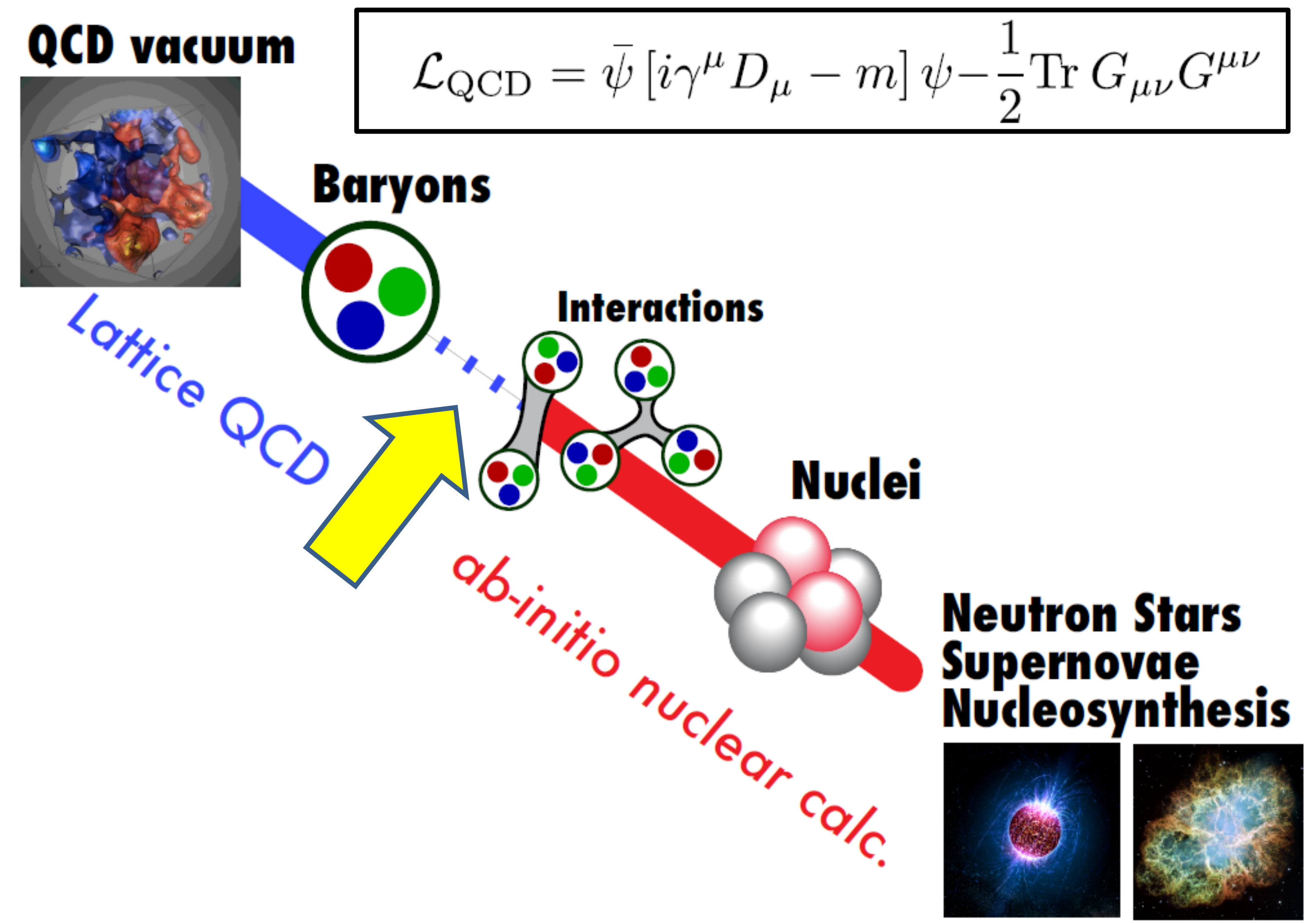
The Most Strange Dibaryon from Lattice QCD

Tetsuo Hatsuda (iTHEMS, RIKEN)

$$\mathcal{L}_{\rm QCD} = \bar{\psi}\left[i\gamma^{\mu}D_{\mu} - m\right]\psi - \frac{1}{2}{\rm Tr}\, G_{\mu\nu}G^{\mu\nu}$$



新学術WS@TIT, Nov.20, 2018

iTHEMS https://ithems.riken.jp

Quantum Chromodynamics (QCD)

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}\gamma^\mu (i\partial_\mu - g t^a A^a_\mu) q - m\bar{q}q$$

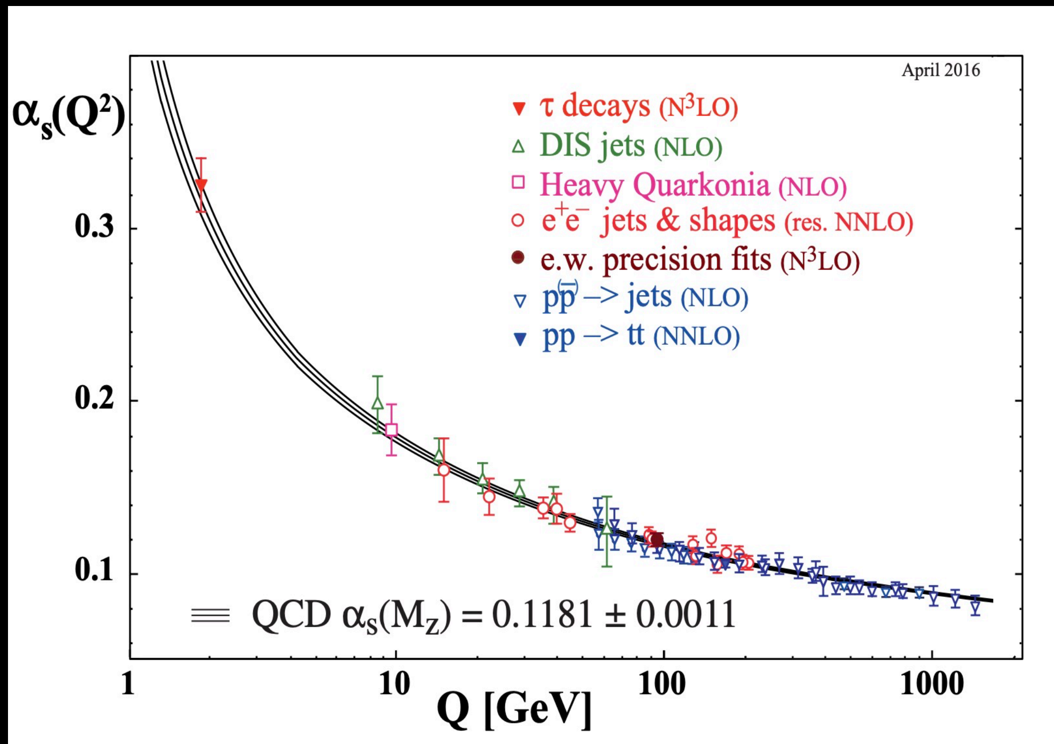
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f_{abc} A^b_\mu A^c_\nu$$

Quark Masses

quark masses (from lattice QCD)	**[MeV]** (MS-bar @ 2GeV)
m_u	2.16 (9)(7)
m_d	4.68 (14)(7)
m_s	92.0(2.1)

FLAG Coll.(2016) http://flag.unibe.ch/

Gauge Coupling

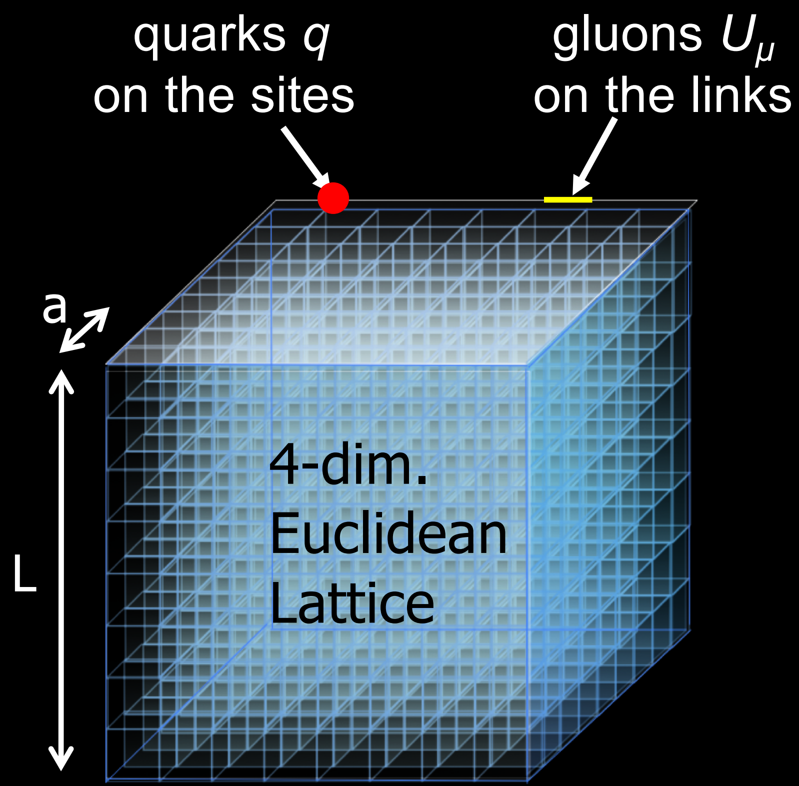


PDG (2018) http://pdg.lbl.gov/

Lattice QCD

Lattice QCD (LQCD)

$$Z = \int [dU][dqd\bar{q}] \ \exp\left[-\int d\tau d^3x \mathcal{L}_{\mathrm{E}}\right]$$



Huge integration variables
~ $10^{9\text{-}10}$ for 96^4 lattice

Importance Sampling

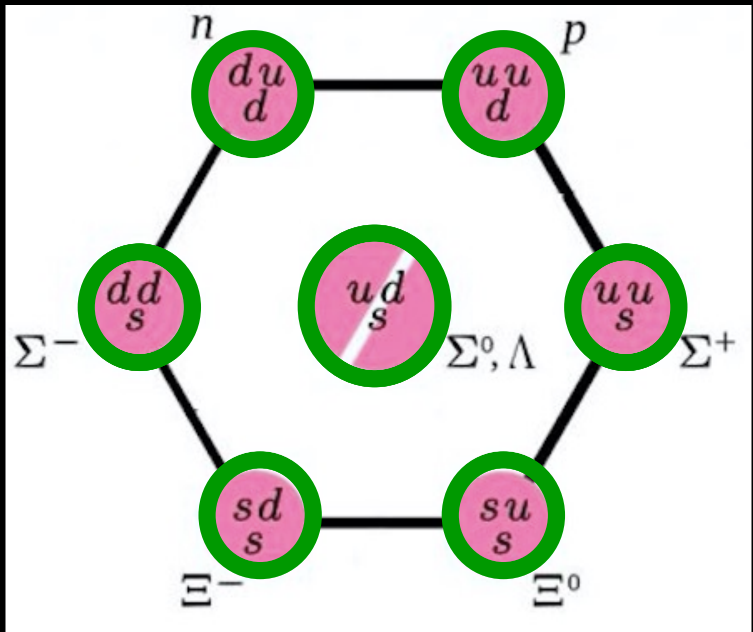
Hybrid MC = MD + Metropolis

Continuum & Thermodynamic Limits

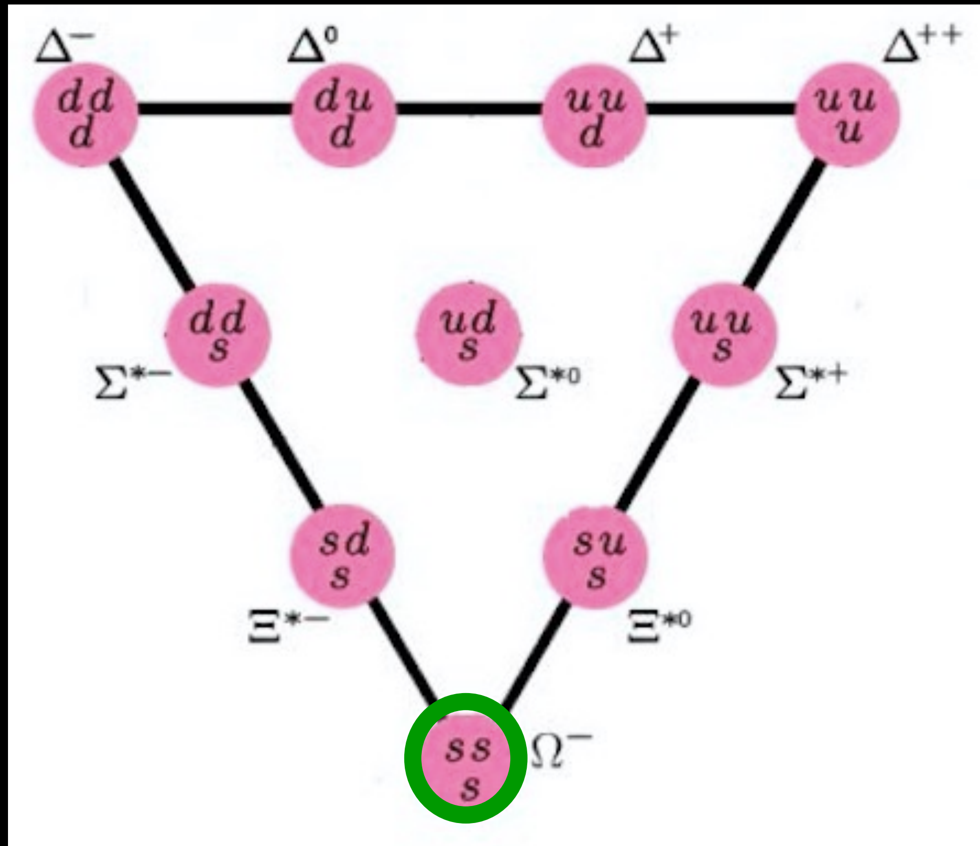
$(a \to 0 \ \& \ L \to \infty)$

B=1 system : SU(3)$_F$ classification

8 (Octet)

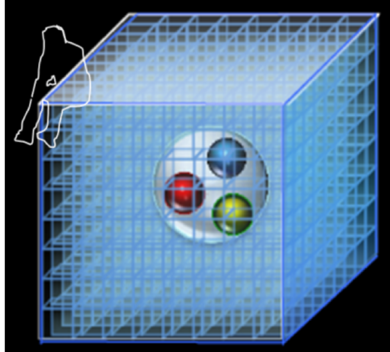


10 (Decuplet)



