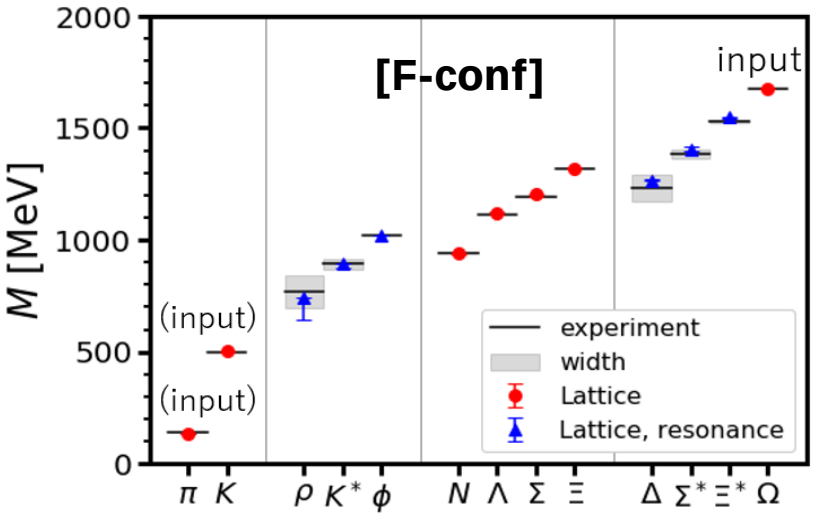
+
I. Kanamori (RIKEN)
K.-I. Ishikawa (Hiroshima U.)
M. Harada (Nagoya U.)
T. Hyodo (Osaka U.)
and many more

LQCD @ near & on the physical point

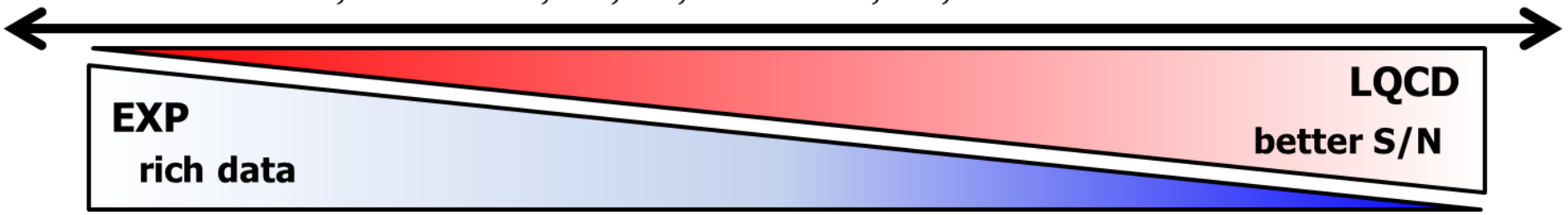
- **Nf = 2 + 1 gauge configs**
  - Iwasaki gauge + clover-uds + (quenched) RHQ-charm
  - $V = (96\ a)^4 = (8.1\text{fm})^4$, $1/a = 2339$ MeV

Fugaku (440PFlops)

- **[K-conf]** PACS Coll., PoS LAT2015, 075
  $(m_\pi, m_K) = (146, 525)$ MeV
  (#confs ~= 400)
- **[F-conf]** HAL QCD Coll., PRD110(2024)094502
  $(m_\pi, m_K) = (137, 502)$ MeV
  (#confs = 1600)

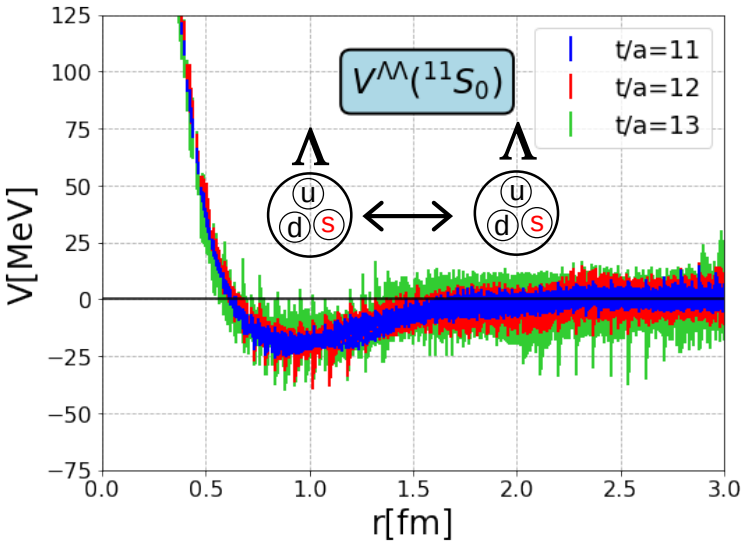


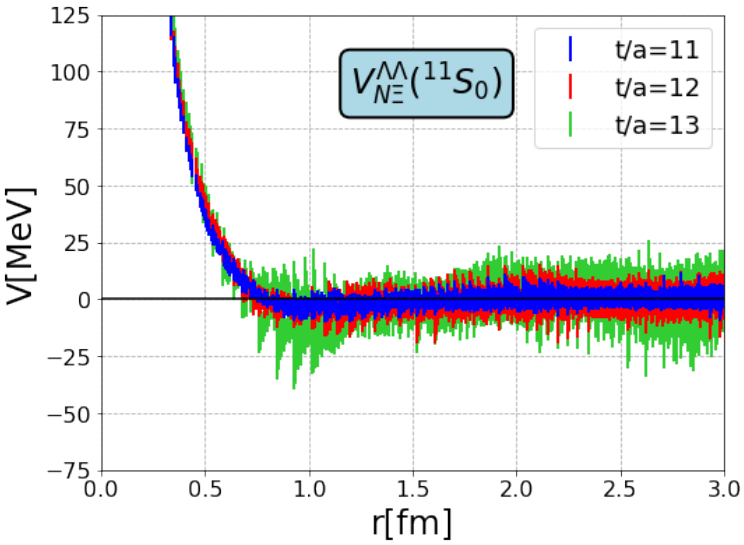
S=0	S=–1	S=–2	S=–3	S=–4	S=–5	S=–6
NN	NΛ, NΣ	ΛΛ, ΛΣ, ΣΣ, NΞ	ΛΞ, ΣΞ, NΩ	ΞΞ	ΞΩ	ΩΩ

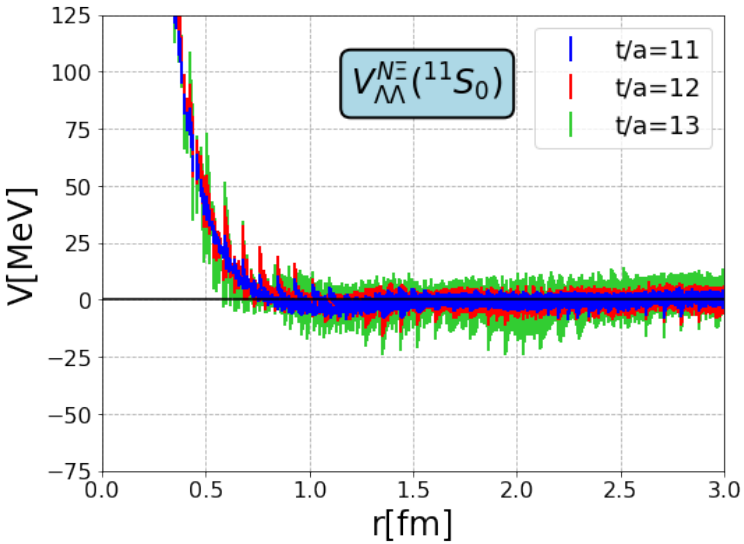


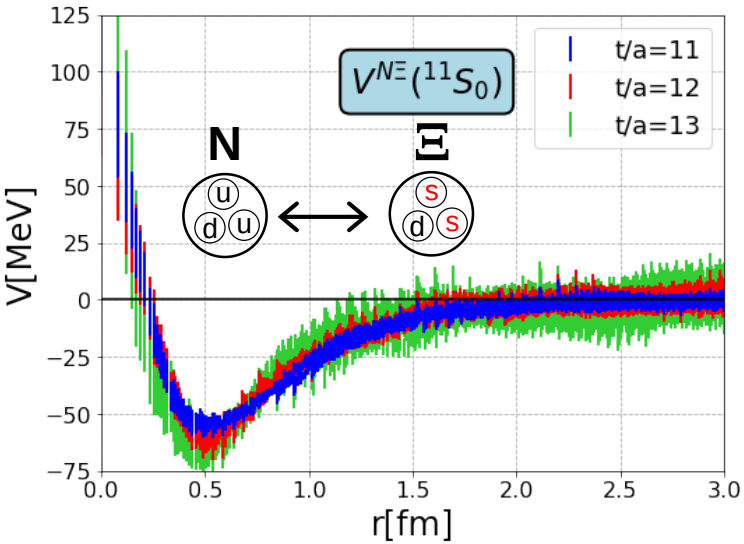
(& charmed interactions)

