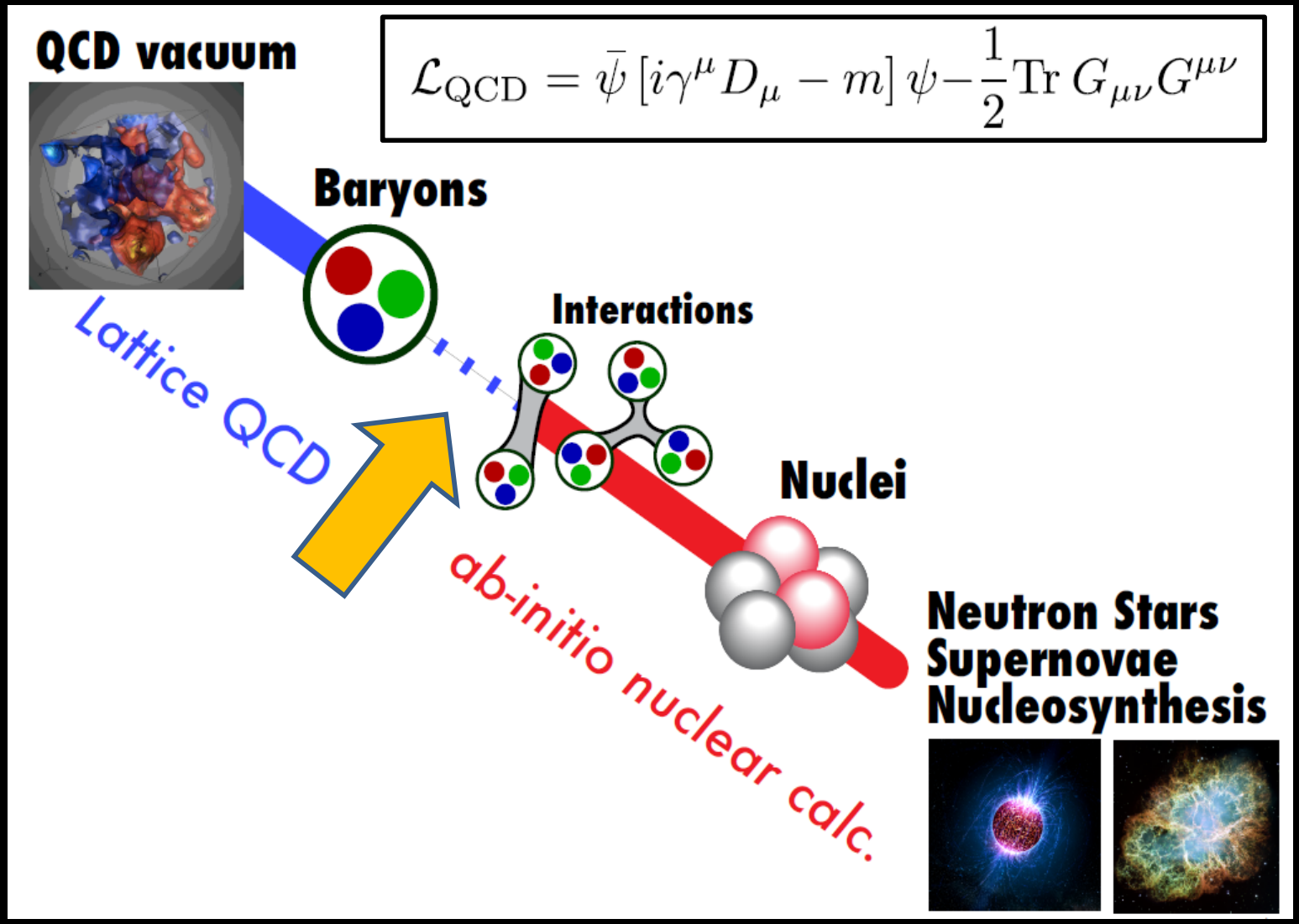
The Most Strange Dibaryon

Tetsuo Hatsuda (iTHEMS, RIKEN)



Tokai, Nov.11, 2018

iTHEMS

https://ithems.riken.jp

Quantum Chromodynamics (QCD)

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

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

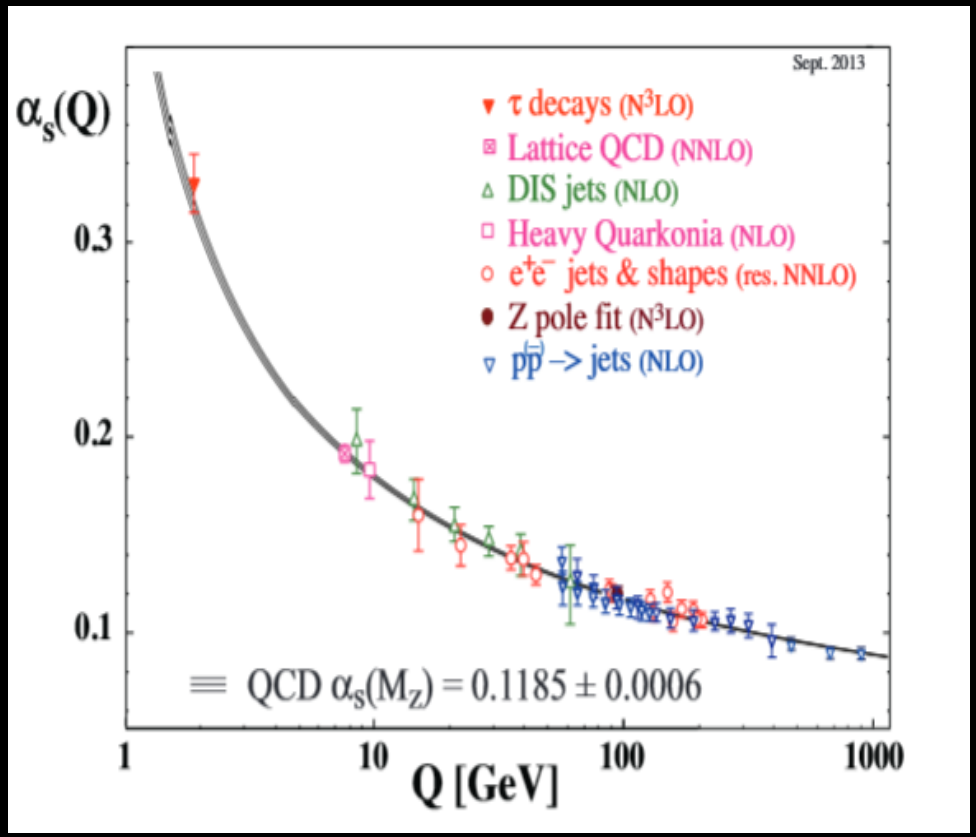
Quark masses: m_q

quark masses (from lattice QCD)	[MeV] (MS-bar @ 2GeV)
m_u	2.16 (9)(7)
m_d	4.68 (14)(7)
m_s	93.8 (1.5)(1.9)