Ω^- (1672)
Weak decay (→ΛK, Ξπ)
Mean Life ~ 0.8 x 10^{-10} sec

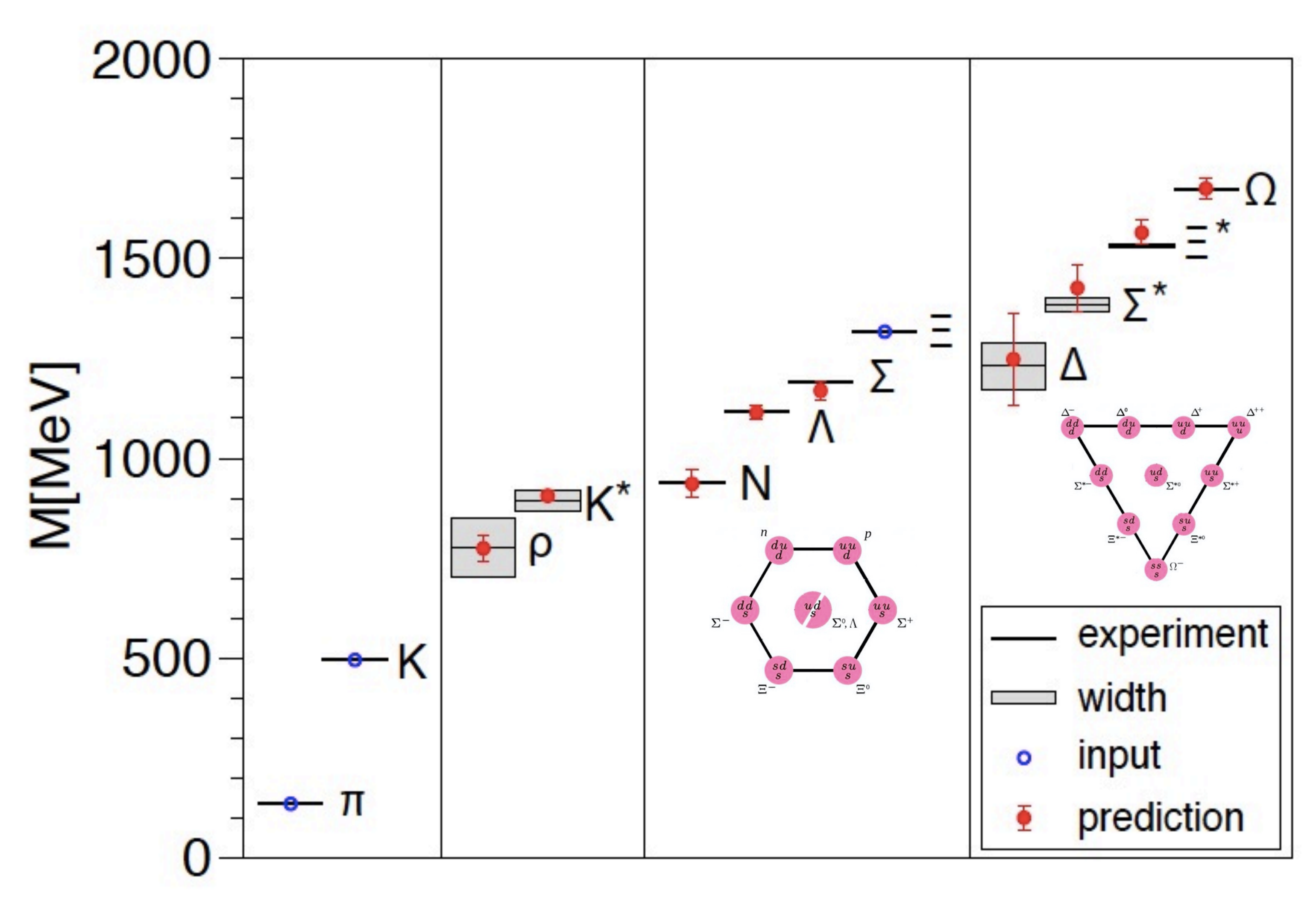
Hadron masses from LQCD



a_{min} = 0.065 fm

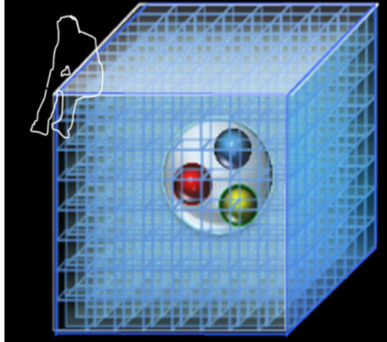
L_{max} = 4.1 fm

$m_{\pi,min}$ =190 MeV



Fodor and Hoelbling, Rev. Mod. Phys. 84 (2012) 449

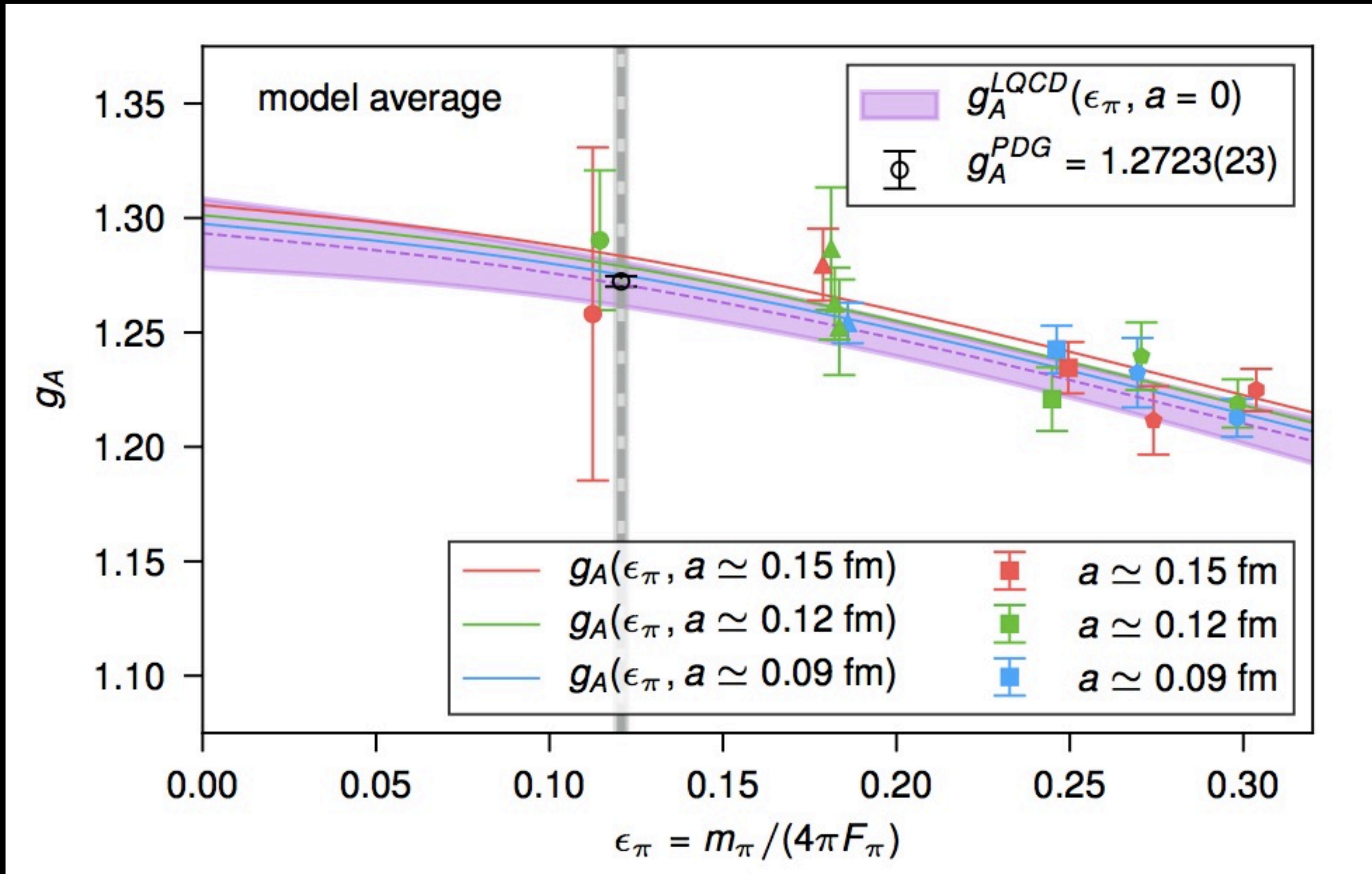
Nucleon axial charge (g_A) from LQCD



a_{min} = 0.09 fm

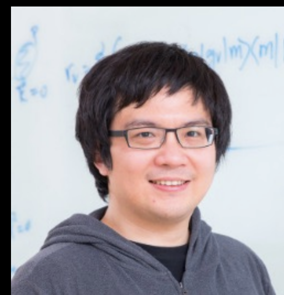
L_{max} = 4.8 fm

$m_{\pi,min}$ =131 MeV



$$(g_A)_{lat} = 1.2711(13)$$
$$(g_A)_{exp} = 1.2723(23)$$

Chang (iTHEMS/LBNL)+, Nature 558 (2018) 91



C. C. Chang

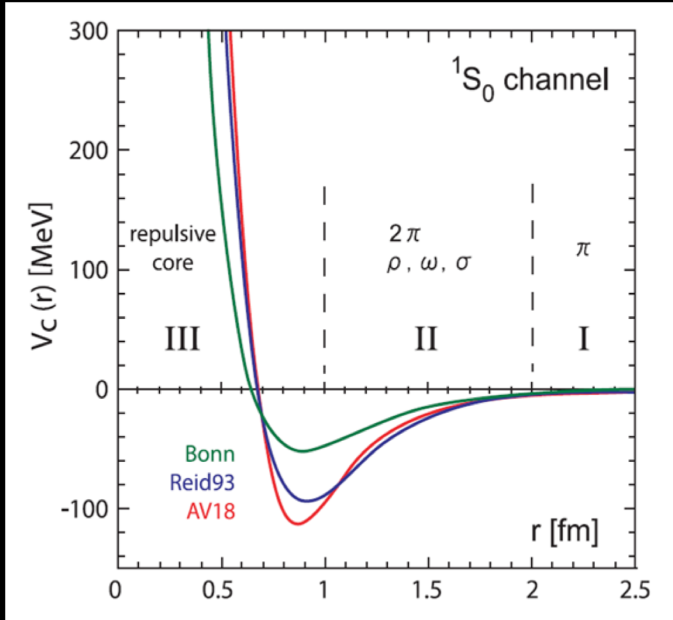
Baryon Interactions

Baryon interactions from lattice QCD

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

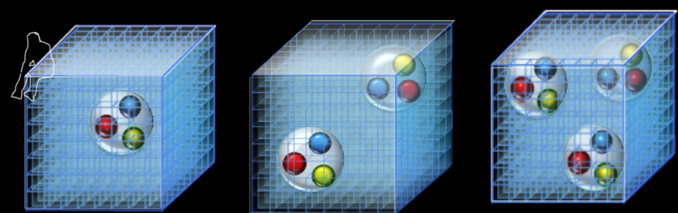
phenomenological NN interactions	# of parameters
CD Bonn (p space)	38
AV18 (r space)	40
EFT in N^{3}LO (nπ+contact)	24

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



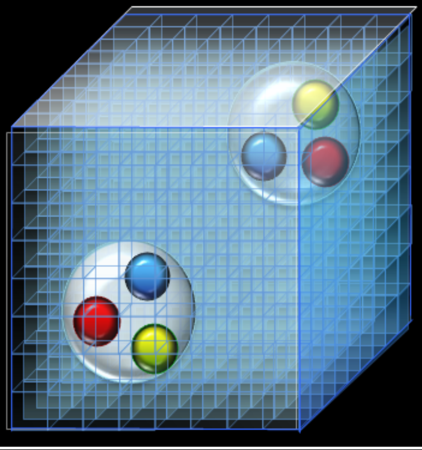
- NNN, YN, YY : data limited
- YYN, YNN, YYY : data very limited

Low energy QCD has only 4 parameters (g, $m_{u,d,s}$)



Baryon interactions from LQCD
almost at physical point
(HAL QCD Collaboration)

Hadrons to Atomic nuclei
HAL
from Lattice QCD



$a = 0.085$ fm

$L = 8.1$ fm

$m_\pi = 146$ MeV

$M_K = 525$ MeV

HAL (Hadrons to Atomic nuclei from Lattice) QCD Collaboration

S. Aoki *(YITP)*	**T. Doi** *(RIKEN)*	**F. Etminan** *(Birjand U.)*	**S. Gongyo** *(RIKEN)*	**T. Hatsuda** *(RIKEN)*
Y. Ikeda *(RCNP)*	**T. Inoue** *(Nihon U.)*	**N. Ishii** *(RCNP)*	**T. Iritani** *(RIKEN)*	**D. Kawai** *(YITP)*
T. Miyamoto *(YITP)*	**K. Murano** *(RCNP)*	**H. Nemura** *(RCNP)*	**T. Aoyama** *(YITP)*	**T.M. Doi** *(RIKEN)*

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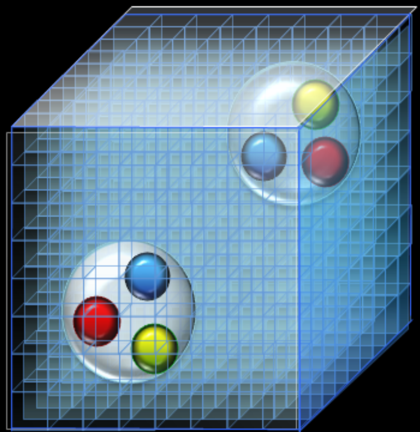