ΛΛ, NΞ (effective) 2x2 coupled channel analysis







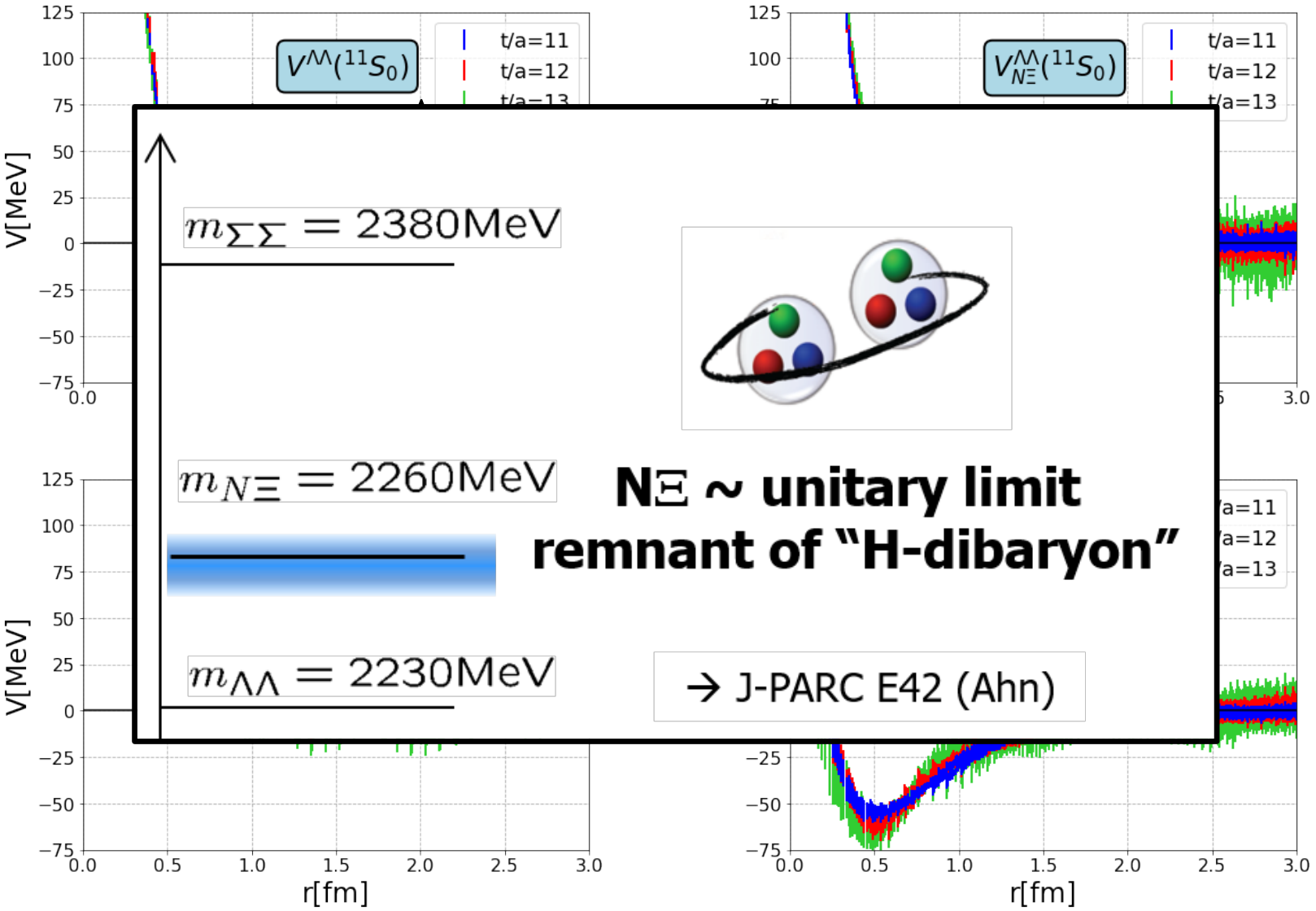


m_π=146MeV

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

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

$\Lambda\Lambda$, $N\Xi$ (effective) 2x2 coupled channel analysis



m_π=146MeV

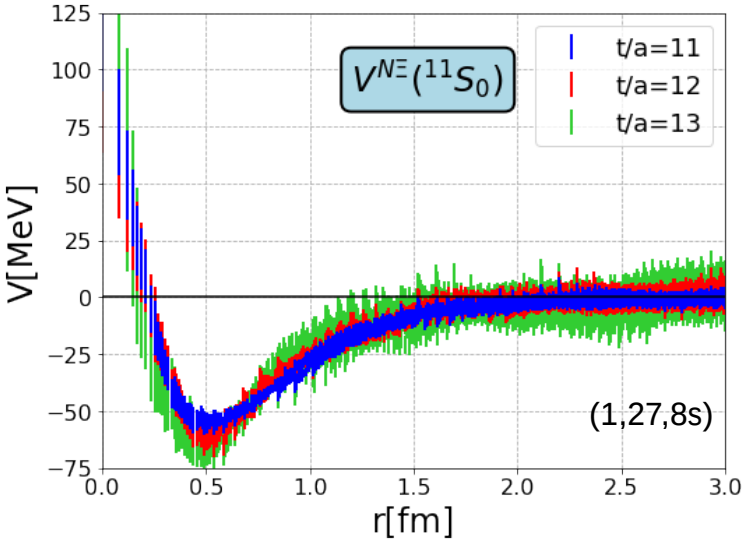
$N\Xi$ ($^1S_0$) channel is attractive
$N\Xi$–$\Lambda\Lambda$ coupling is small

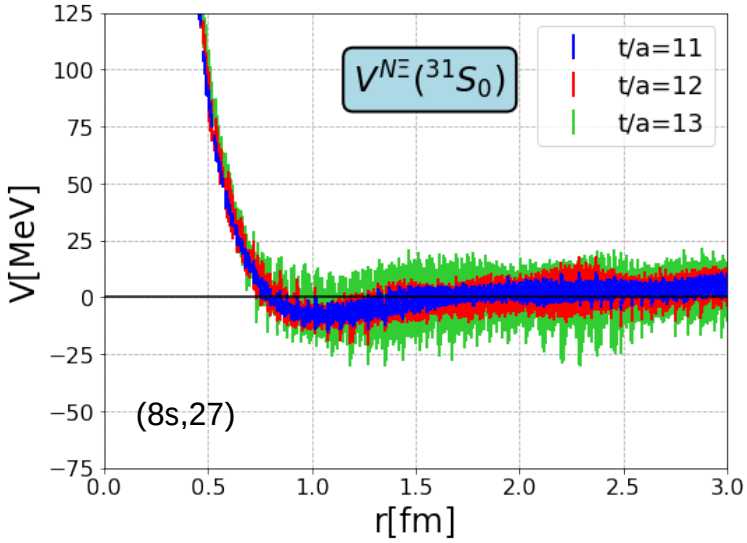
K. Sasaki et al., (HAL Coll.), NPA998(2020)12137

Spin-Isospin dependence of NΞ potentials

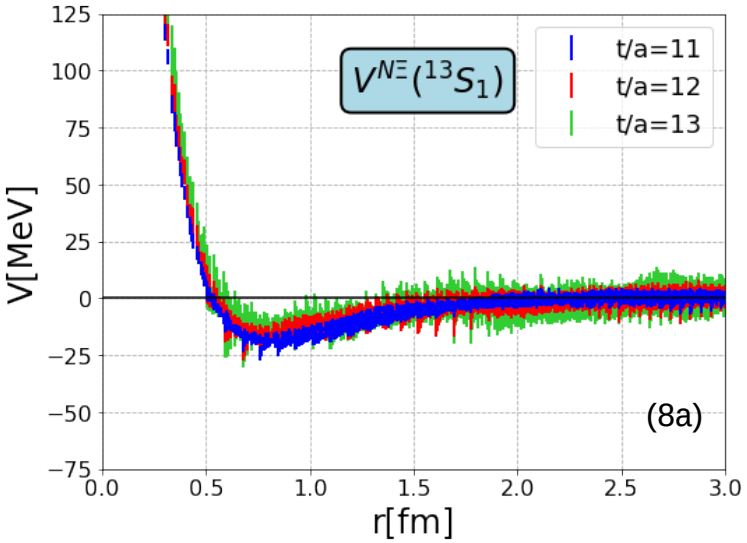
I=0 **I=1**

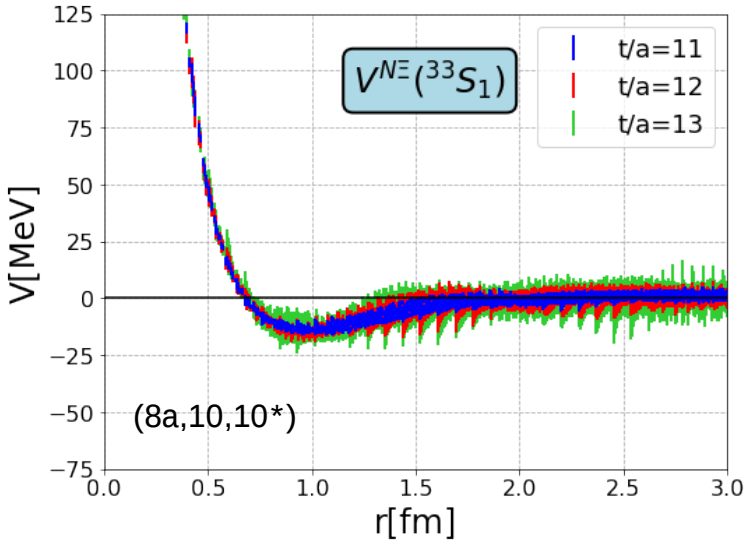
S=0





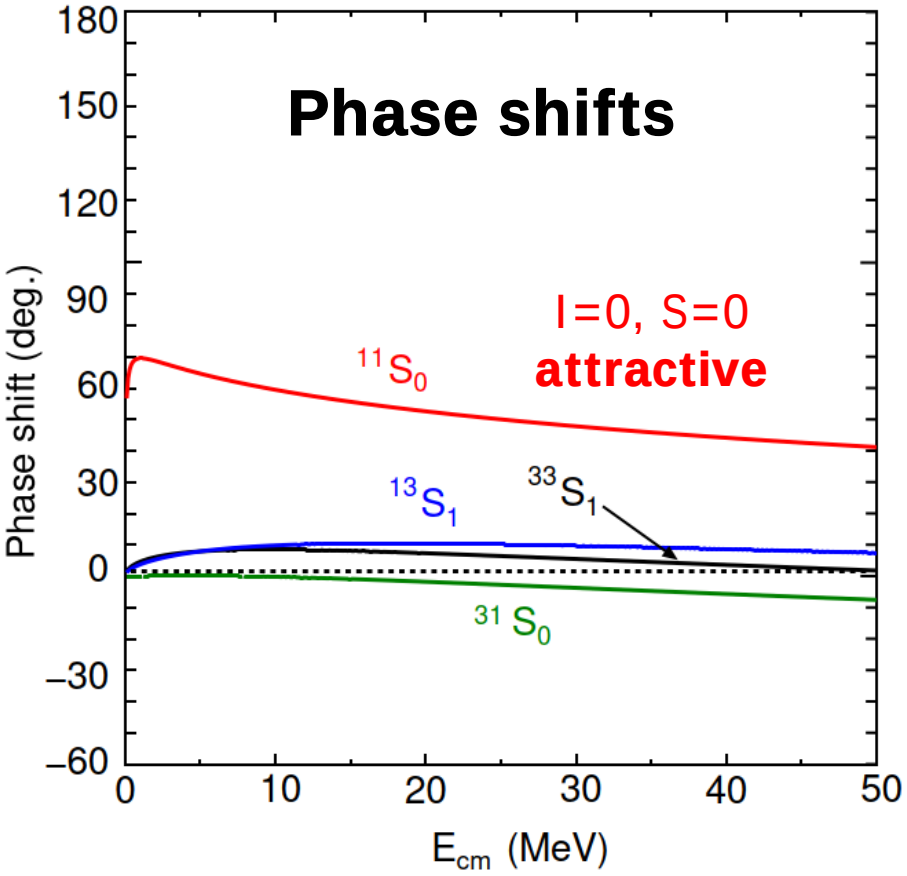
S=1

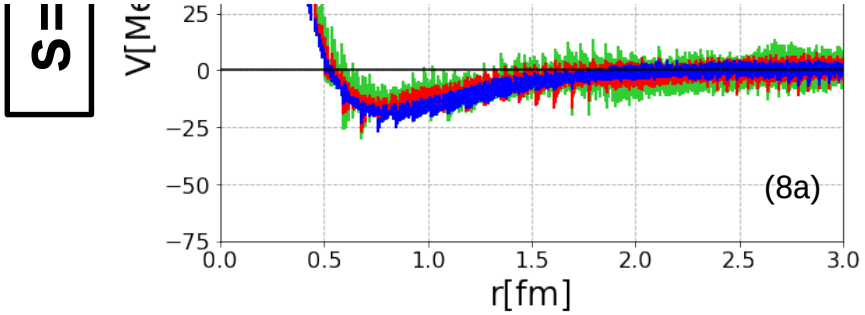




K. Sasaki et al., (HAL Coll.), NPA998(2020)12137

Spin-Isospin dependence of NΞ potentials

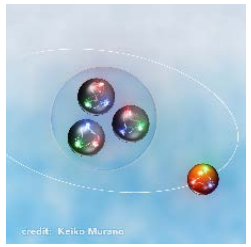




K. Sasaki et al., (HAL Coll.), NPA998(2020)12137

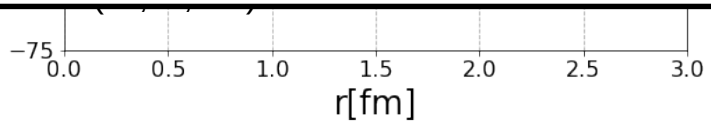
Light Ξ–nuclei predicted!