FLAG Coll.(2015)

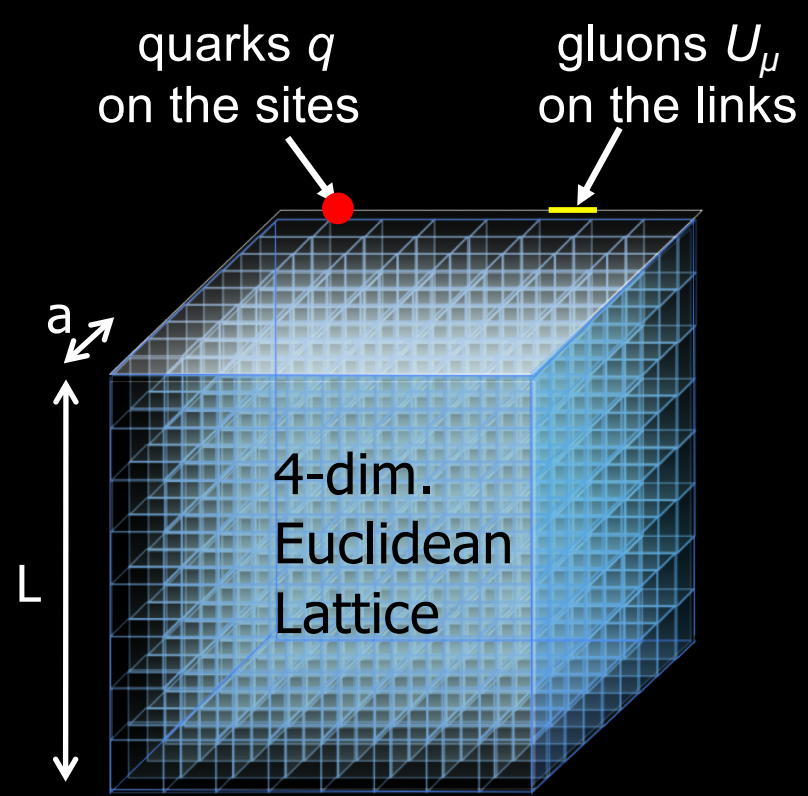
PDG (2014)

Gauge coupling: $\alpha_s = g^2/4\pi$



Lattice QCD (LQCD)

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



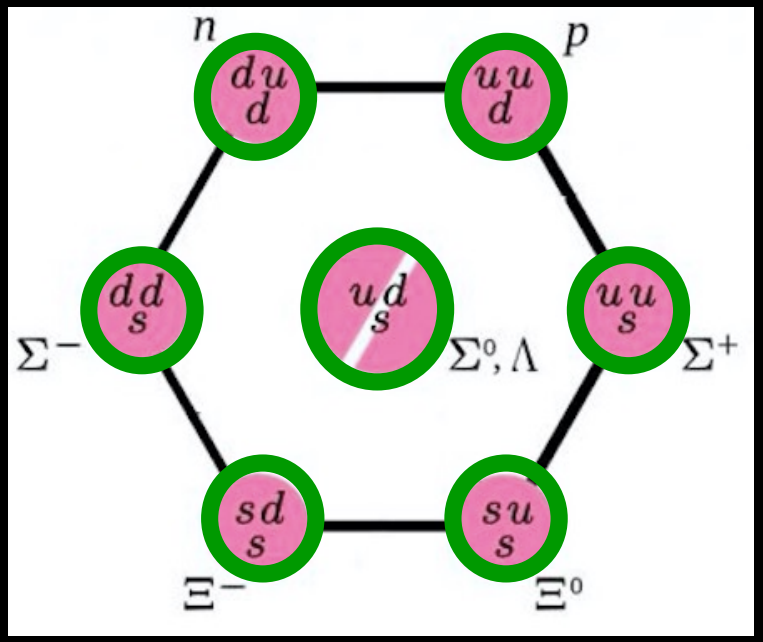
Huge integration variables
~ $10^{9\text{-}10}$ for 96^4 lattice