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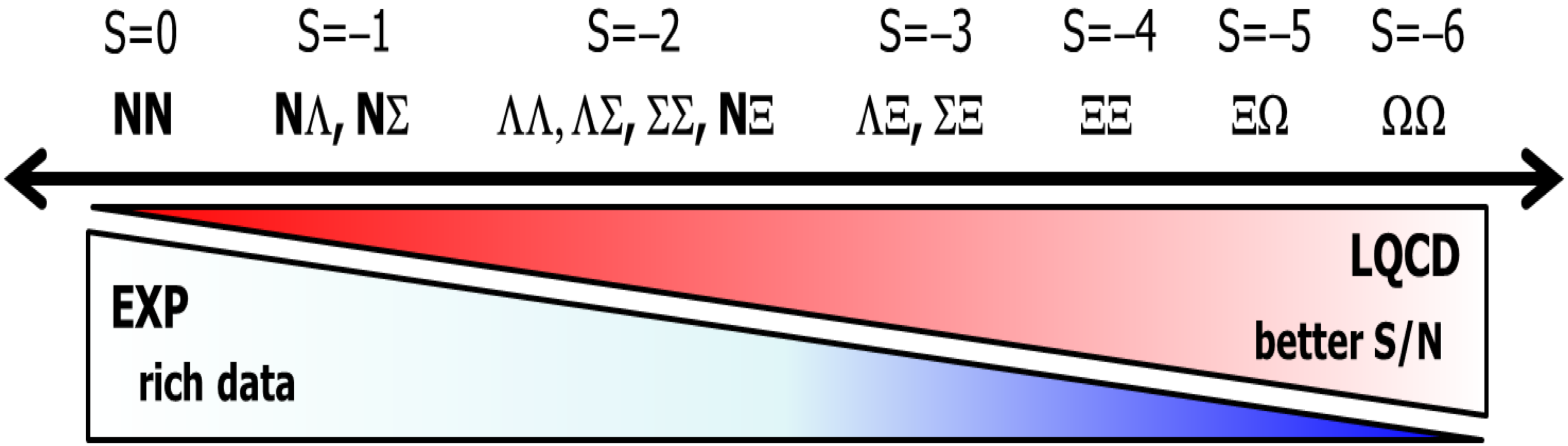
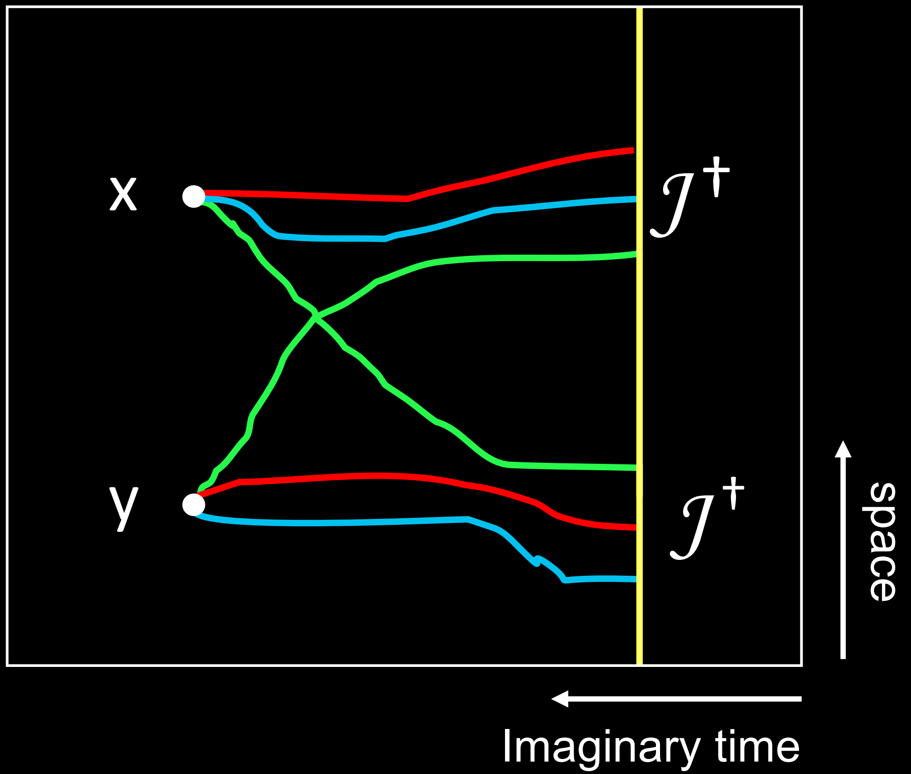


Scattering problem in LQCD



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

HAL QCD Method

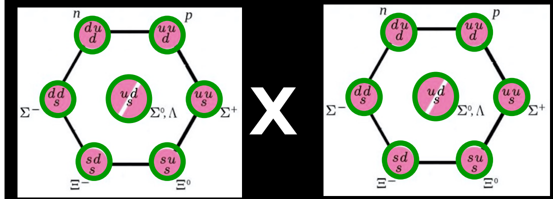
ϕ(r,t) → 2PI kernel (T=U+GUT) → phase shift, binding energy

Ishii, Aoki & Hatsuda, PRL 99 (2007) 022001
Ishii+ [HAL QCD Coll.], PLB 712 (2012) 437

Results of
Physical Point Simulations
and
Their Applications

B=2 system : $SU(3)_F$ classification

c.f. M. Oka, Phys. Rev. D38 (1988)
A. Gal, arXiv:1511.06605 [nucl-th]

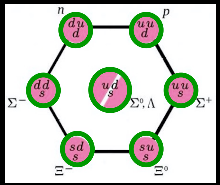


$$8 \times 8 = 27 + 8_s + 1 + 10^* + 10 + 8_a$$

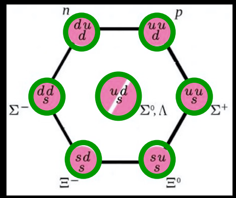
NN($^1S_0$) → 27

$H_{\Lambda\Lambda-N\Xi-\Lambda\Sigma}$ ($^1S_0$) → 1
Jaffe (1977)

NN($^3S_1$) → 10*



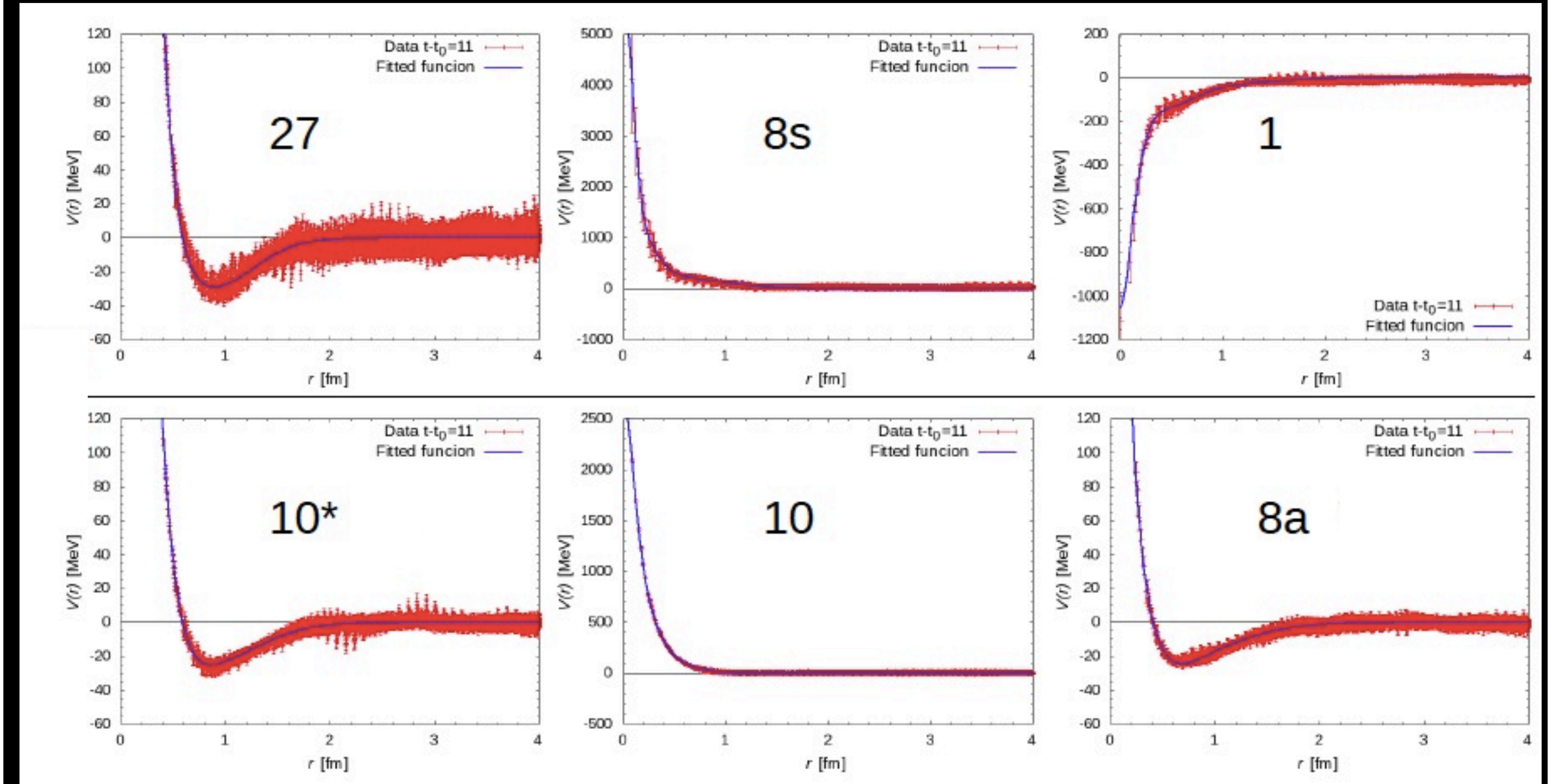
x

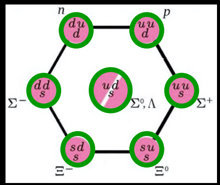
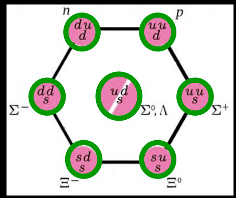


T. Inoue+ [HAL QCD Coll.], arXiv:1809.08932 [hep-lat]

T. Inoue

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




x


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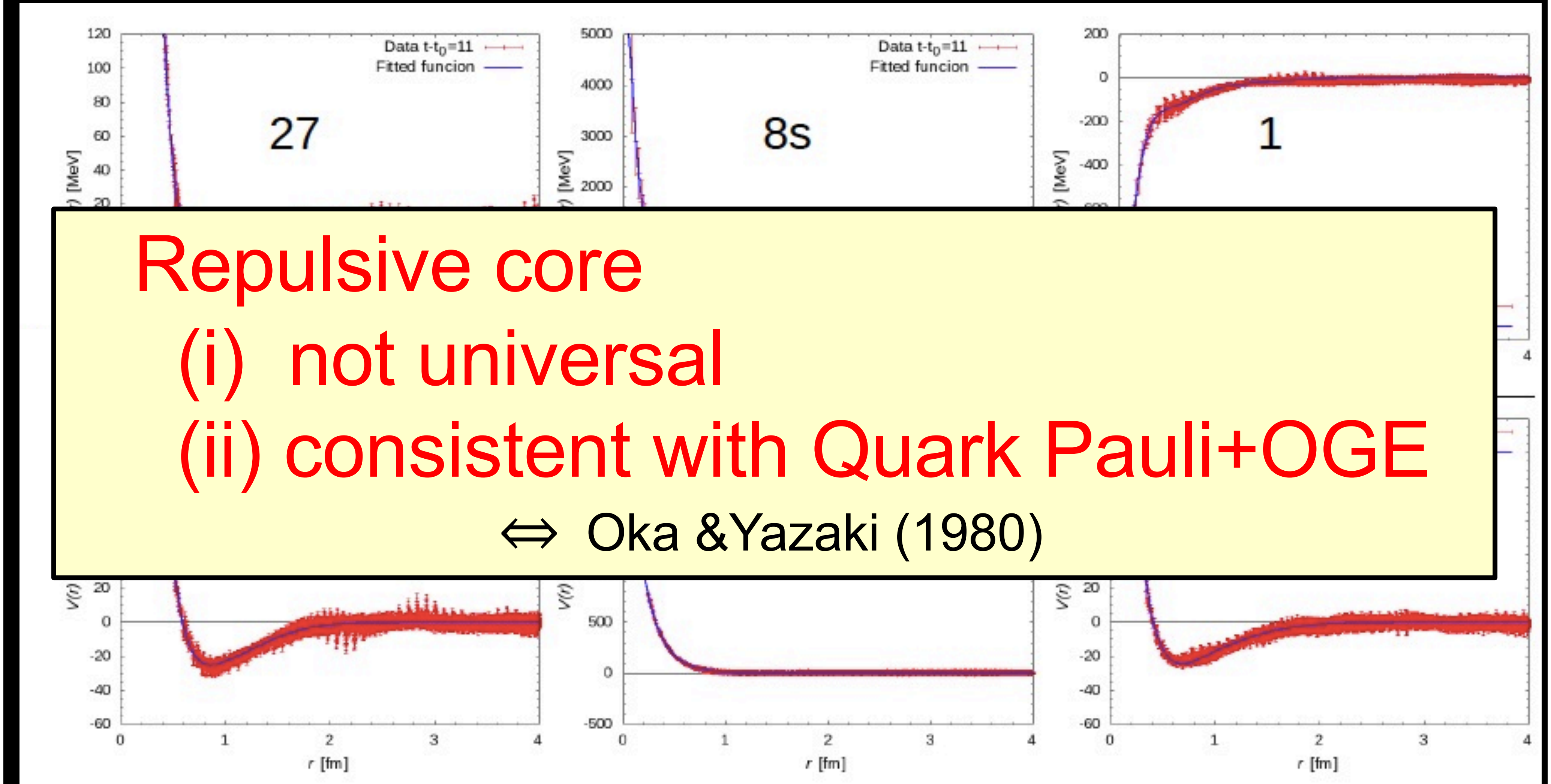


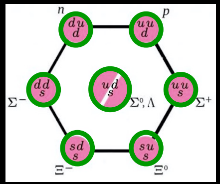
Repulsive core

(i) not universal

(ii) consistent with Quark Pauli+OGE

⇔ Oka &Yazaki (1980)

T. Inoue+ [HAL QCD Coll.], arXiv:1809.08932 [hep-lat]



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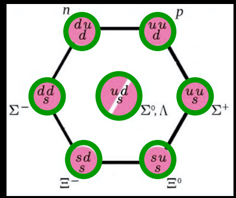