- NNNΞ ($I=0$, $J^P=1^+$)
  lightest Ξ–nucleus



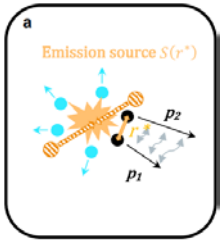
- ααNΞ ($I=0,1$, $J^P=1^-,2^-$)
  characteristic level inversion
  due to spin-isospin dep of NΞ-pot
- ααNNΞ : calc in progress
  to probe parity-odd NΞ-pot

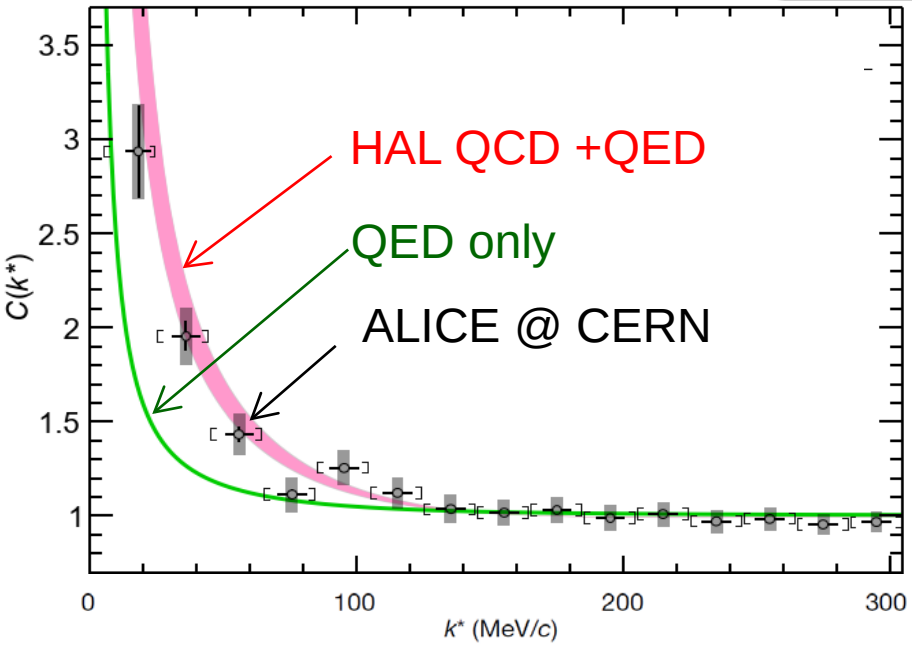
E. Hiyama et al. PRL124('20), PRC106('22)
Talk @ HYP2025



LQCD predictions meet Experiments

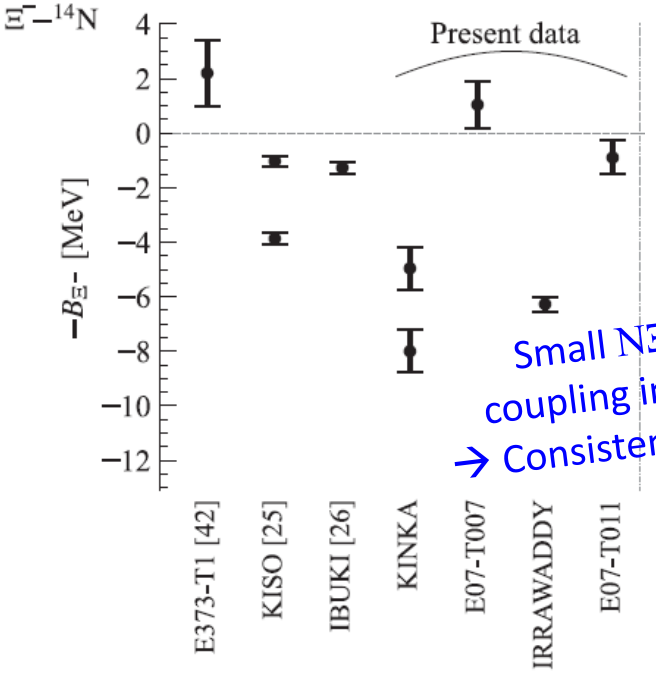
Femtoscopy in nuclear collision (N-Ξ correlation)





ALICE Coll., Nature 588, 232 (2020)
Y. Kamiya et al., PRC105, 014915 (2022)

Spectrum of Ξ - Hypernuclei

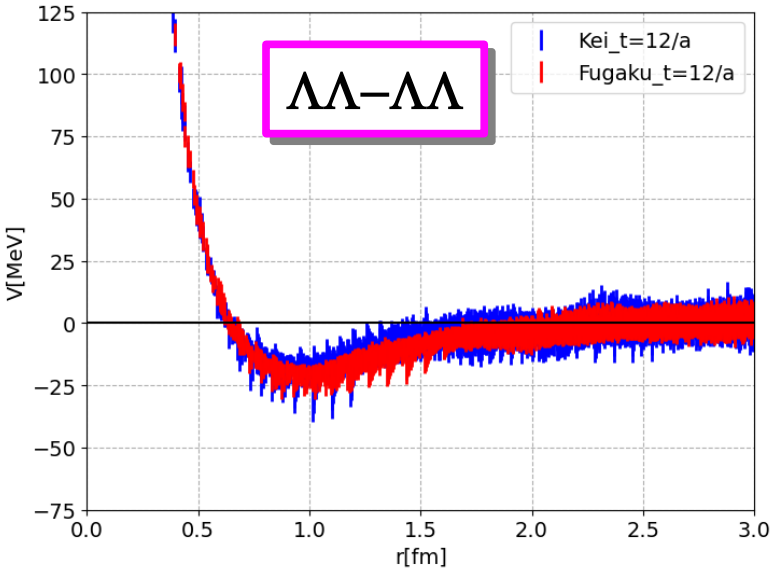


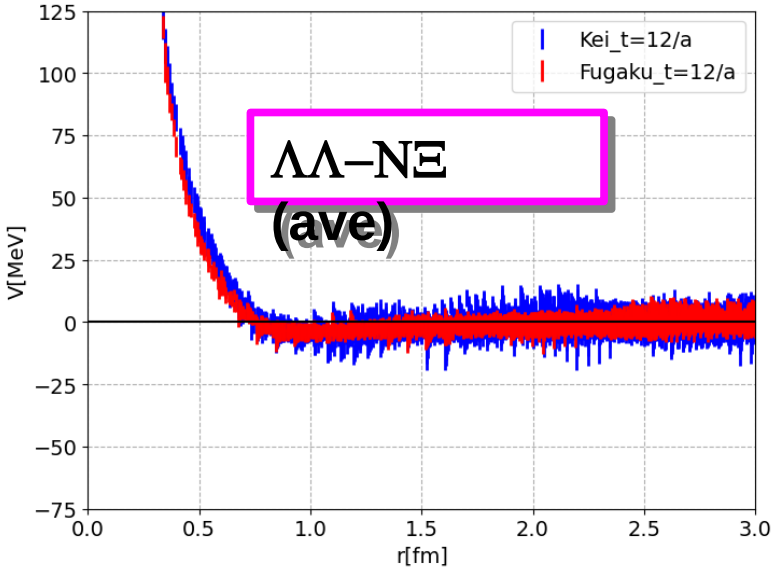
M. Yoshimoto et al., PTEP2021, 073D02
See also W. S. Jung et al., PTEP2025, ptaf064

LHC-ALICE

J-PARC

From m_π=146MeV to 137MeV: ΛΛ, NΞ potentials

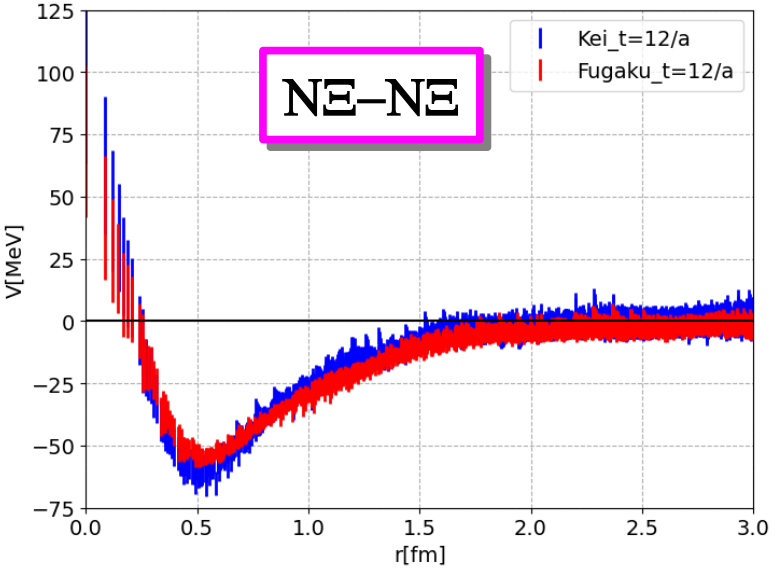




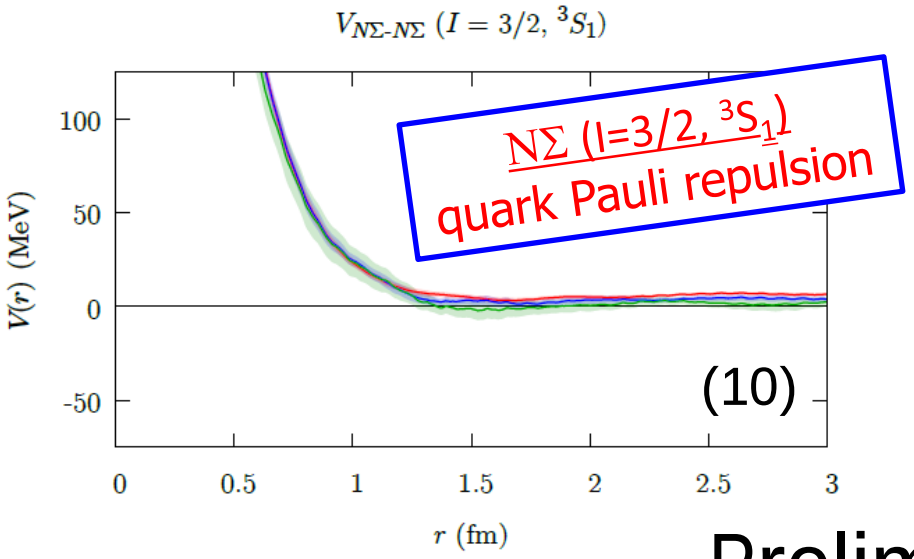
m_π=146MeV [K-conf]
m_π=137MeV [F-conf]