Importance Sampling
Hybrid MC = MD + Metropolis

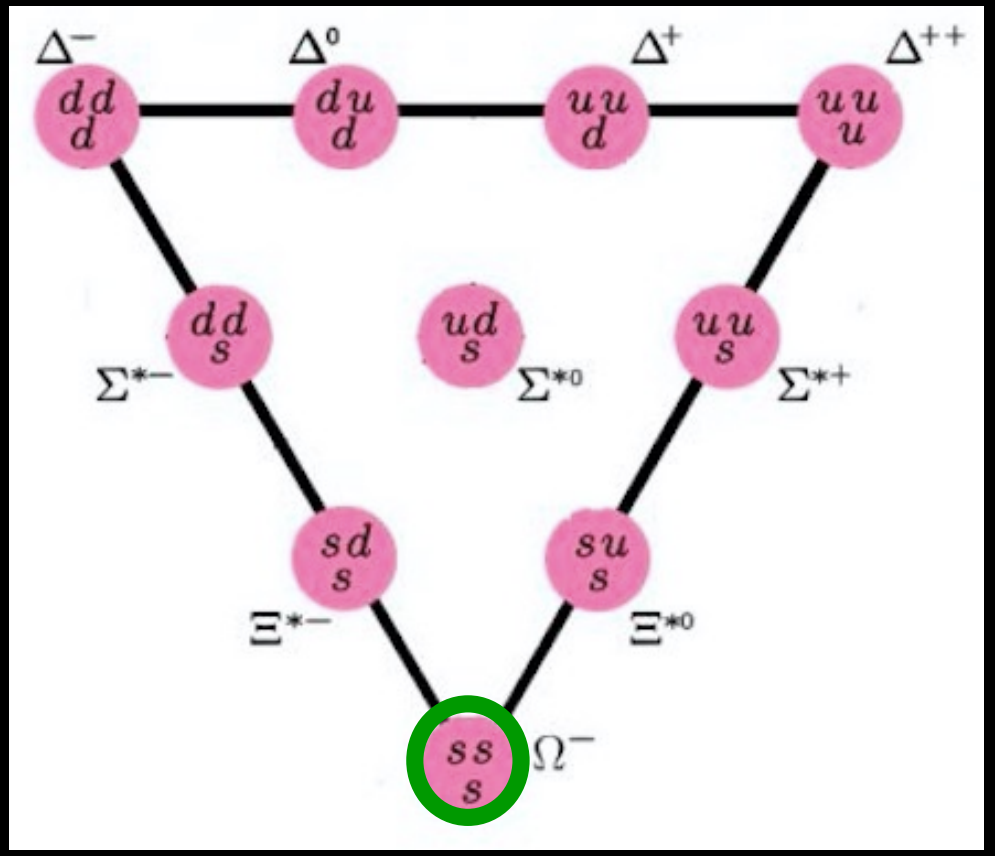
Continuum & Thermodynamic Limits
($a \rightarrow 0$ & $L \rightarrow \infty$)

Flavor SU(3) Classification : B=1

8 (Octet)

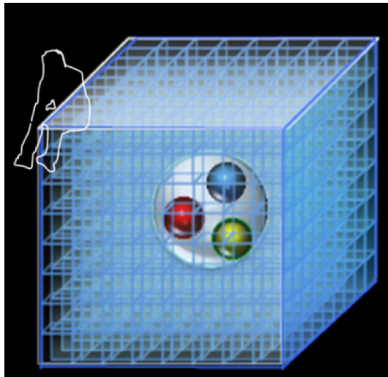


10 (Decuplet)



$\Omega^-(1672)$
Only weak decay ($\rightarrow \Lambda K, \Xi\pi$)
Mean Life ~ 0.8 x 10^{-10} sec