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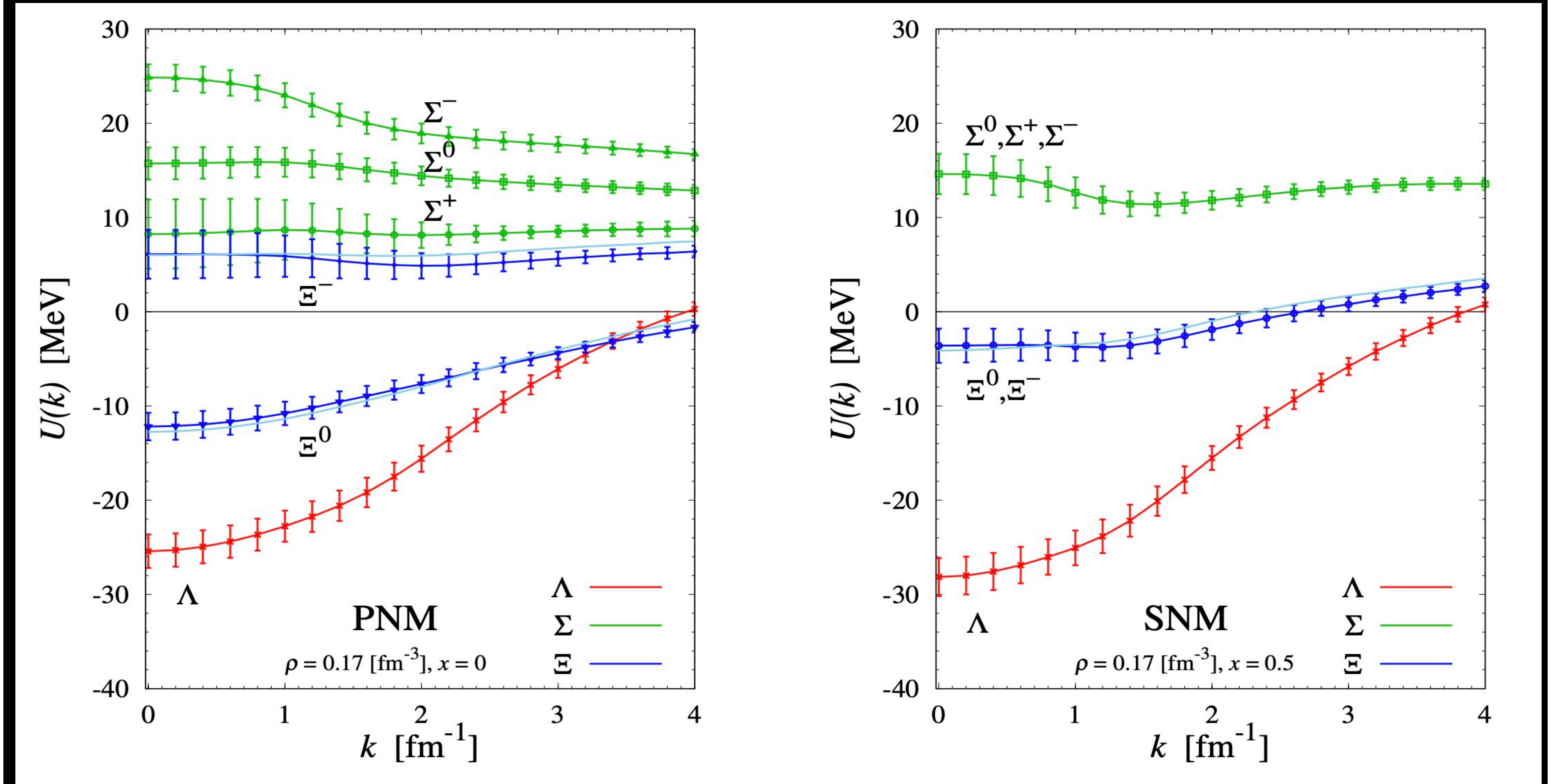
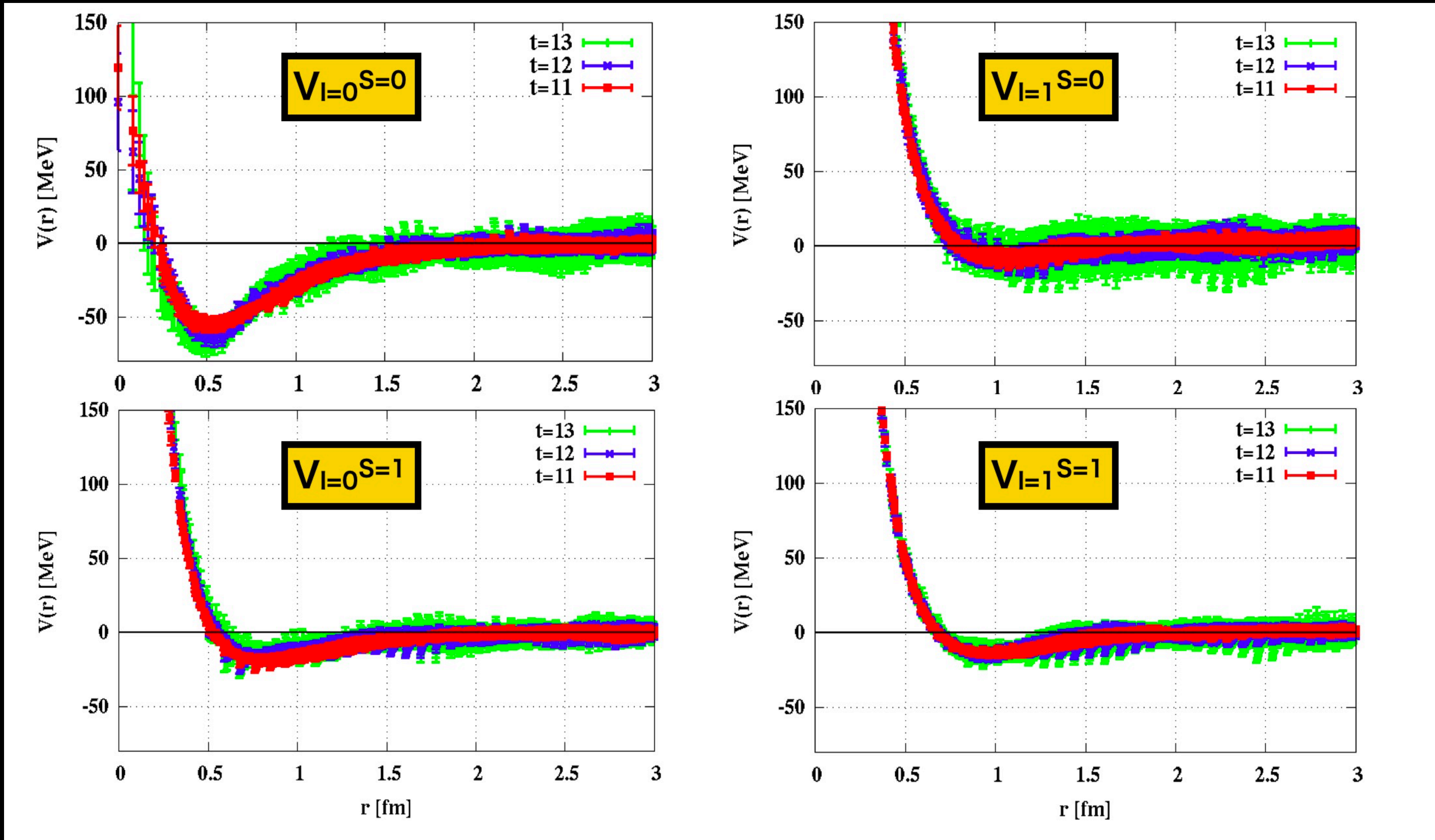


<u>NΞ interaction</u> $V_I^S(r)$
-- spin-Isospin dependence --

K. Sasaki+
[HAL QCD Coll.]
in preparation

K. Sasaki



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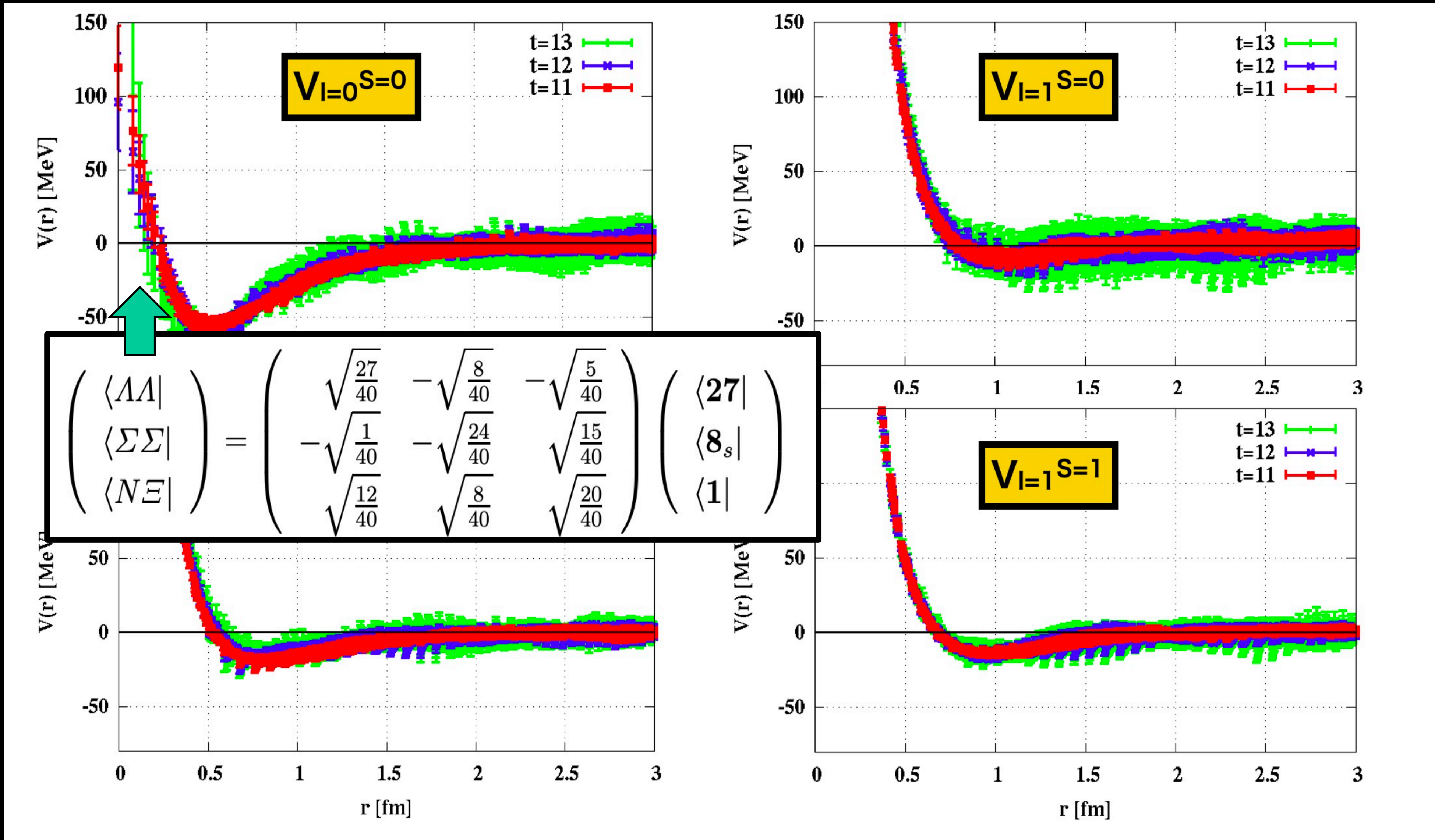

$$\begin{pmatrix} \langle \Lambda\Lambda | \\ \langle \Sigma\Sigma | \\ \langle N\Xi | \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{27}{40}} & -\sqrt{\frac{8}{40}} & -\sqrt{\frac{5}{40}} \\ -\sqrt{\frac{1}{40}} & -\sqrt{\frac{24}{40}} & \sqrt{\frac{15}{40}} \\ \sqrt{\frac{12}{40}} & \sqrt{\frac{8}{40}}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

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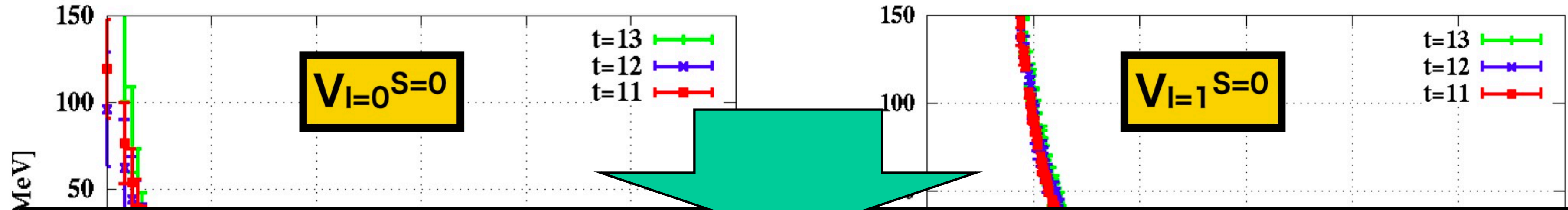
K. Sasaki+
[HAL QCD Coll.]
in preparation

K. Sasaki



H dibaryon around NΞ threshold
by Sasaki and Miyamoto

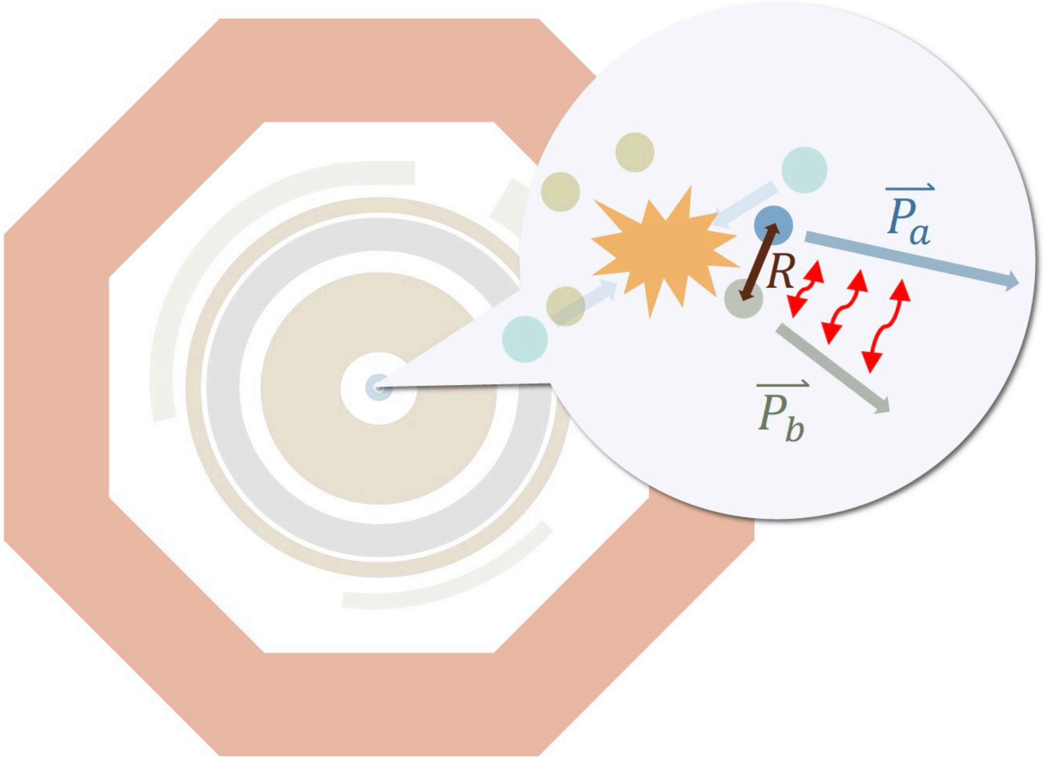
ΛΛ and NΞ correlations in p+p, p+Pb collisions
at LHC (ALICE Coll.)