Pole near NΞ threshold

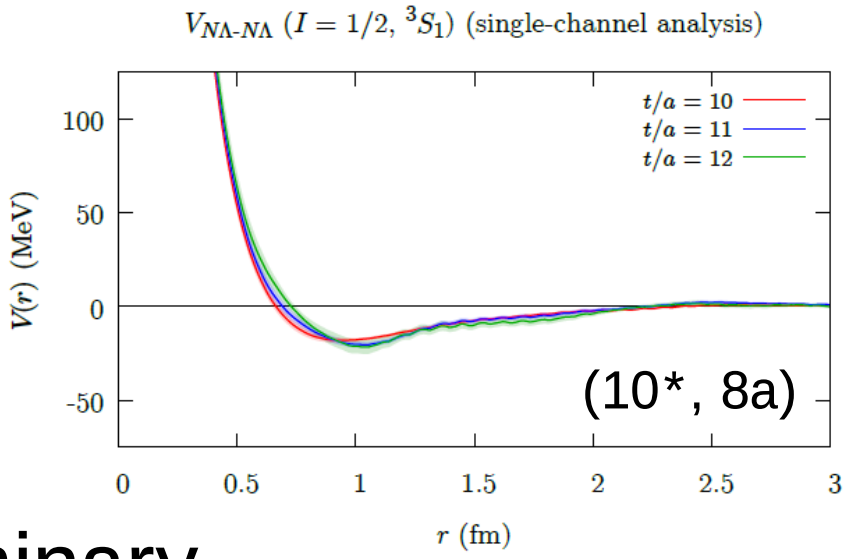
[K. Sasaki @ HYP2025]



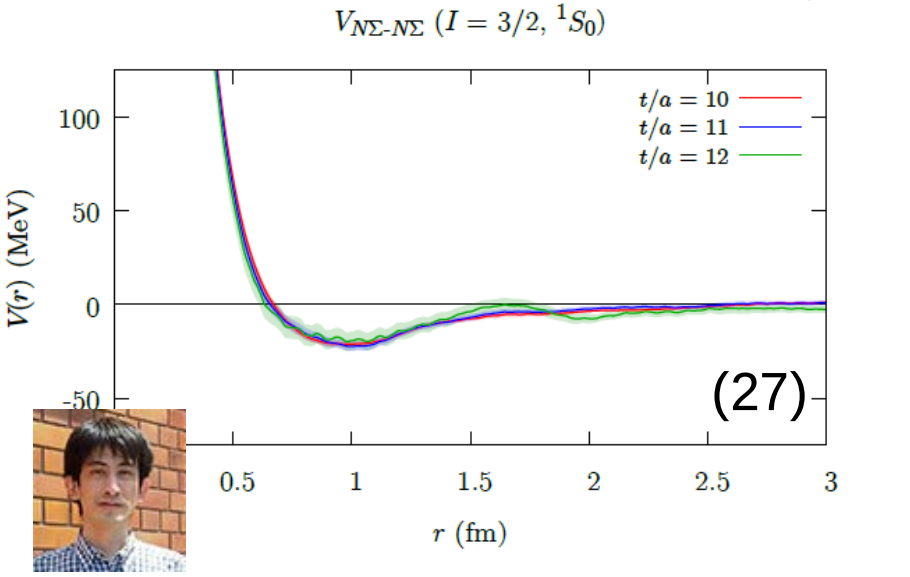
Potentials in S= -1 channel (NΛ, NΣ) at m_π=137MeV

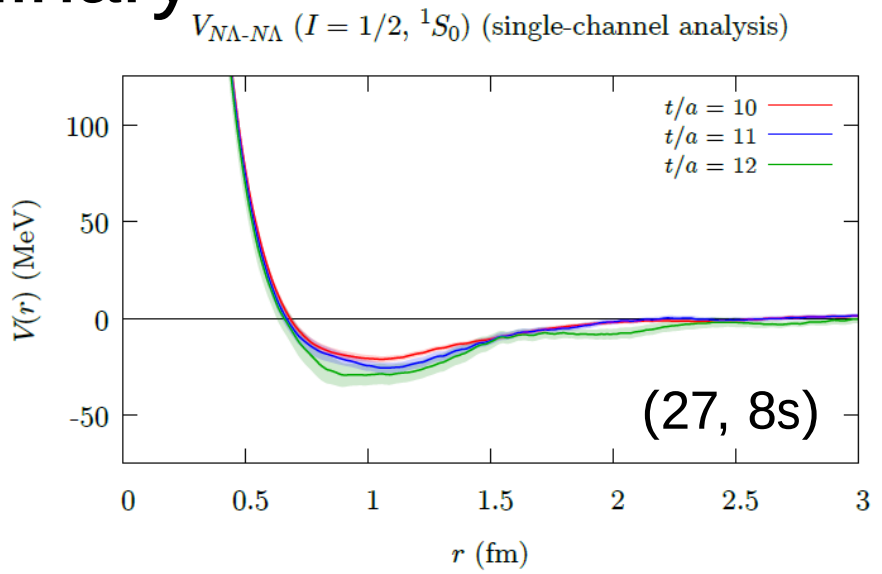


NΣ (I=3/2, $^3S_1$)
quark Pauli repulsion



Preliminary



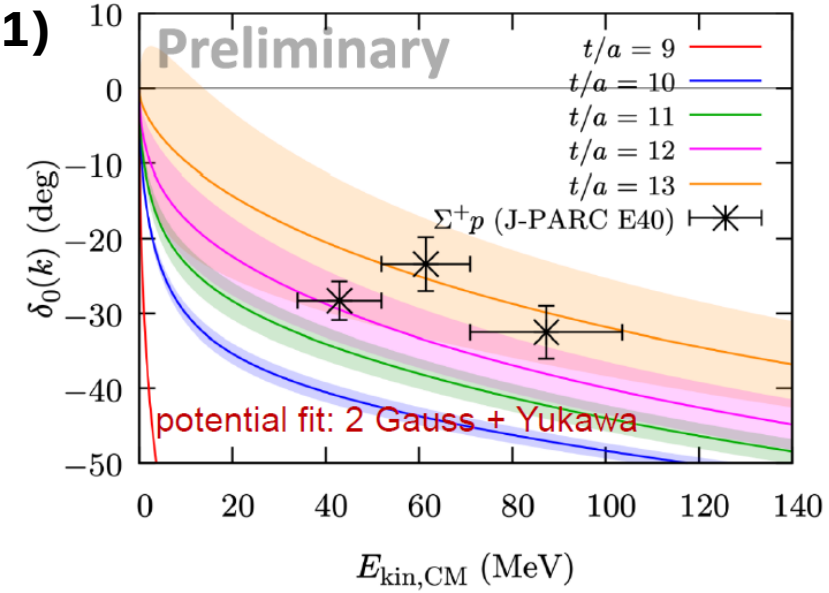


K. Murase

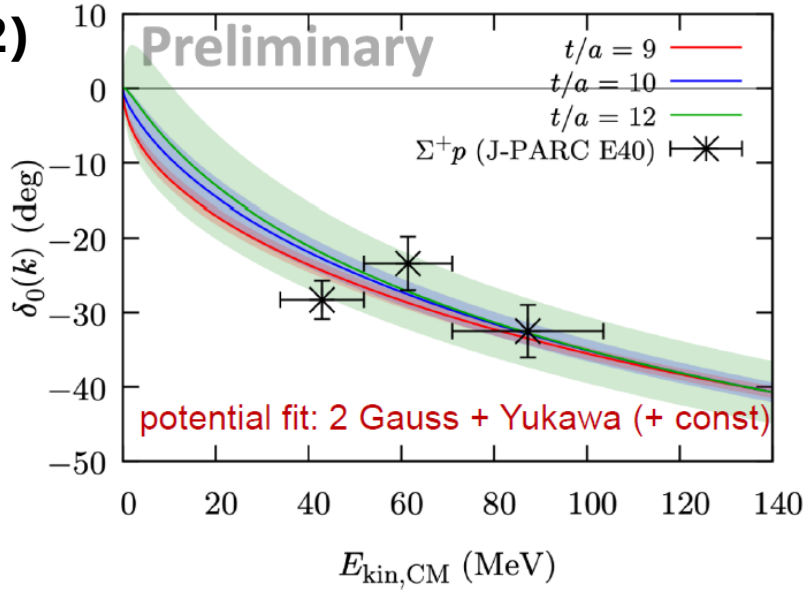
[K. Murase @ HYP2025, Lat2025]