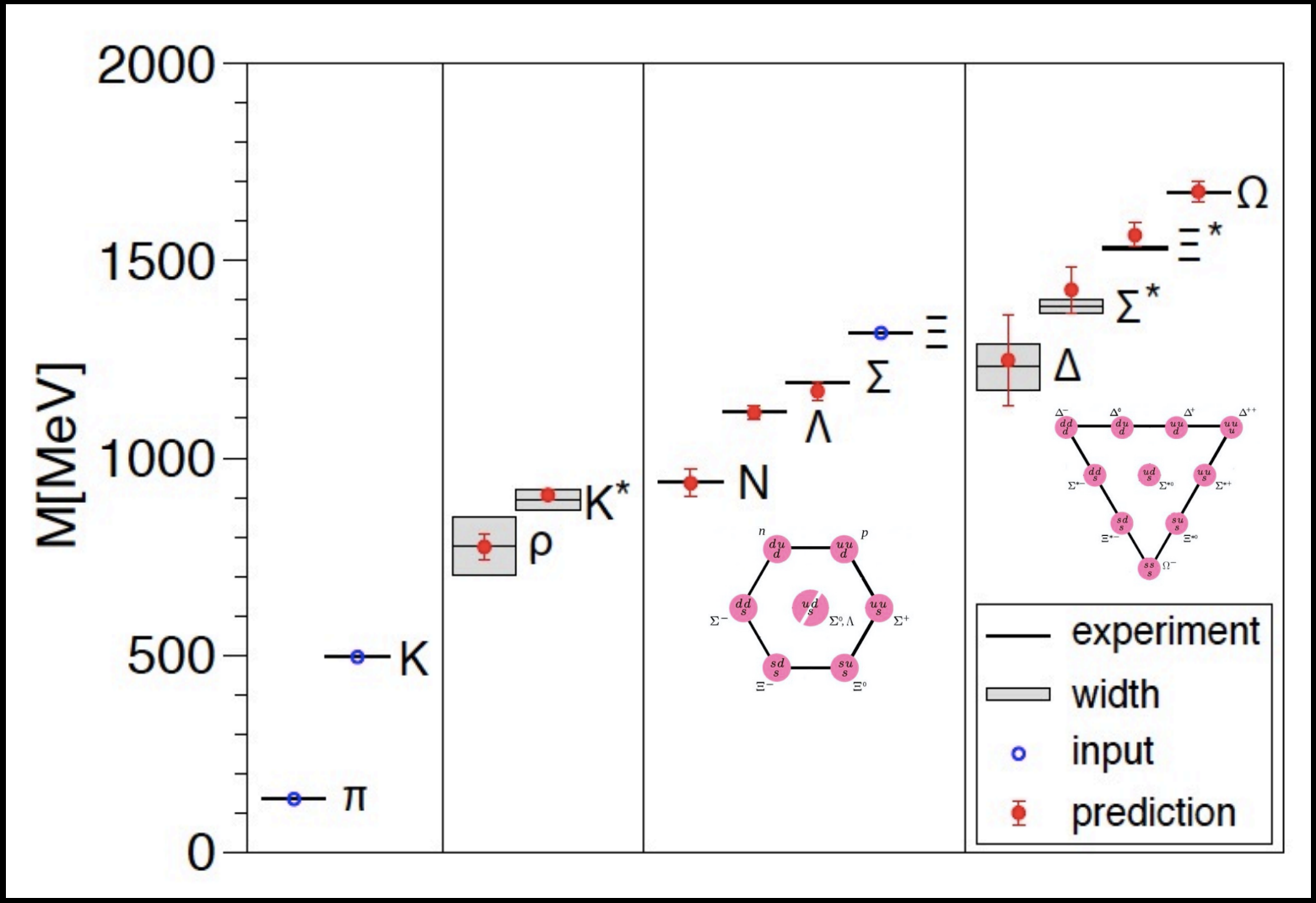
Hadron masses from LQCD



a_{min} = 0.065 fm

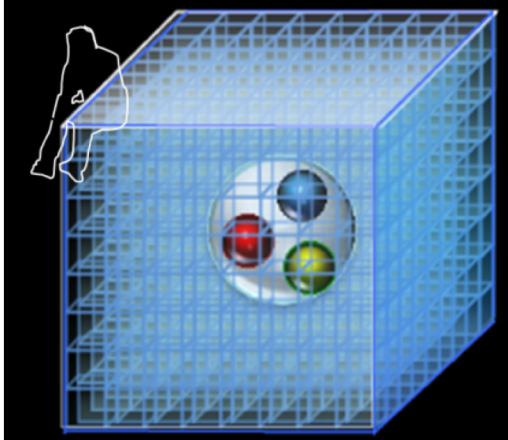
L_{max} = 4.1 fm

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



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

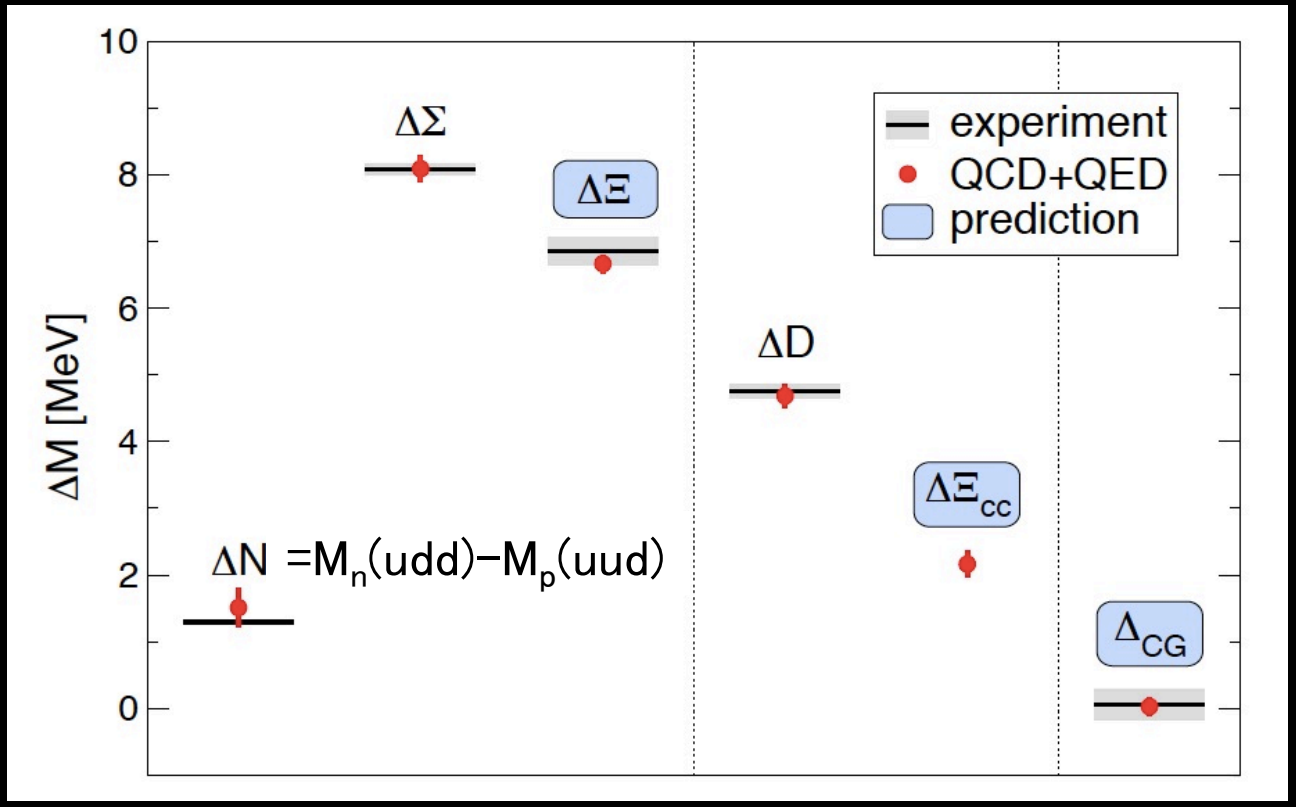
proton-neutron mass difference from LQCD