Hypernuclei e.g. NNΞ and NNNΞ
by Hiyama+ in progress

Femtoscopy

$$C(k) = \int S(\vec{r},k)|\psi(\vec{r},k)|^2 \, d\vec{r}$$

The ALICE data sets



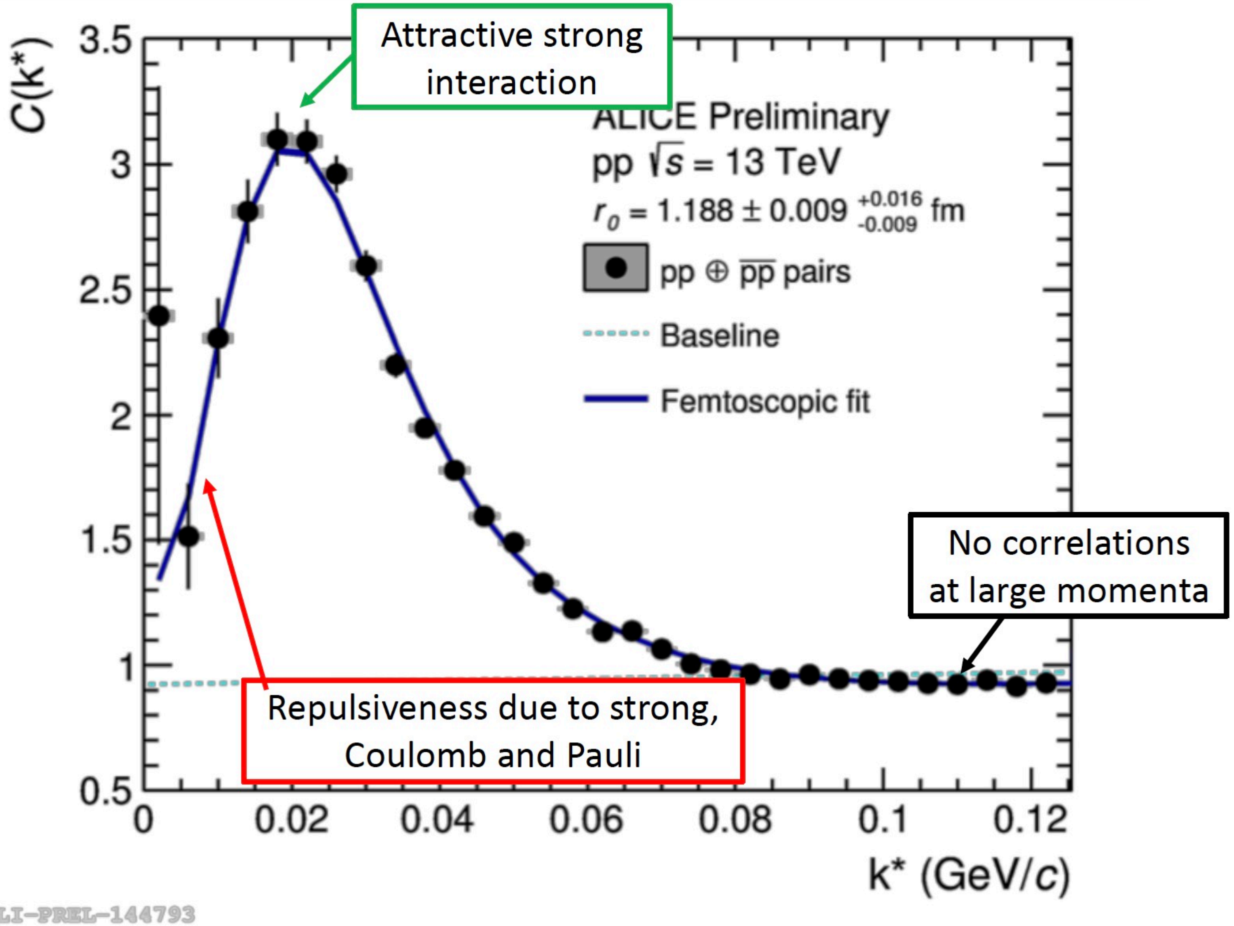
- We measure **p-p**, **p-Λ**, **Λ-Λ**, **p-Ξ**, **p-K**
- Proton identification with TPC and TOF
- Reconstruction of hyperons
  - $\Lambda \rightarrow p\pi^-$ (BR ~ 64%)
  - $\Xi^- \rightarrow \Lambda\pi^-$ (BR ~ 100%)
- Datasets:
  - **pp 7 TeV: 3.4·10^8 Events**
  - **pp 13 TeV: 10·10^8 Events**
  - **p-Pb 5.02 TeV: 6.0·10^8 Events**

Femtoscopy

$$C(k) = \int S(\vec{r}, k) |\psi(\vec{r}, k)|^2 \, d\vec{r}$$

Correlation function and Interactions

$C(k^*) \longrightarrow$
- > 1 attraction
- $= 1$ no interaction
- < 1 repulsion

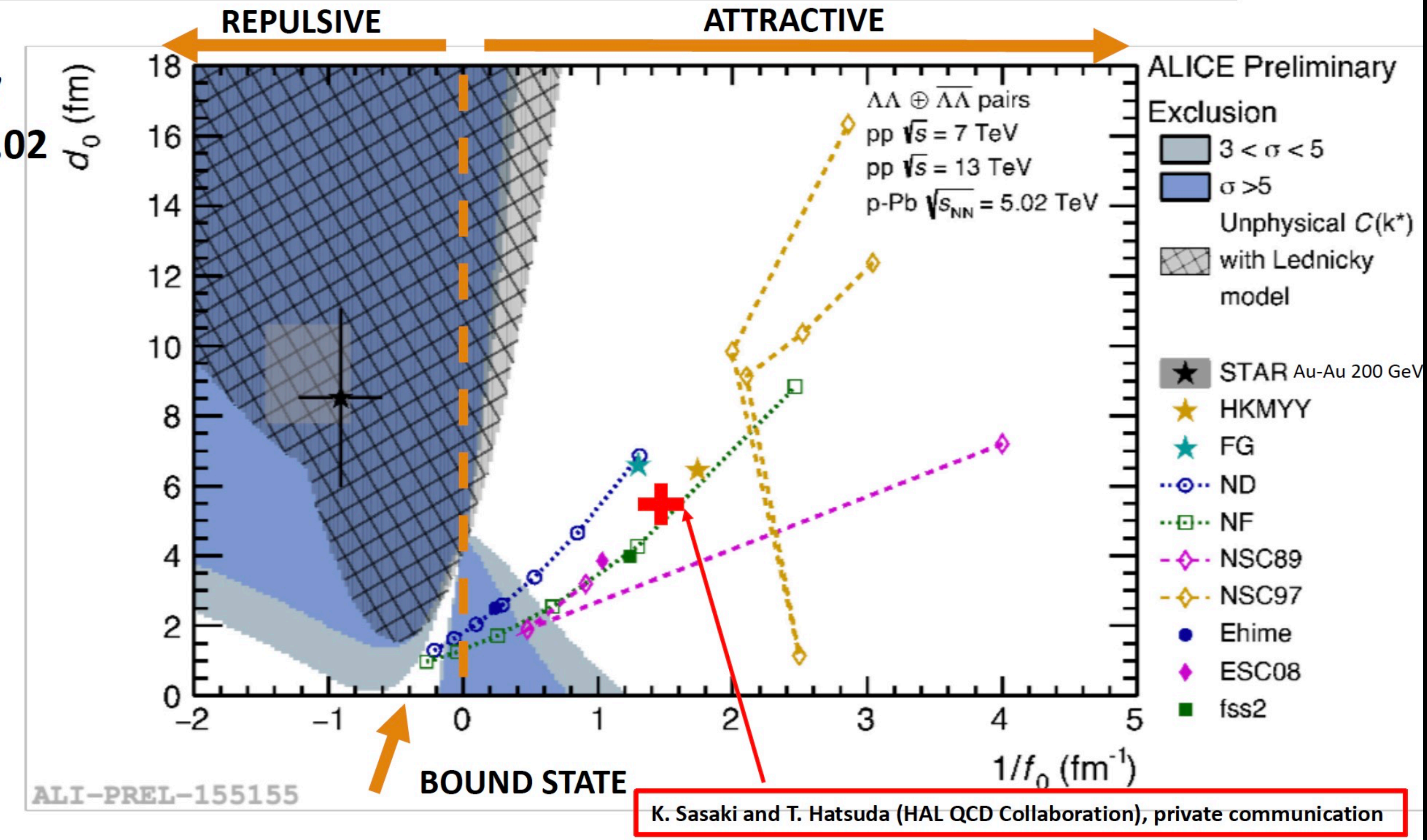


Femtoscopy

$$C(k) = \int S(\vec{r},k)\,|\psi(\vec{r},k)|^2\, d\vec{r}$$

Λ–Λ Correlations: Combined Exclusion Plot

- Combination of all available datasets: **pp 7 TeV, pp 13 TeV, p-Pb 5.02 TeV**
- **Full scan** of scattering parameters space with the **Lednicky model**
- Test of the **agreement between data and the prediction by the Lednicky model by nσ**



(STAR data: STAR coll. Phys.Rev.Lett. 114 (2015) no.2,022301)

Femtoscopy

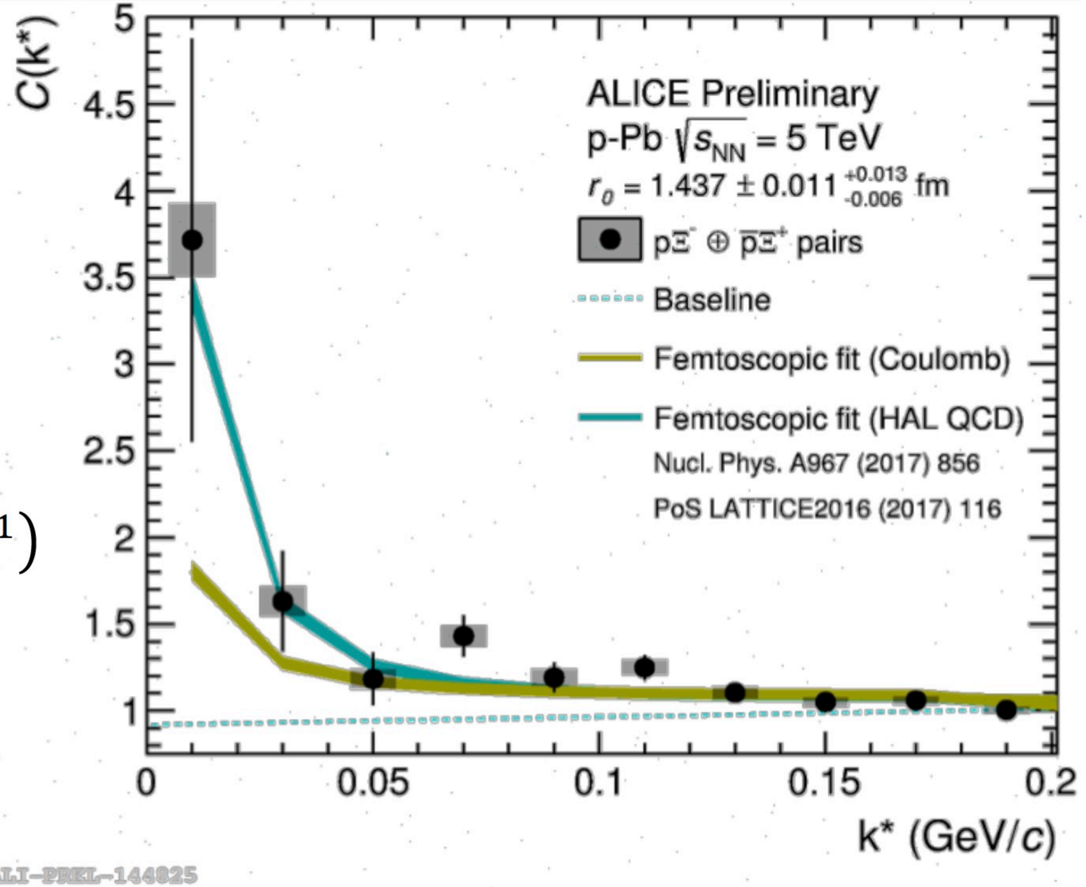
$$C(k) = \int S(\vec{r},k)\,|\psi(\vec{r},k)|^2\, d\vec{r}$$

p-Ξ^- Correlation Function in p-Pb 5.02 TeV

- **<u>First observation of strong attractive interaction in p-Ξ^-</u>**
- modeled with preliminary QCD strong potential by the HAL QCD collaboration
  Potential from Hatsuda et al., NPA967 (2017) 856, PoS Lattice2016 (2017) 116

$$C(k^*) = \frac{1}{8}\left(C_{I=0}^{S=0} + C_{I=1}^{S=0}\right) + \frac{3}{8}\left(C_{I=0}^{S=1} + C_{I=1}^{S=1}\right)$$

COULOMB-ONLY HYPHOTESIS EXCLUDED AROUND 3σ



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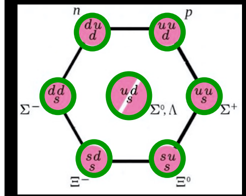
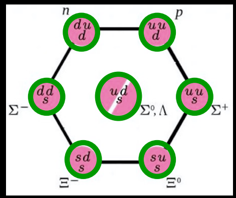
 x 

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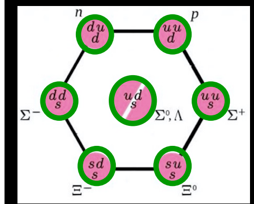
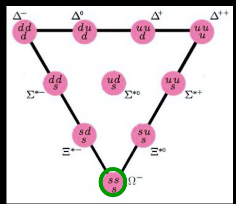
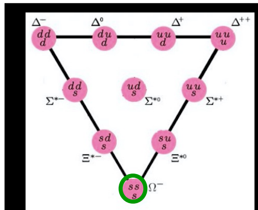
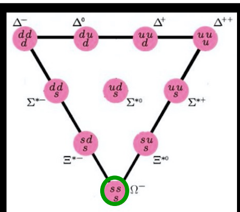
 x 