$N\Sigma$ (I=3/2, $^3S_1$) phase shift analyses

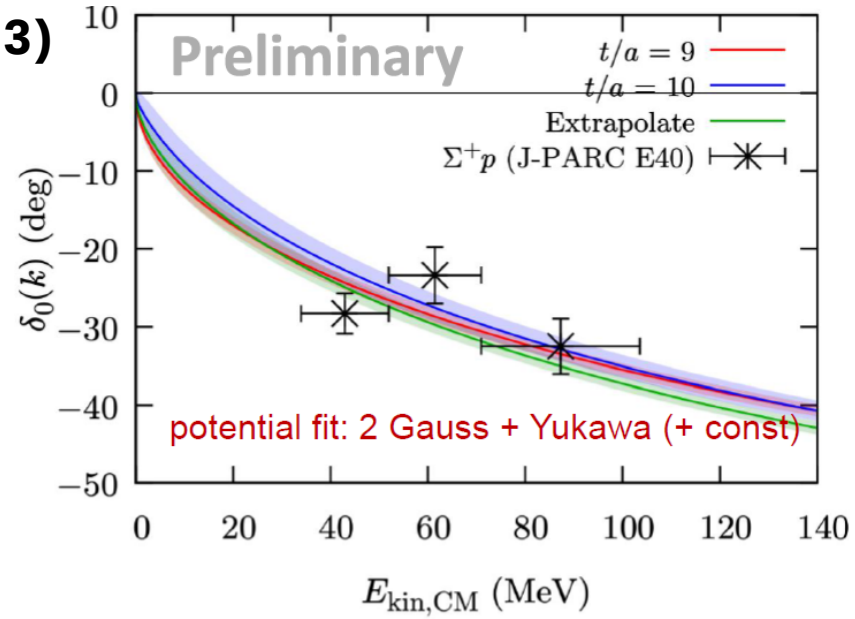
(1)



(2)



(3)

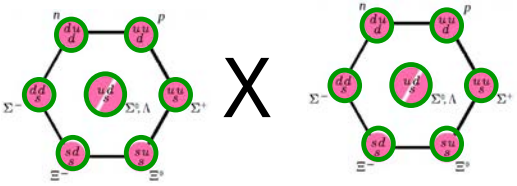


This channel suffers from sys err from inelastic state contaminations

Several analyses are explored
Extrapolation in t/a seems to work

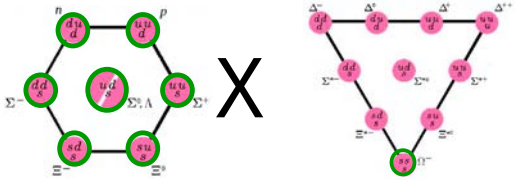
Further study to control sys err necessary

“Stranger world” and Exotic di-baryons



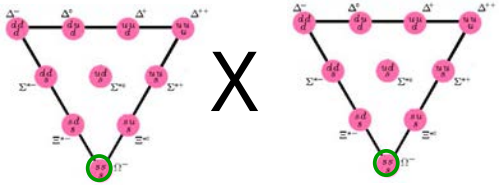
$8 \times 8 = 27 + 8s + \mathbf{1} + 10^* + 10 + 8s$

H-dibaryon
(J=0)



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

$N\Omega$ (J=2)



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

$\Omega\Omega$ (J=0)

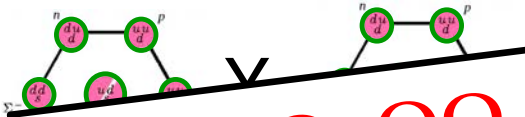
S. Gongyo et al. (HAL Coll.), PRL120(2018)212001
Y. Lyu, H. Tong et al., PRL127(2021)072003
T. Iritani et al. (HAL Coll.), PLB792(2019)284

Goldman et al. (‘87)
Oka (‘88)
Zhang et al. (‘97)

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

“Stranger world” and Exotic di-baryons

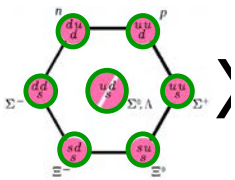
$N\Omega$, $\Omega\Omega$, $\Omega_{ccc}\Omega_{ccc}$ dibaryons near unitarity!

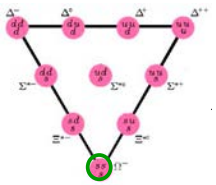


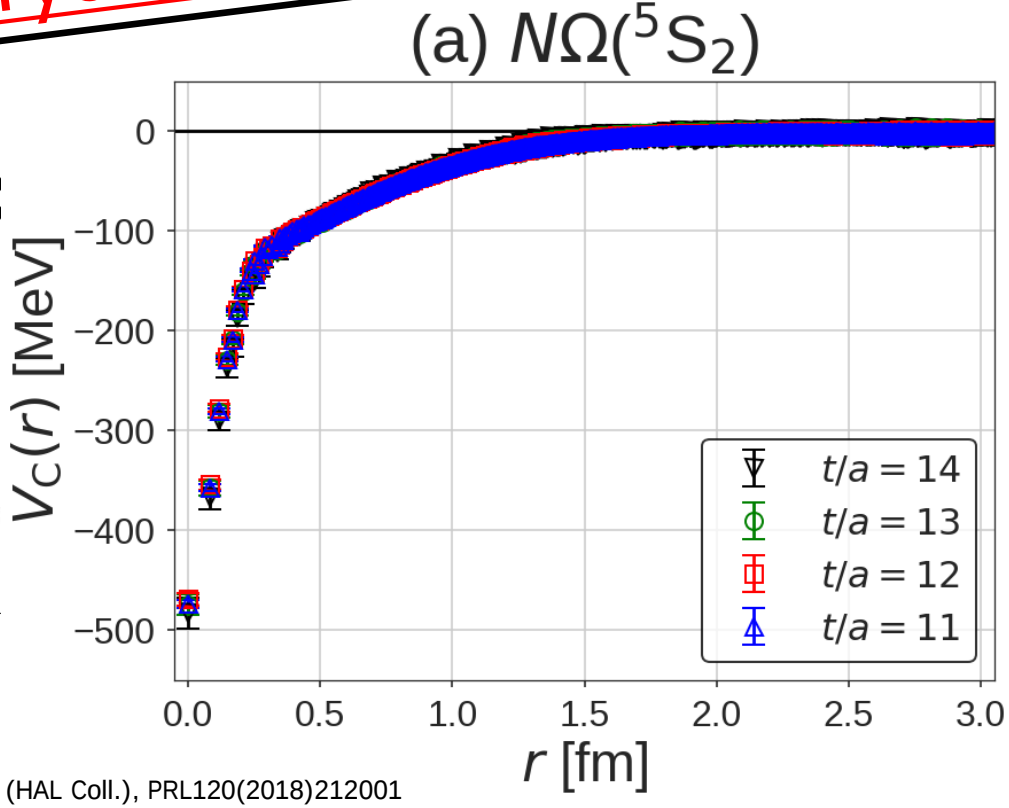
8s + 1 + 10* + 10 + 8s

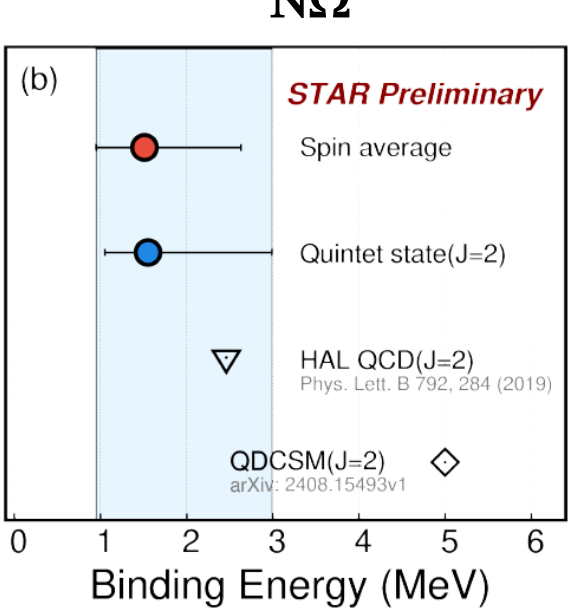
H-dibaryon

(I=0)









K. Zhang@QM2025

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

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

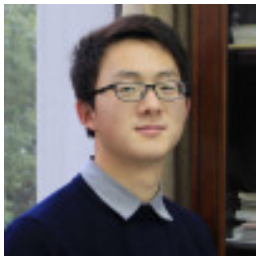
T. Iritani et al. (HAL Coll.), PLB792(2019)284

Goldman et al. (‘87)
Oka (‘88)
Zhang et al. (‘97)

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

“Charming world” and Exotic tetraquark T_{cc}^{+}

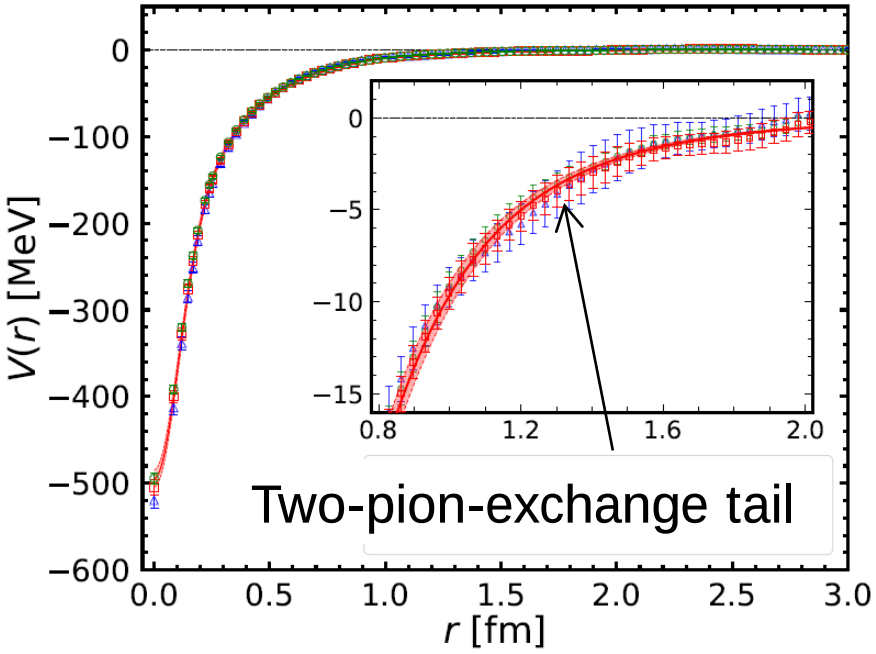
Y. Lyu, et al., PRL131(2023)161901 (Editor’s suggestion)