a_{min} = 0.054 fm

L_{max} = 8 fm

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

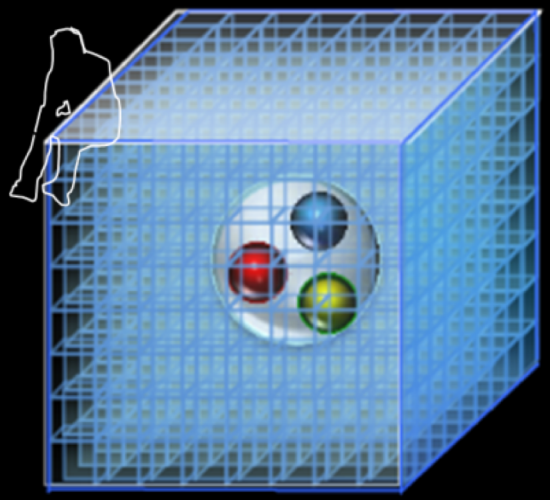


$(M_n - M_p)_{lat}$ = 1.51(16)(23) MeV

$(M_n - M_p)_{exp}$ = 1.29 MeV

BMW Coll., Science 347 (2015) 1452

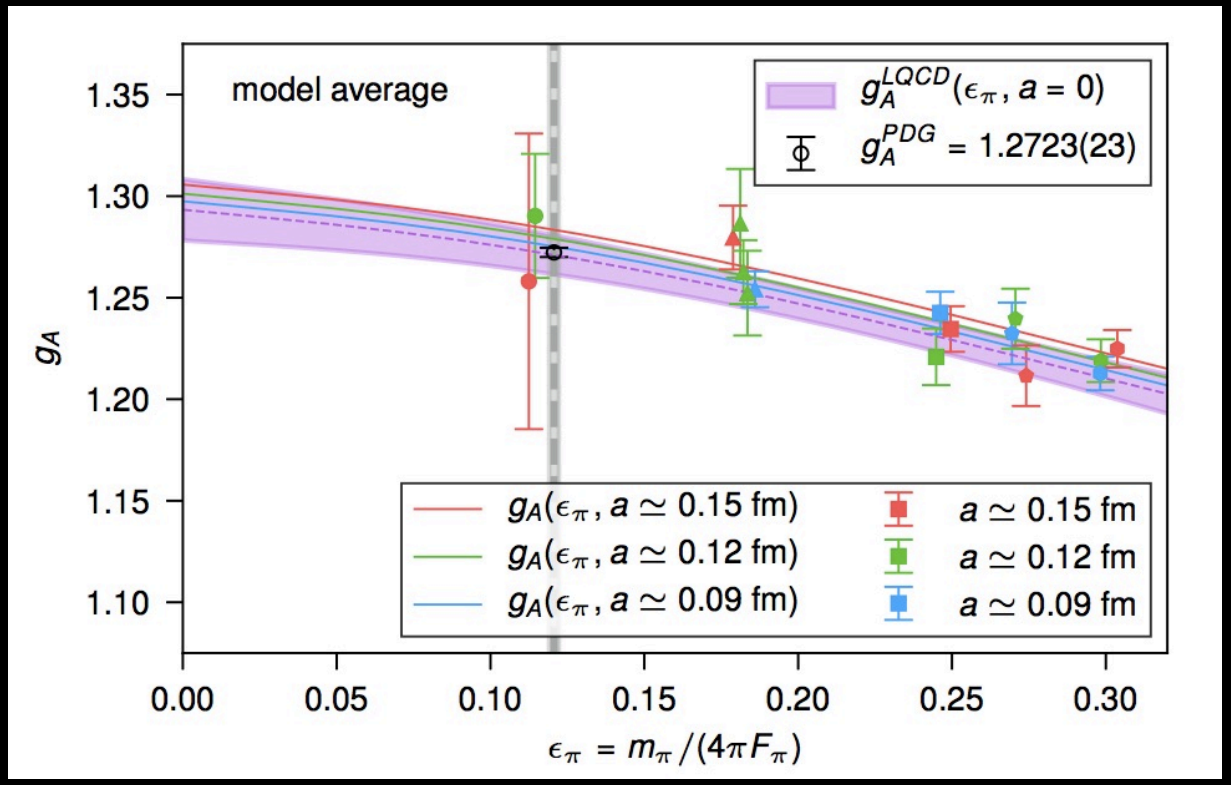
Nucleon axial charge g_A from LQCD



a_{min} = 0.09 fm

L_{max} = 4.8 fm

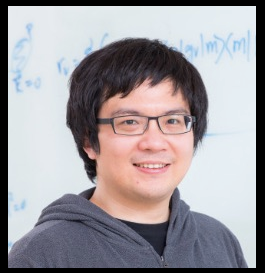
$m_{\pi,min}$ =131 MeV



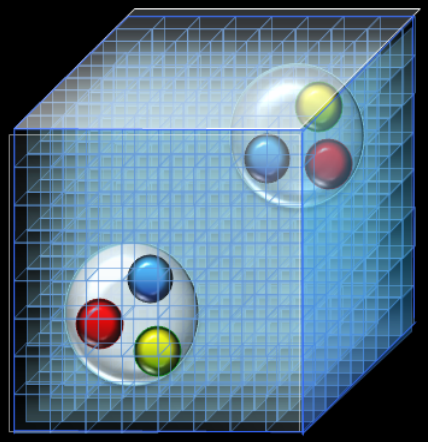
$(g_A)_{lat}$ = 1.2711(13)

$(g_A)_{exp}$ = 1.2723(23)

Chang et al., Nature 558 (2018) 91



Baryon-baryon Interactions from LQCD



a = 0.085 fm

L = 8.1 fm

m_π = 146 MeV

M_K = 525 MeV

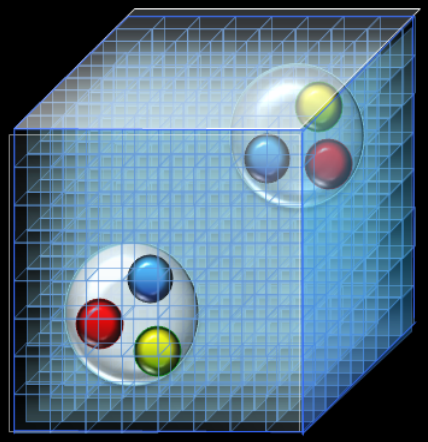
K computer at RIKEN (11 PFlops)

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*)