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

$N\Omega\ (^5S_2)$ → 8
Goldman+ (1987)
Oka (1988)

 x 

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

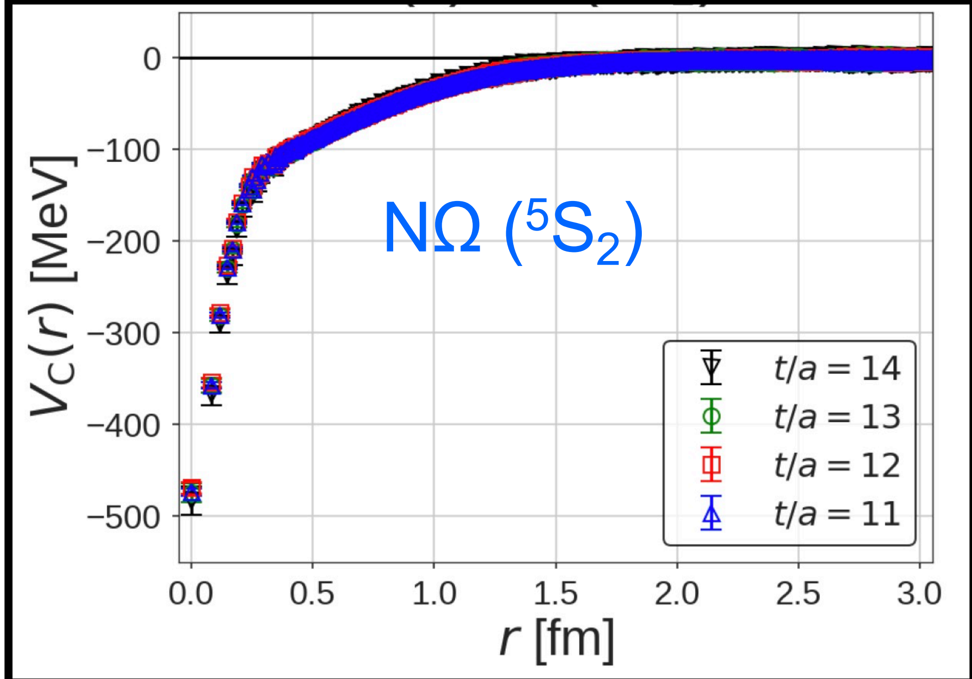
Kopeliovich+ (1990)
$\Omega\Omega(^1S_0)$ → 28

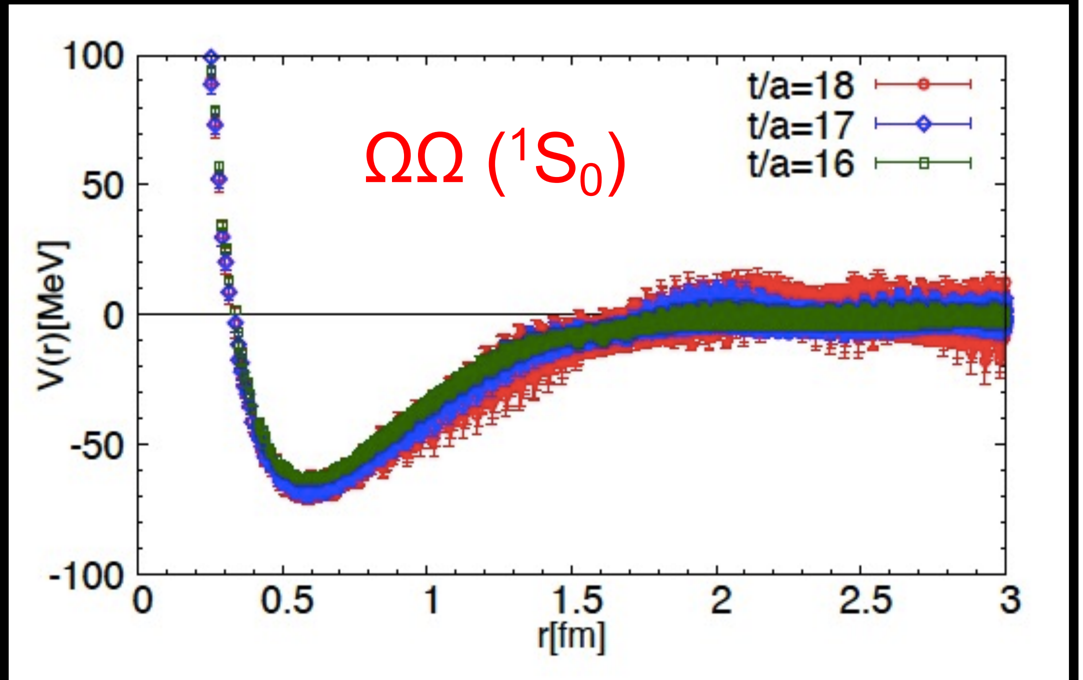
$\Delta\Delta(^7S_3)$ → 10*
Dyson+ (1964)
Oka & Yazaki (1980)

S=-3 system (8-plet)

S=-6 system (28-plet)

Both Pauli allowed





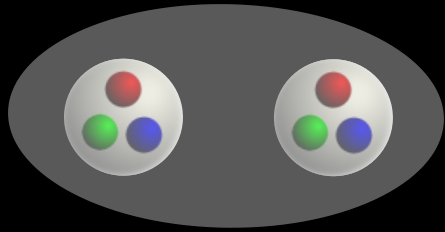
T. Iritani

Iritani+ [HAL QCD Coll.],
arXiv:1810.03416 [hep-lat]

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

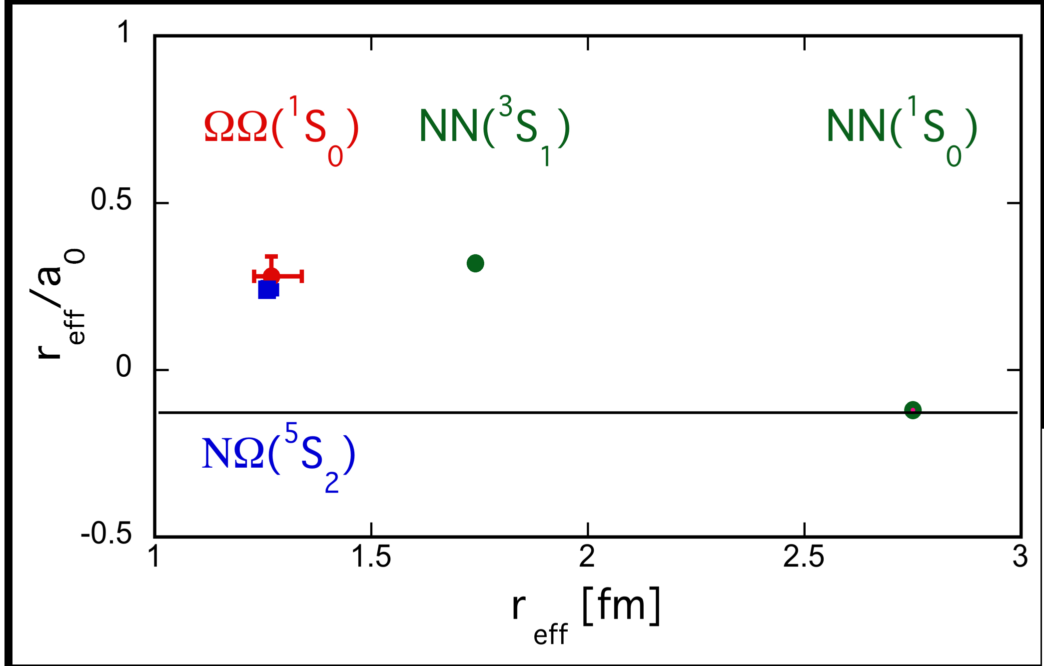
S. Gongyo

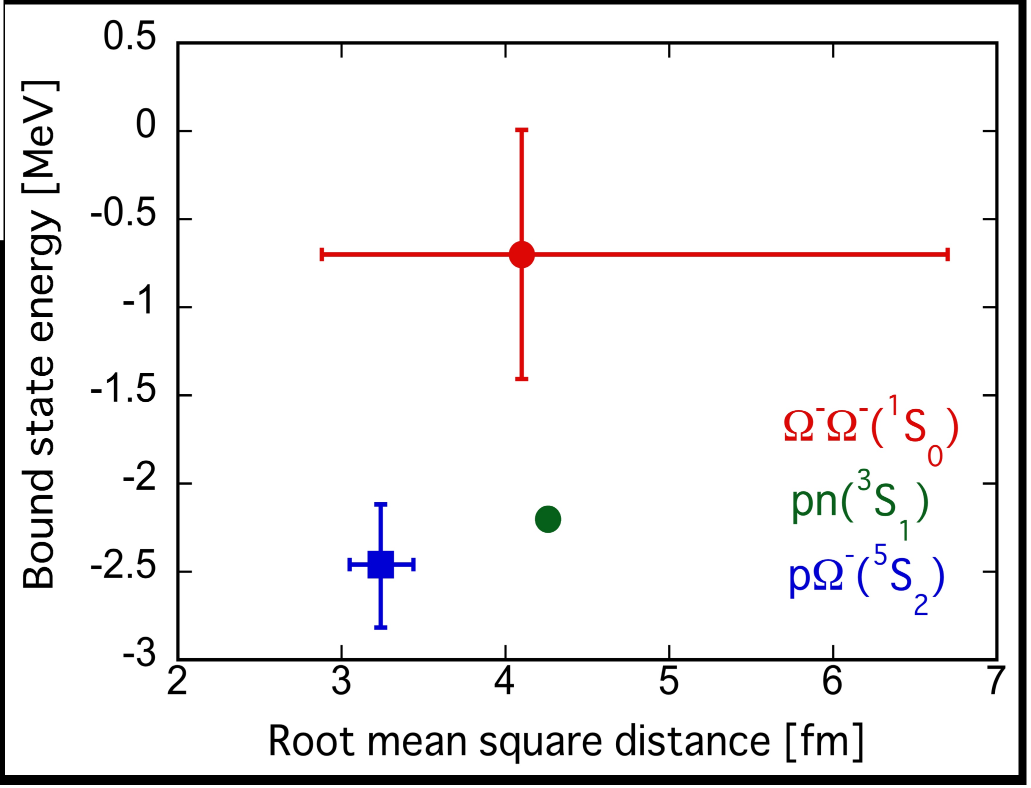
New quasi-stable dibaryons?



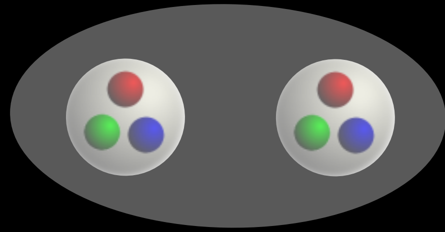
Gongyo et al. [HAL QCD Coll.], PRL 120 (2018) 212001

Iritani et al. [HAL QCD Coll.], arXiv:1810.03416v2 [hep-lat]





New quasi-stable dibaryons?



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

Iritani et al. [HAL QCD Coll.], arXiv:1810.03416v2 [hep-lat]

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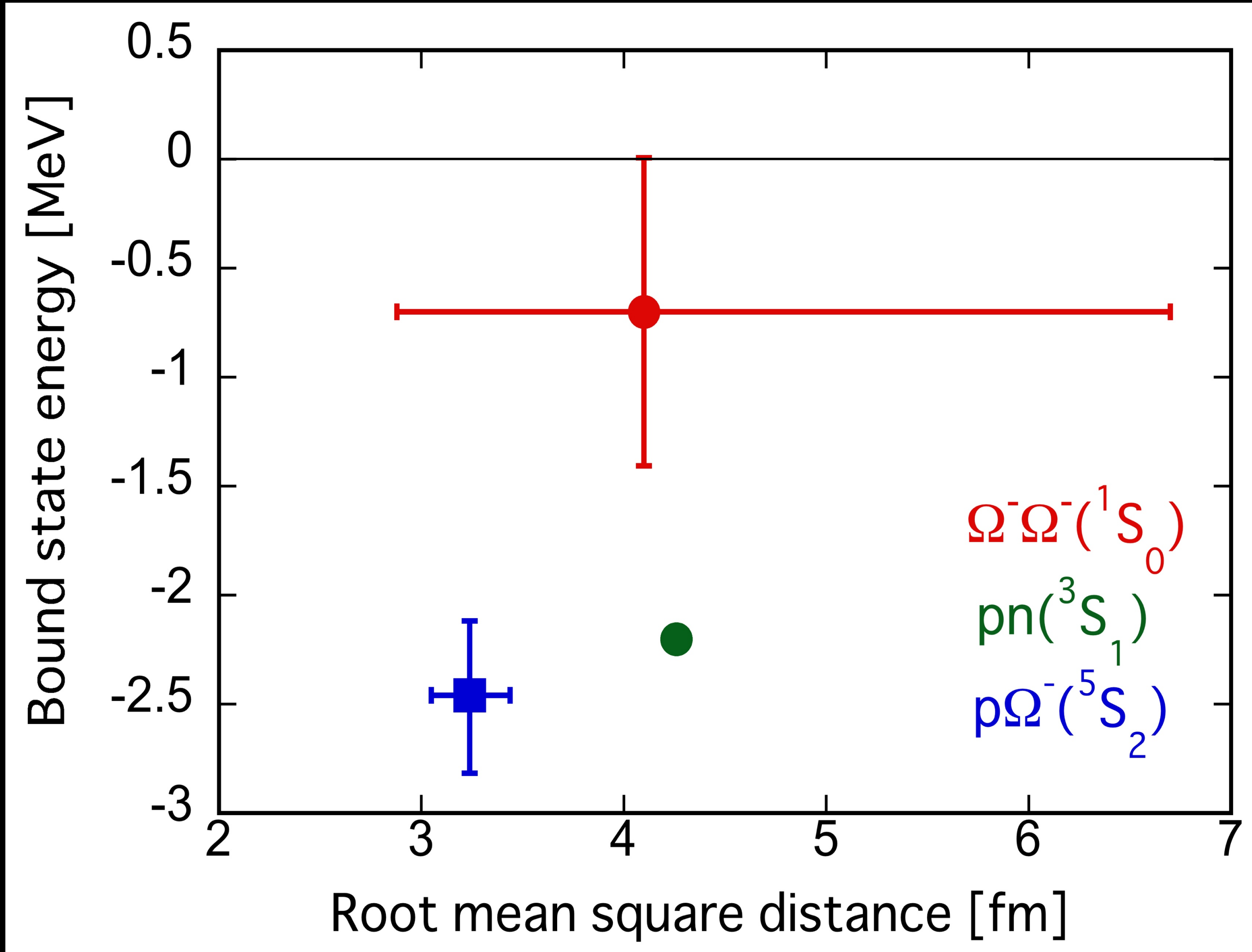
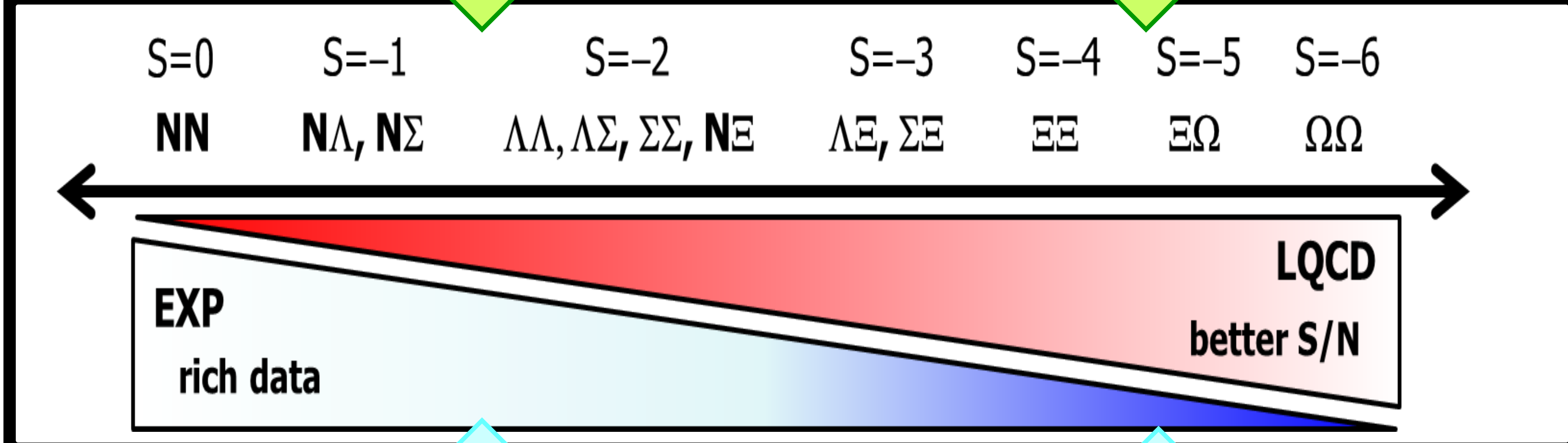