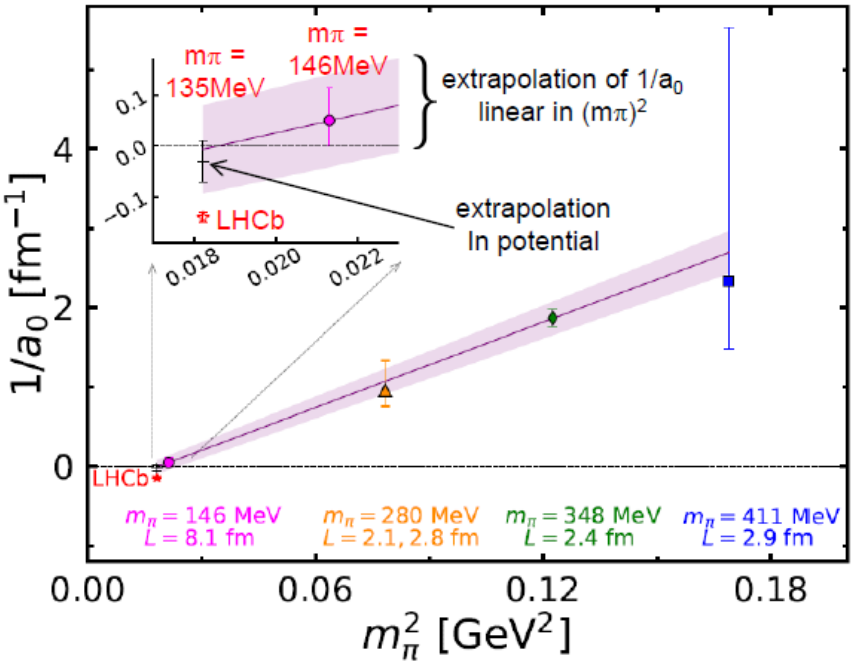
Y. Lyu

- LQCD calc of D-D* (I=0, $J^P=1^+$) interactions at $m\pi$=146MeV

Potential



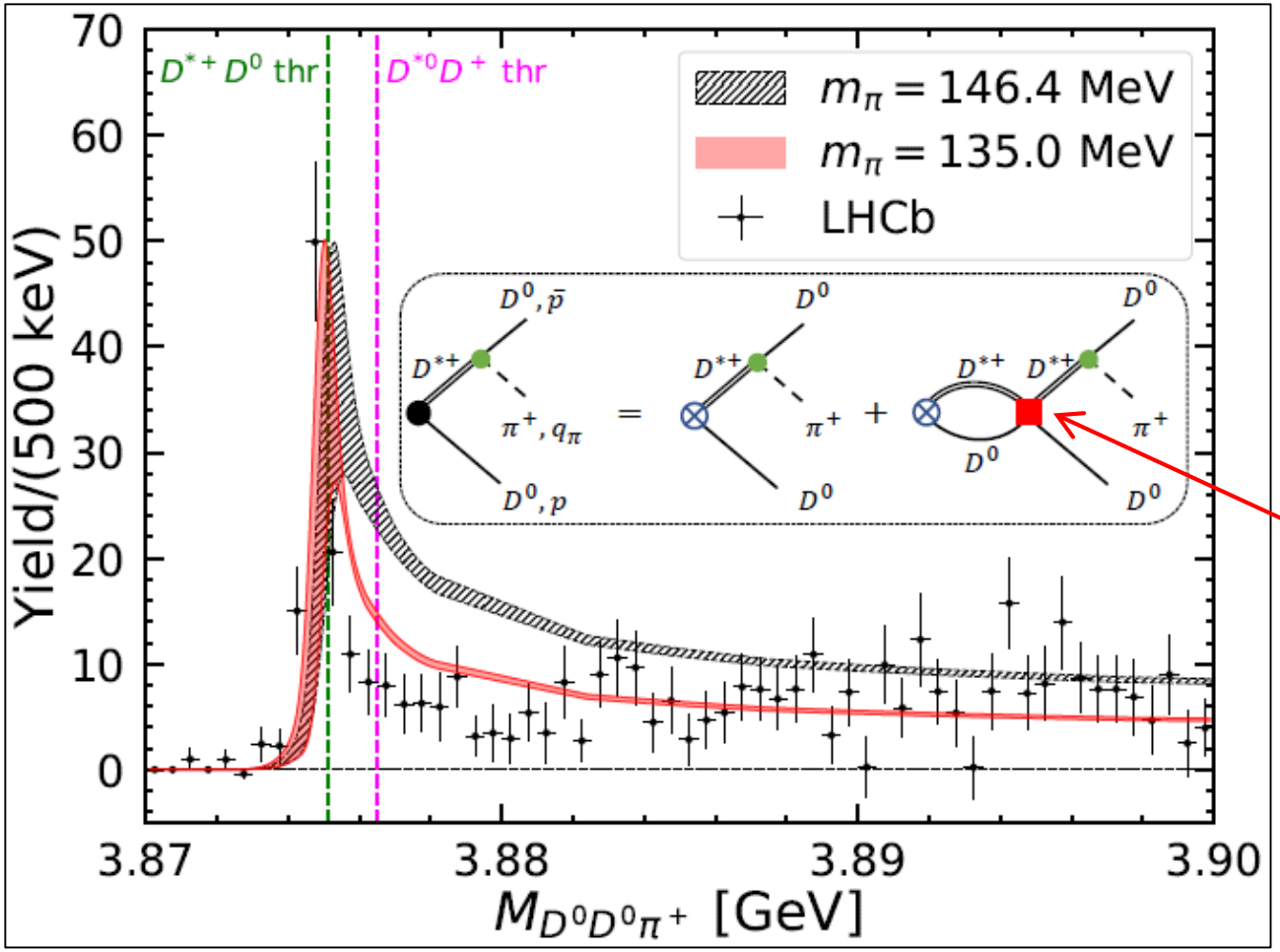
Quark mass dependence of $1/a_0$



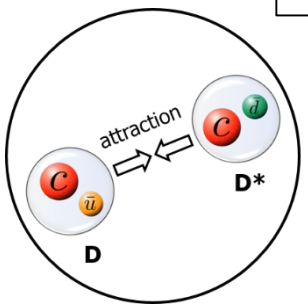
virtual state @ $m\pi$ = 146 MeV evolves to
a shallow bound state near unitarity @ $m\pi$ = 135 MeV

($m\pi$-dep w/ TPE form assumed)

Mass spectrum of $D^0D^0\pi^+$



LQCD potential



Tcc : ~ meson molecular like state of D-D*

Exploring hadron interactions in broader families

- N-Ω (=N-Ω_{sss}) interactions
  - Distinct quark flavor config, attractive at all distances

- N-Ω_{ccc} interactions

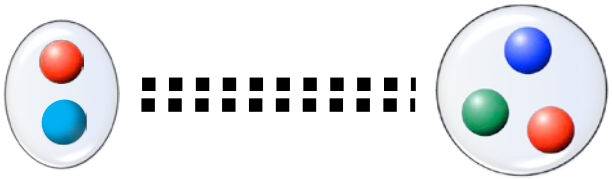
→ Talk by L. Zhang (T. Hatsuda)
(Nov.13, parallel-B)


L. Zhang

spin-dep can be examined ← NΩ_{ccc} is below $\Lambda_c\Xi_{cc}$, $\Sigma_c\Xi_{cc}$

(c.f. $\Lambda\Xi$, $\Sigma\Xi$ are open channels for NΩ)

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



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

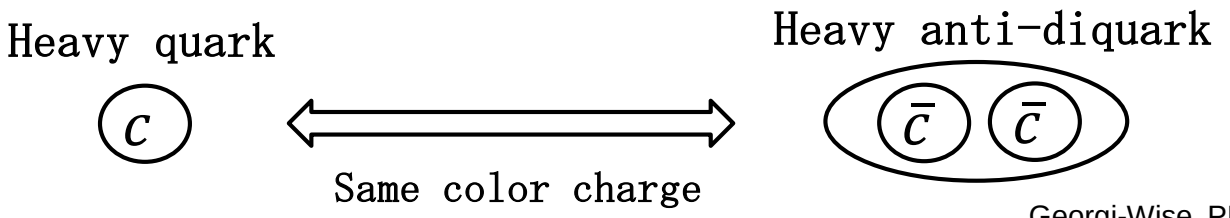
Vector meson mass shift in the medium

How color-dipole interacts w/ other hadrons?

Role of two-pion-exchange (TPE)

→ Talk by T. Hatsuda
(Nov.13, parallel-B)

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, PRD110(2024)074030

OBEP + superflavor sym → Bound state could exist

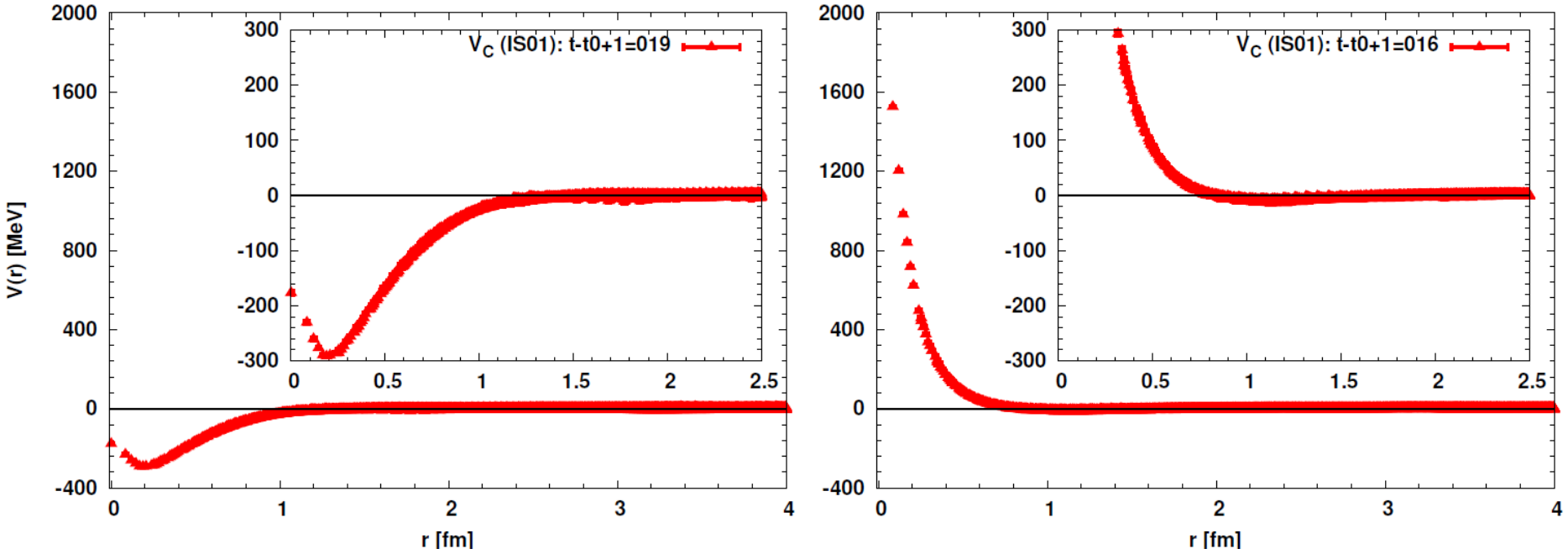
⟺ Hexaquark state? (Ξ_{cc}–Ξ_{cc})

(cc u) – (cc d)

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

Comparison of central potential in $^3SD_1$ channel

Ξ_{cc}—Ξ_{cc} Ξ_{ss}—Ξ_{ss} benchmark system



Completely different!