Hadrons to Atomic nuclei
HAL
from Lattice QCD

Baryon-baryon Interactions from LQCD



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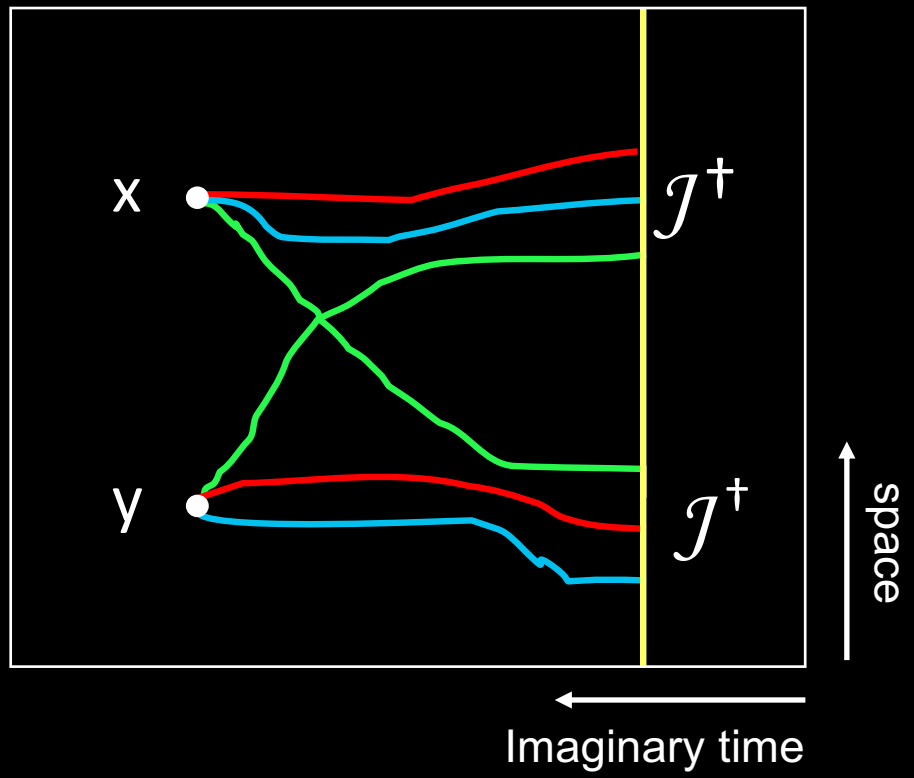
K computer at RIKEN (11 PFlops)

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

EXP
rich data

LQCD
better S/N

Scattering amplitude in LQCD



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

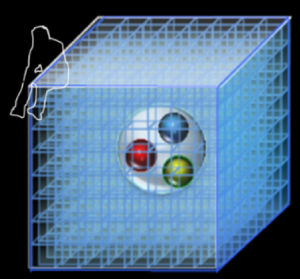
Finite volume Method

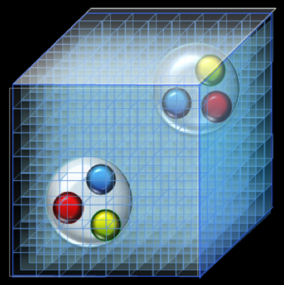
E_n (L)

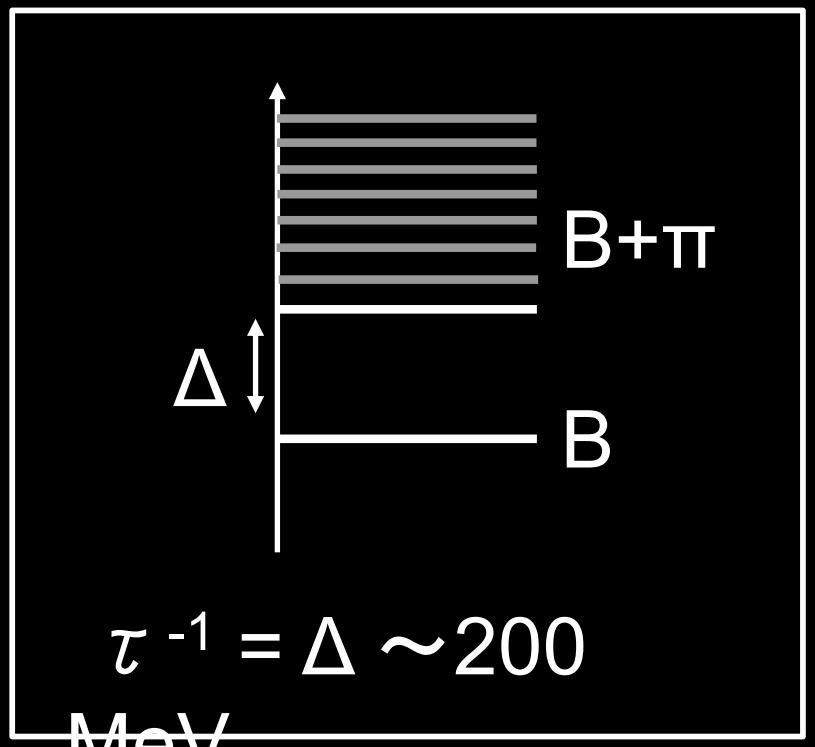
→ phase shift, binding energy

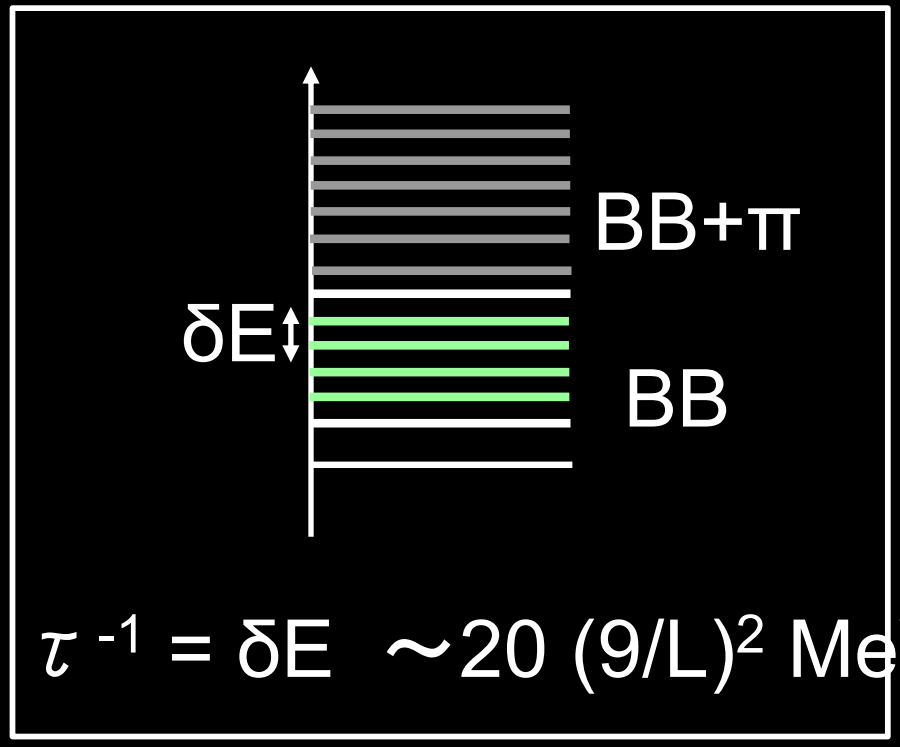
Luscher (1991)