Summary

Hadrons to Atomic nuclei HAL from Lattice QCD

Baryon interactions from LQCD

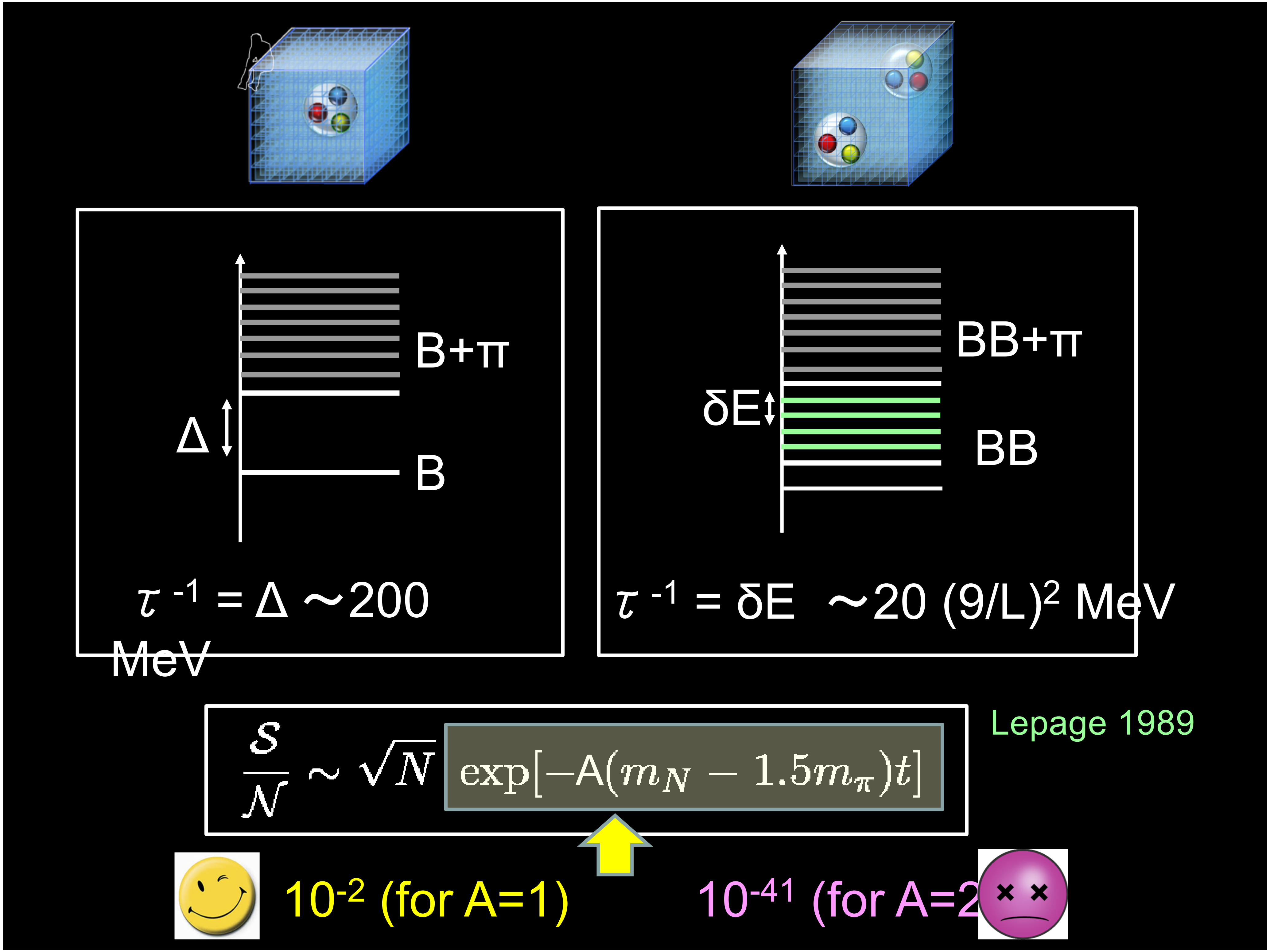
Prediction by HAL QCD Coll. (L=8.1fm, m_π=146 MeV, m_K= 525 MeV)



Femtoscopy at RHIC, LHC
Hypernuclei at J-PARC

Femtoscopy at upgraded LHC
FAIR? J-PARC?

Backup slide


B+π
Δ
B
$\tau^{-1} = \Delta \sim 200$ MeV
BB+π
δE
BB
$\tau^{-1} = \delta E \sim 20\,(9/L)^2$ MeV
$\frac{S}{N} \sim \sqrt{N} \exp[-A(m_N - 1.5 m_\pi)t]$
Lepage 1989
10^{-2} (for A=1)
10^{-41} (for A=2

Collapse of the Plateau Method for B=2

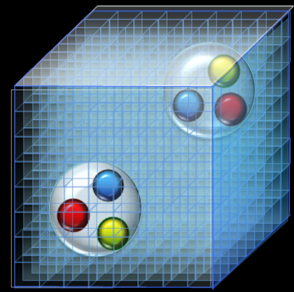
"Mirage in temporal correlation functions for baryon-baryon interactions in lattice QCD",
JHEP 10 (2016) 101 by HAL QCD Coll.

"Are two nucleons bound in lattice QCD for heavy quark masses ?
– Sanity check with Lucsher's finite volume formula –"
Phys. Rev. D96 (2017) 034521 by HAL QCD Coll.

"Sanity check for NN bound states in lattice QCD with Luscher's finite volume formula -- Disclosing Symptoms of Fake Plateaux -- "
EPJ Web Conf. 175 (2018) 05006 by Aoki, Doi, Iritani

	$NN(^1S_0)$				$NN(^3S_1)$			
		Consistency check				Consistency check		
Data	Source independence	(i)	(ii)	(iii)	Source independence	(i)	(ii)	(iii)
YKU2011 [24]	†	No	No	*	†	No	No	*
YIKU2012 [25]	No	†	No	*	No	†	No	*
YIKU2015 [26]	†	†	No	*	†	†	No	No
NPL2012 [27]	†	†	No	*	†	†	*	*
NPL2013 [28,29]	No	*	*	No	No	*	*	?
NPL2015 [30]	†	No	*	No	†	No	*	No
CalLat2017 [31]	No	?	*	No	No	?	*	No

Nuclear Force: $V_C(r)$ and $V_T(r)$



a = 0.085 fm

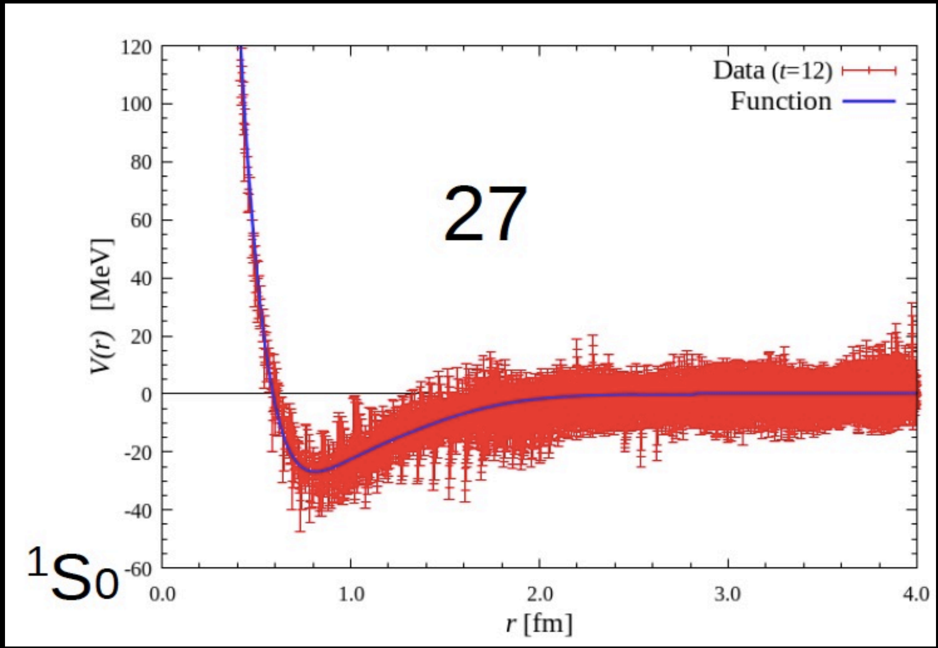
L = 8.1 fm

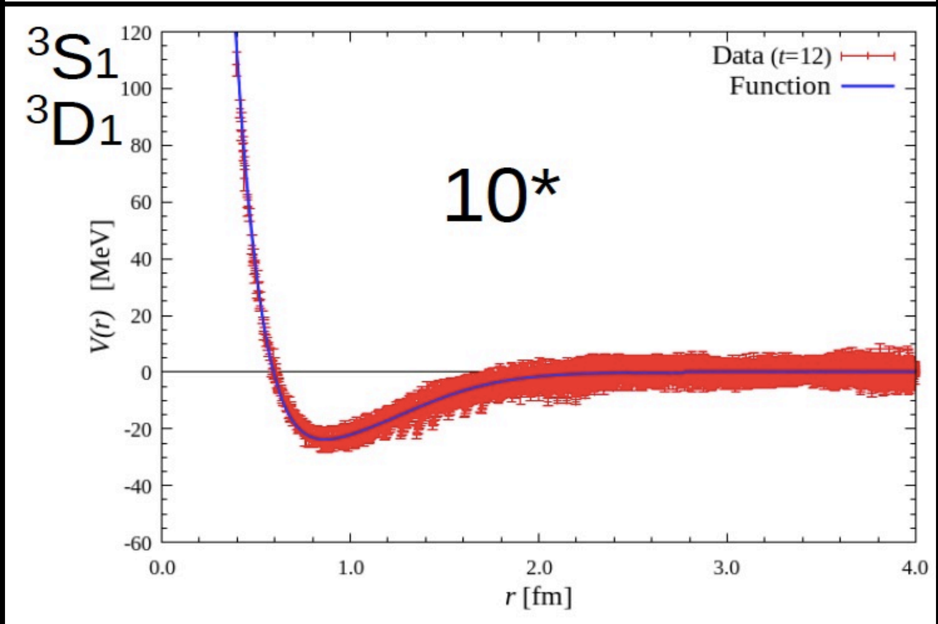
m_π = 146 MeV

M_K = 525 MeV

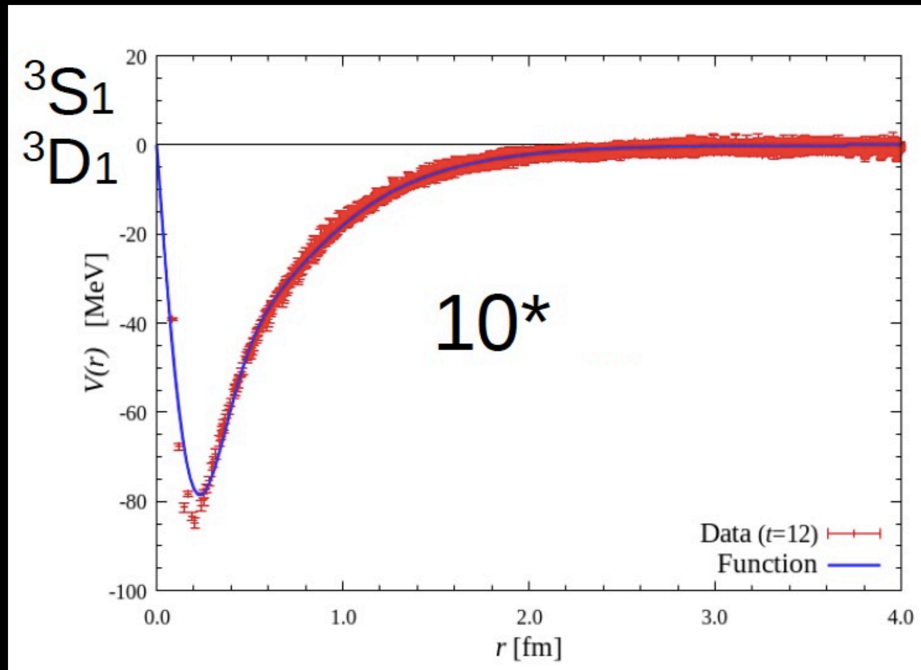
T. Inoue et al.
[HAL QCD Coll.]