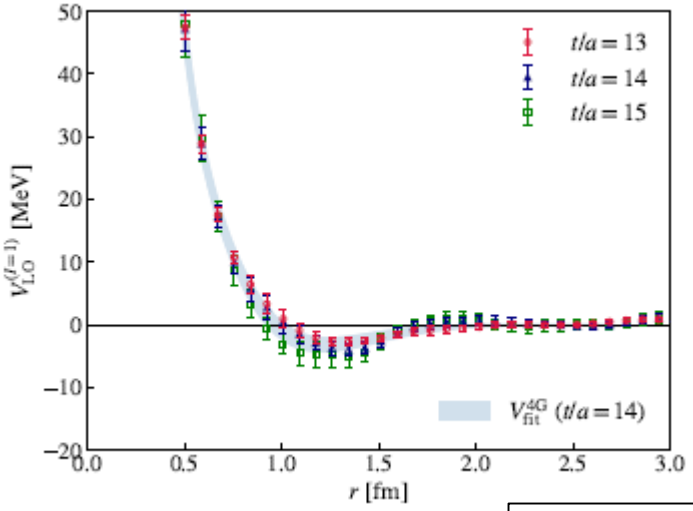
(N.B. There exists open channel, $\Lambda_c\Omega_{ccc}$, below $\Xi_{cc}\Xi_{cc}$ channel)

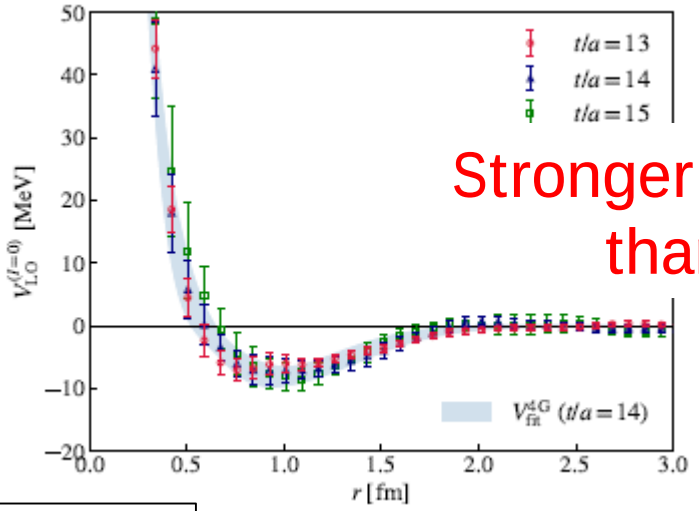
c.f. Talk on phen/HQS study by M. Sakai (Nov.13, parallel-B)

Dbar-N interactions

W. Yamada

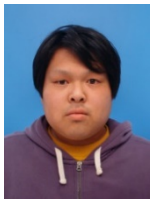
I = 1 **potentials** **I = 0**





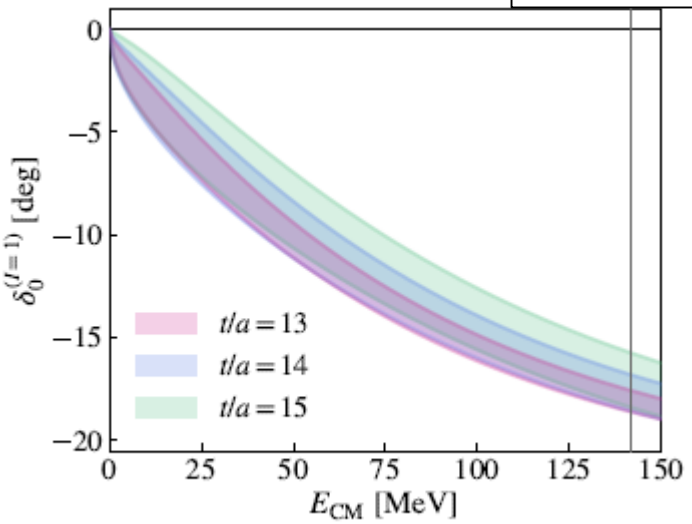
Stronger attraction than KN

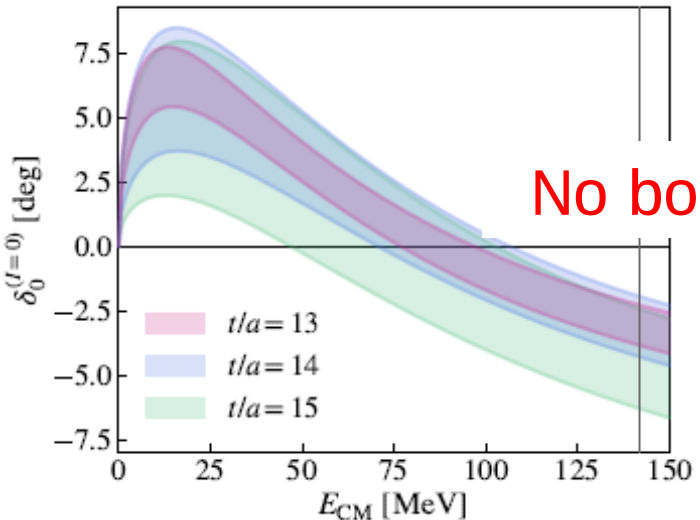
→ Talk on KN by K. Murakami (Nov.11, parallel-A)



K. Murakami

Phase shifts





No bound state

The challenge towards precise calc w/ light quark sector

- Signal/Noise issue

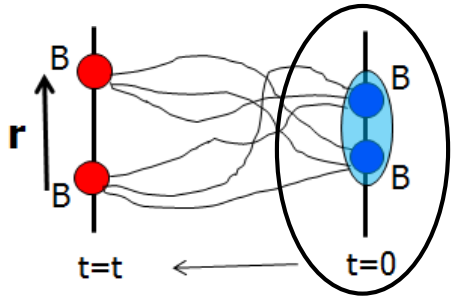
Parisi ('84), Lepage ('89)

$$\frac{\text{Signal}}{\text{Noise}} \rightarrow \exp[-\mathbf{A}(\mathbf{m_N} - \mathbf{3/2m_\pi})\mathbf{t}]$$

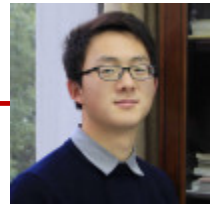
A: mass number

t: Euclidean time

- HAL QCD method
  - t >> 1/(elastic excitation energy) NOT required
  - t >> 1/(inelastic excitation energy) still required
- Optimized operator could cure the problem
  - If inelastic states are suppressed, we can take smaller t → exponential S/N improvement
  - This requires (multi-) hadron level optimization, while (simple) LQCD can make quark level optimization



New optimized (source) operators



Y. Lyu

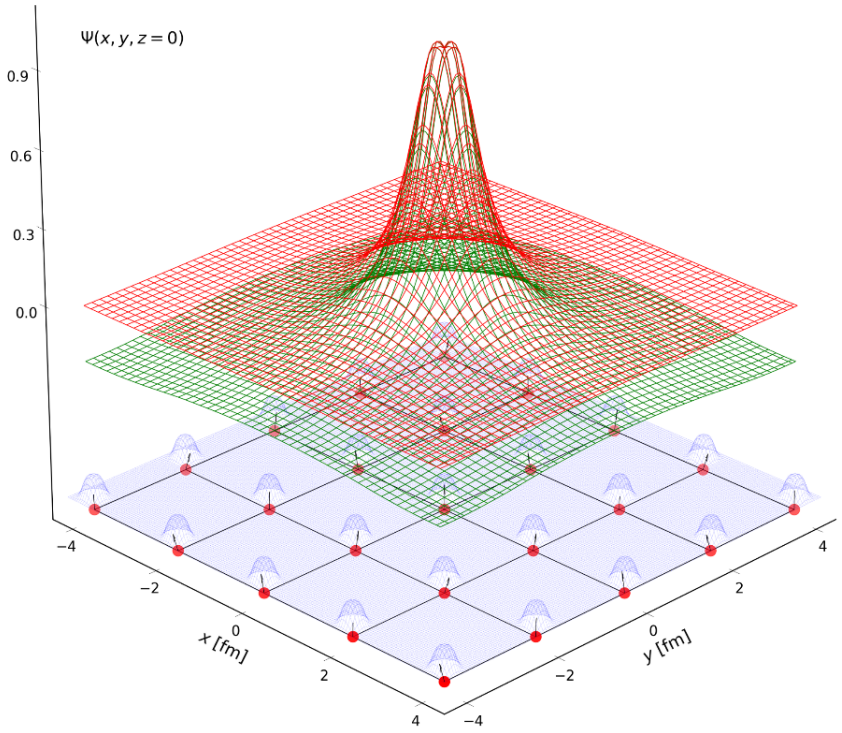
- In LQCD, quark propagators are calculated with given sources
  - Spatial index is contracted at source → challenging
  - Spatial index is open at sink → straightforward

1-hadron internal structure
2-hadron relative structure
can be optimized together

- Novel quark smearing techenique at the source

$$G(\vec{r}) = f(\vec{r})$$

$$F_n(\vec{r}) = \frac{1}{V_{\text{sub}}^{1/3}} \sum_{\vec{r}_0 \in \Lambda_{\text{sub}}} Z_3(\vec{r}_0)\Psi_n^{1/3}(\vec{r}_0) f(\vec{r} - \vec{r}_0)$$



- $f(\vec{r})$ fined tuned for single hadron
- Each point is weighted by $\Psi_n^{-1/3}(\vec{r}_0)$
- Z_3 noise variable ensures no mixing terms

$$G^3 F_n^3 \Rightarrow \frac{1}{V_{\text{sub}}} \bar{\hat{B}}(\vec{0}) \sum_{\vec{r}_0 \in \Lambda_{\text{sub}}} \Psi_n(\vec{r}_0) \bar{\hat{B}}(\vec{r}_0)$$

$$\simeq \frac{1}{V} \bar{\hat{B}}(\vec{0}) \sum_{\vec{r}_0 \in \Lambda} \Psi_n(\vec{r}_0) \bar{\hat{B}}(\vec{r}_0)$$