Exponentially small
S/N for two baryons









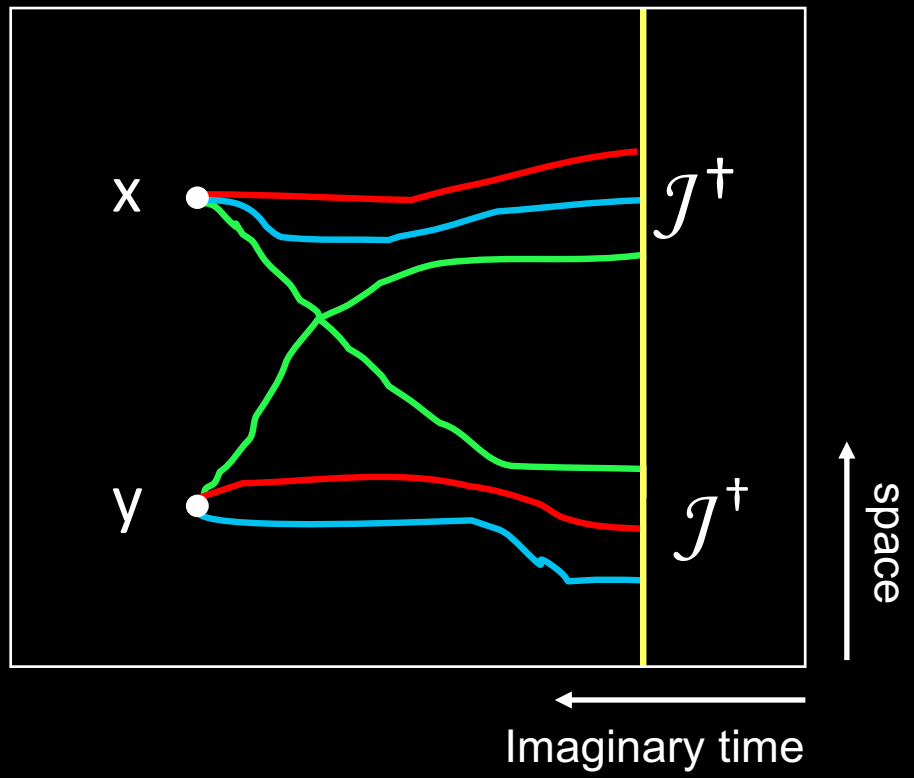
$$\frac{\mathcal{S}}{\mathcal{N}} \sim \sqrt{N}\,\exp[-A(m_N - 1.5m_\pi)t]$$

Lepage 1989

10^{-2} (for A=1)

10^{-41} (for A=2

Scattering amplitude in LQCD



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

$$\xrightarrow{t>t^*} \phi(\mathbf{r},t) = \sum_{n<n^*} b_n \phi_n(\mathbf{r}) e^{-E_n t}$$

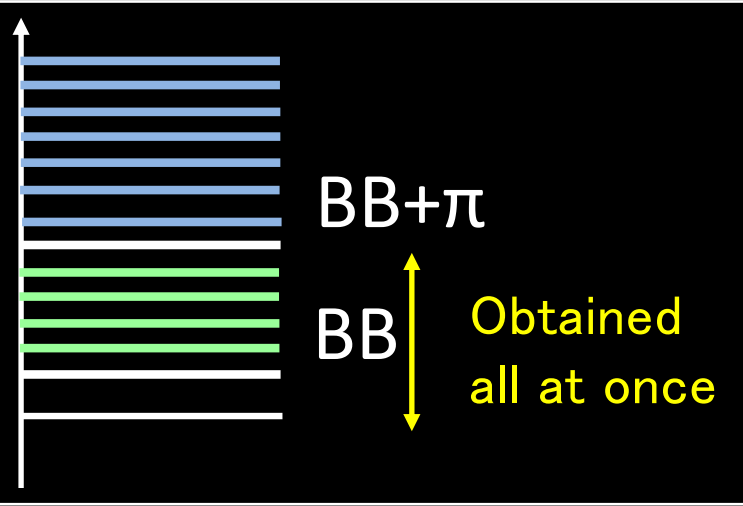
HAL QCD Method

ϕ(r,t) → 2PI kernel (T=U+GUT)

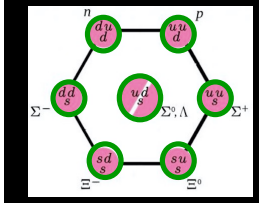
→ phase shift, binding energy

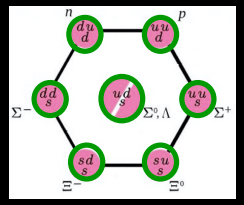
Ishii, Aoki & Hatsuda, PRL 99 (2007) 022001