Central force





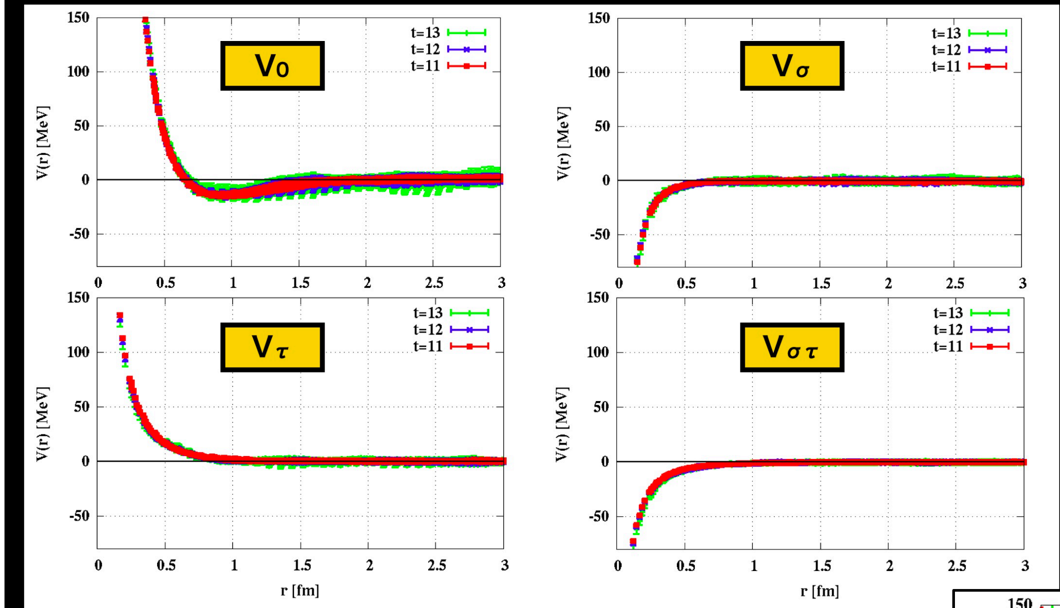
Tensor force

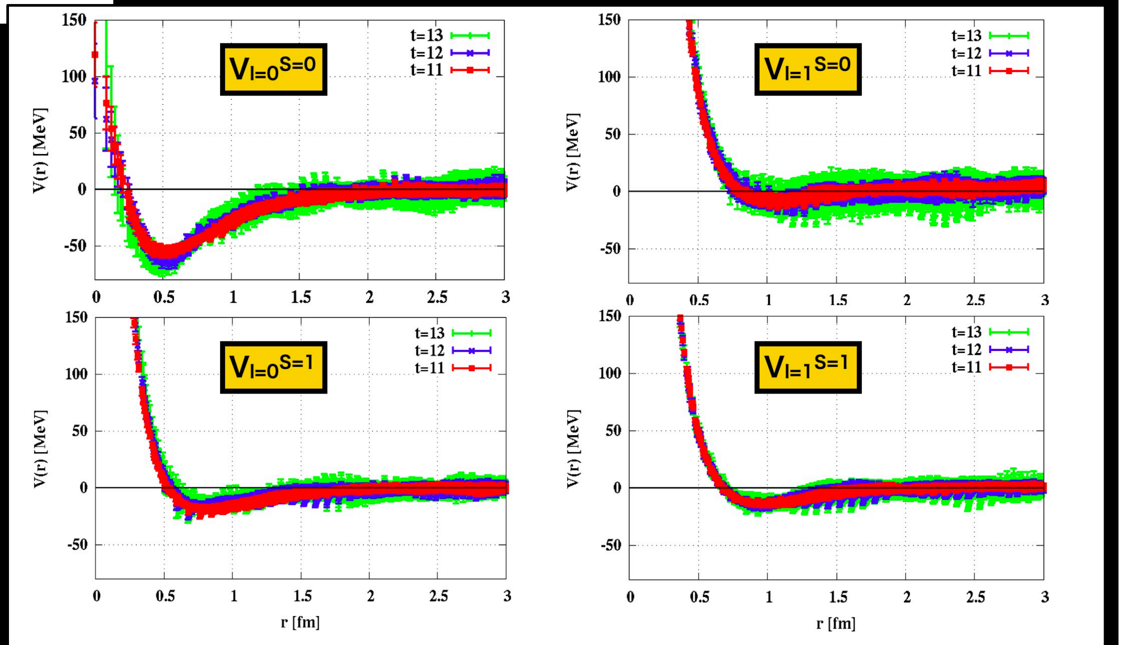


Spin-Isospin dependence of the NΞ interaction

$$\begin{pmatrix} V_{I=0}^{S=0} \\ V_{I=0}^{S=1} \\ V_{I=1}^{S=0} \\ V_{I=1}^{S=1} \end{pmatrix} = \begin{pmatrix} 1 & -3 & -3 & 9 \\ 1 & 1 & -3 & -3 \\ 1 & -3 & 1 & -3 \\ 1 & 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} V_0 \\ V_\sigma \\ V_\tau \\ V_{\sigma\tau} \end{pmatrix}$$

K. Sasaki+ [HAL QCD Coll.] in preparation



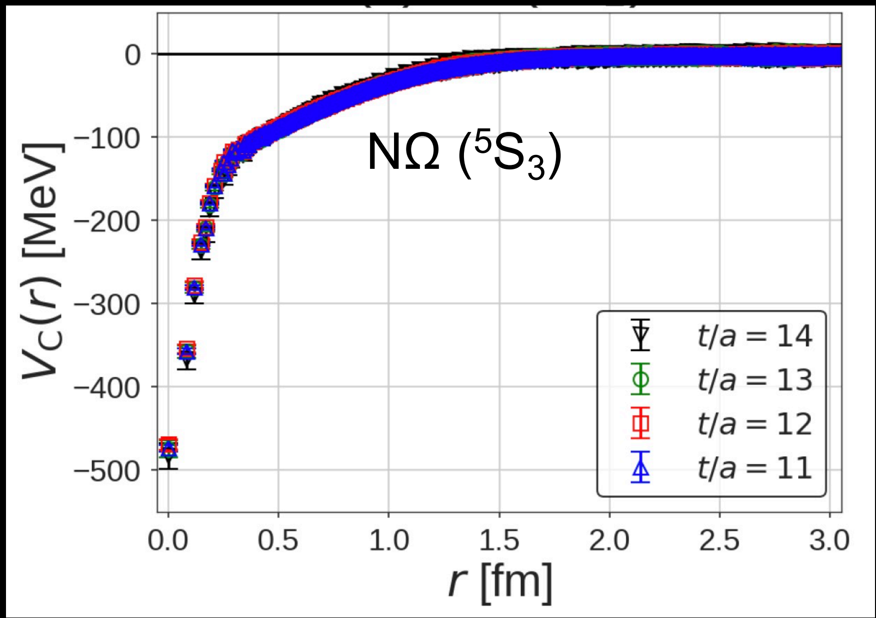


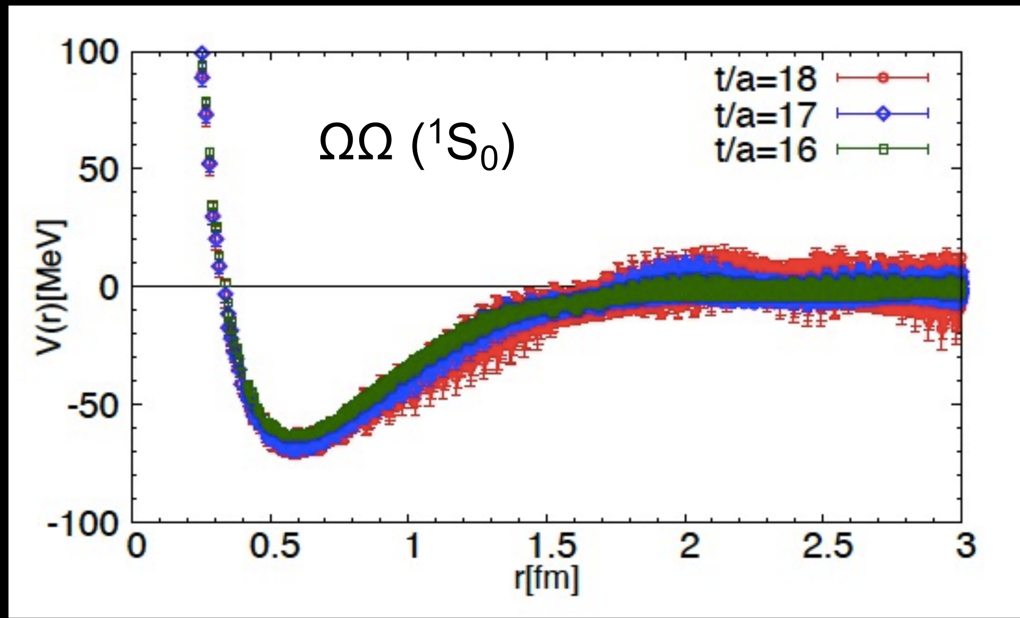
S=-3

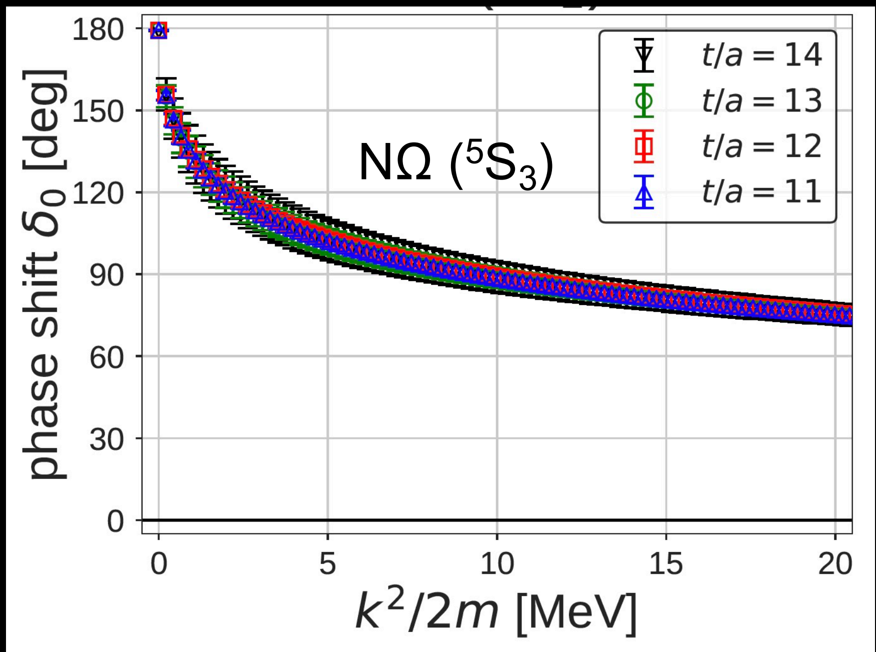
Iritani+ [HAL QCD Coll.], arXiv:1810.03416 [hep-lat]

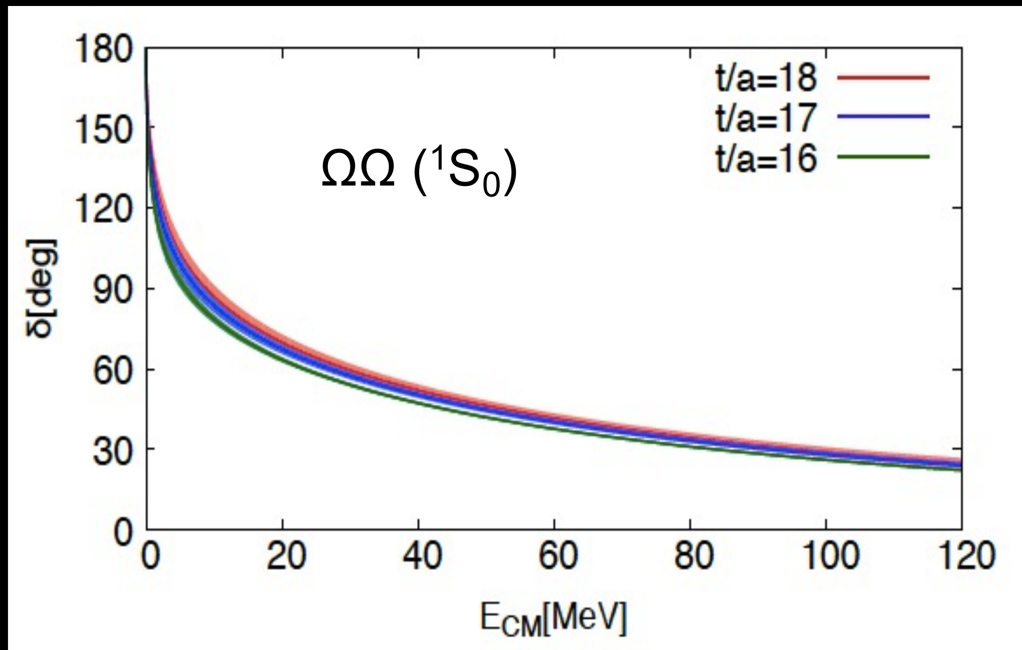
S=-6

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









Inoue+ [HAL QCD Coll.], Prog. Theor. Phys. 124 (2010) 591

S=−1, I=1/2, $^1S_0$ sector.

$$\begin{pmatrix} \langle N\Lambda| \\ \langle N\Sigma| \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{9}{10}} & -\sqrt{\frac{1}{10}} \\ \sqrt{\frac{1}{10}} & \sqrt{\frac{9}{10}} \end{pmatrix} \begin{pmatrix} \langle \mathbf{27}| \\ \langle \mathbf{8}_s| \end{pmatrix}$$

S=−1, I=1/2, $^3S_1$ sector.

$$\begin{pmatrix} \langle N\Lambda| \\ \langle N\Sigma| \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{1}{2}} & -\sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{pmatrix} \begin{pmatrix} \langle \mathbf{10}^*| \\ \langle \mathbf{8}_a| \end{pmatrix}$$

S=−2, I=0, $^1S_0$ sector.

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

S=−2, I=1, $^1S_0$ sector.

$$\begin{pmatrix} \langle N\Xi| \\ \langle \Sigma\Lambda| \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{2}{5}} & -\sqrt{\frac{3}{5}} \\ \sqrt{\frac{3}{5}} & \sqrt{\frac{2}{5}} \end{pmatrix} \begin{pmatrix} \langle \mathbf{27}| \\ \langle \mathbf{8}_s| \end{pmatrix}$$

S=−2, I=1, $^3S_1$ sector.

$$\begin{pmatrix} \langle N\Xi| \\ \langle \Sigma\Lambda| \\ \langle \Sigma\Sigma| \end{pmatrix} = \begin{pmatrix} -\sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{3}} \\ -\sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & 0 \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{6}} & \sqrt{\frac{4}{6}} \end{pmatrix} \begin{pmatrix} \langle \mathbf{10}^*| \\ \langle \mathbf{10}| \\ \langle \mathbf{8}_a| \end{pmatrix}$$