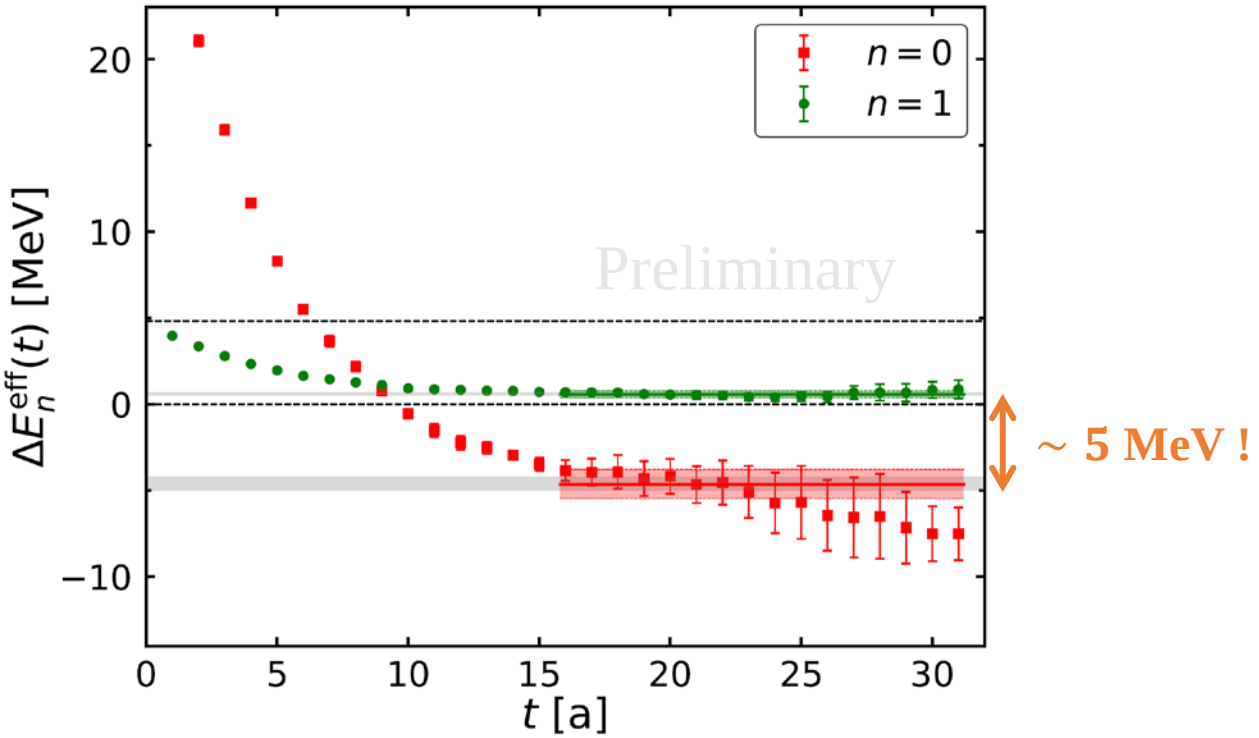
Y. Lyu+, arXiv:2507.09930, 2507.09933

Benchmark w/ $\Omega_{ccc}\Omega_{ccc}$: Effective energies

- The ground/first excited state energy derived from

$$R_0(t) = \langle \hat{O}_0(t)\hat{O}_0^\dagger(0)\rangle = \sum_{\vec{r}\in\Lambda} \Psi_0(\vec{r}) R_0(\vec{r},t)$$

$$R_1(t) = \langle \hat{O}_1(t)\hat{O}_1^\dagger(0)\rangle = \sum_{\vec{r}\in\Lambda} \Psi_1(\vec{r}) R_1(\vec{r},t)$$

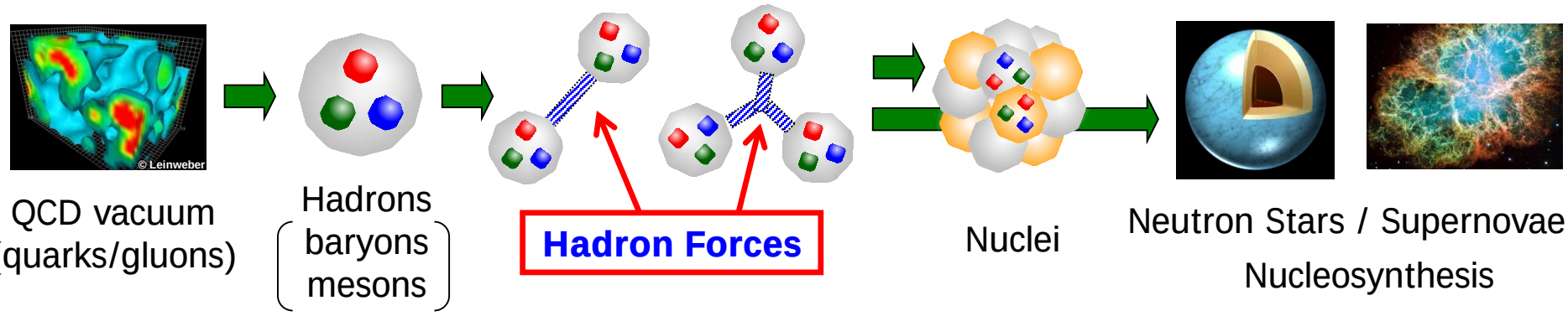


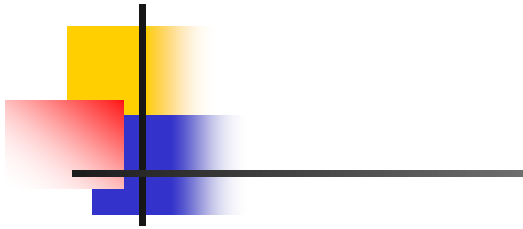
- Spectra identification is achieved for states with energy gap ~5 MeV
- Spectra are consistent with the engine values (gray bands) from the potential
- Without $\hat{O}_{0,1}$, it would require $t > 1000\ [a](90\text{ fm})$ to archive $e^{-\Delta E t} < 10\%$

Summary

- The 1st LQCD for Hadron Interactions
  near and on the physical quark mass point by Fugaku
  - Various hadron interactions w/ strange, charm dof
  - Interactions relevant to exotics
  - LQCD meets experiments
    - Femtoscopy, Scatterings, Hypernuclei

- Future
  - New optimized operator method could bring significant improvement
  - Interactions w/ bottom, (general) exotics, 3-body forces





Backup Slides

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

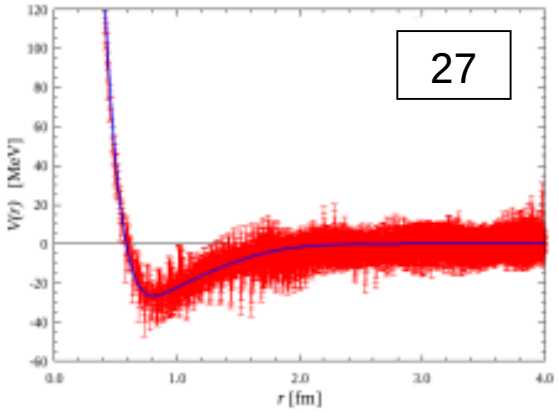
8 X 8 = 27 + 8s + 1 + 10* + 10 + 8a

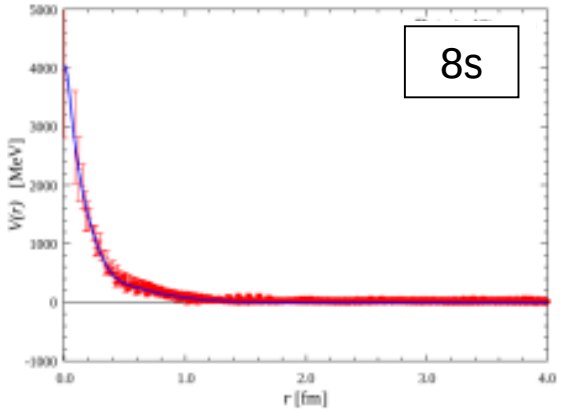
T.Inoue (HAL), AIP Conf. Proc. 2130 (2019) 020002

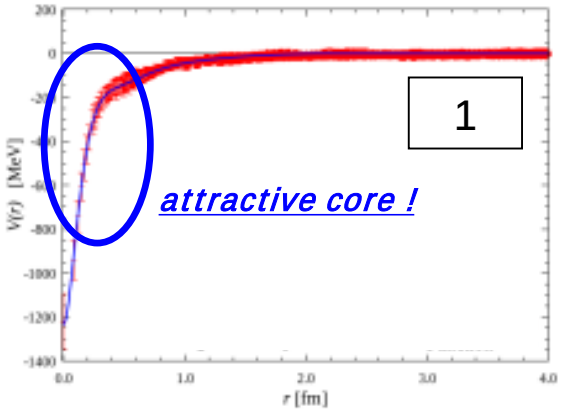
m_π=146MeV

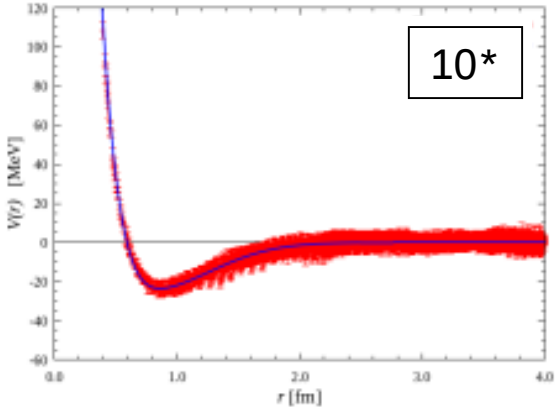
$^1S_0$

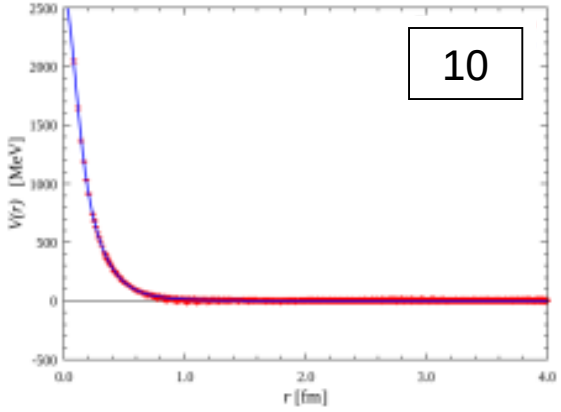
$^3S_1 - ^3D_1$

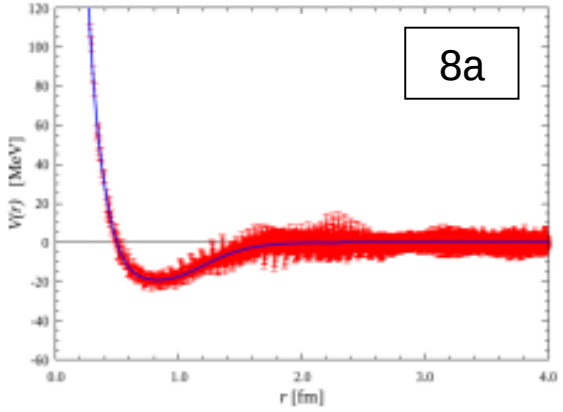












27,10*:
NN-type

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