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



Flavor SU(3) Classification of BB system

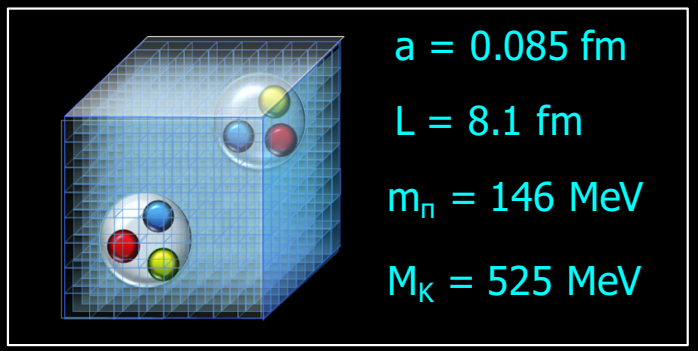


x


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

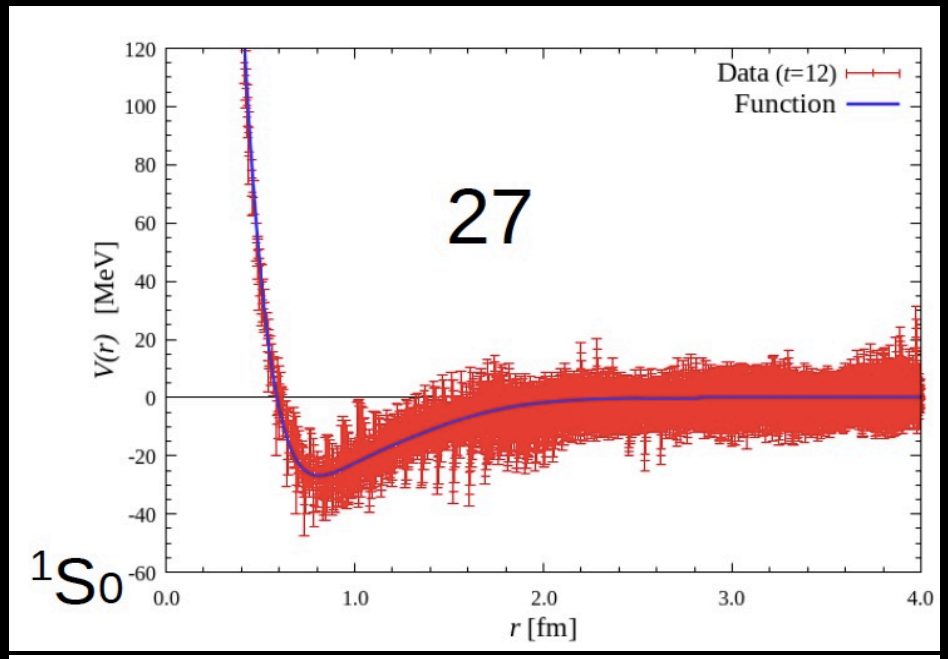
D_{pn} (J=1)

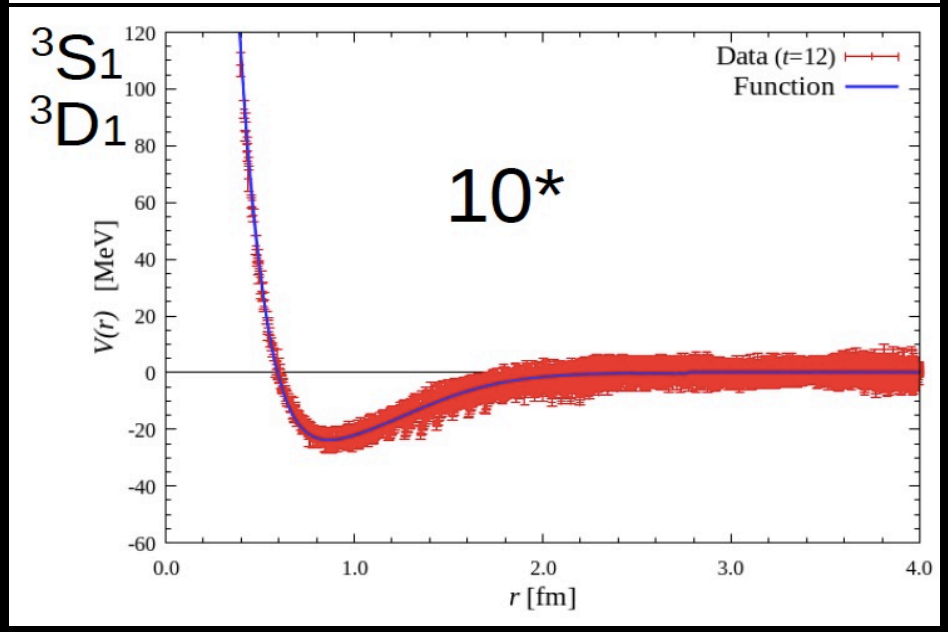
Nuclear Force: $V_C(r)$ and $V_T(r)$



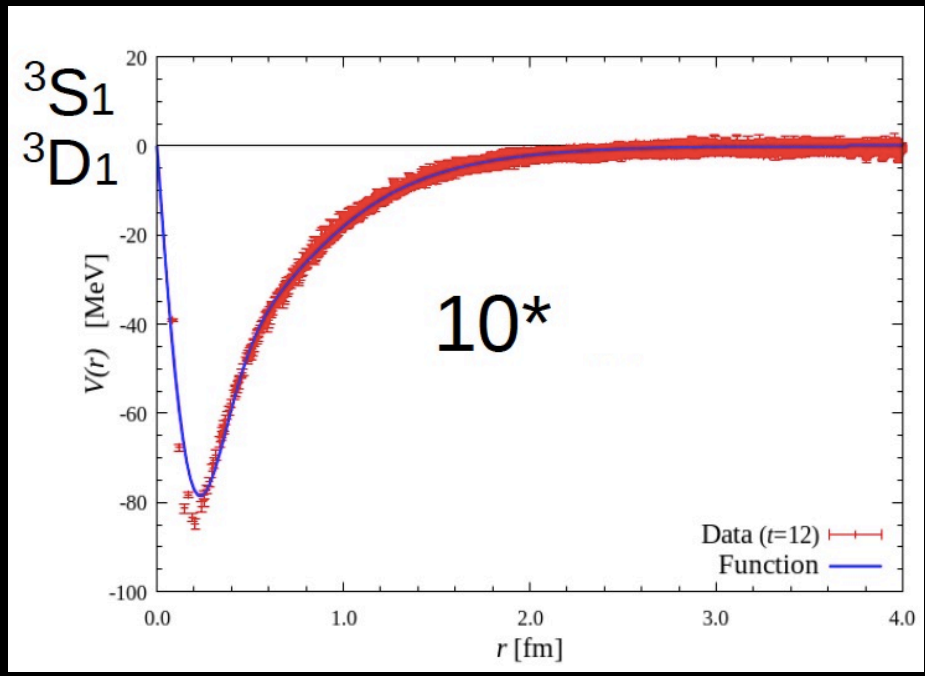
T. Inoue et al.
[HAL QCD Coll.]

Central force



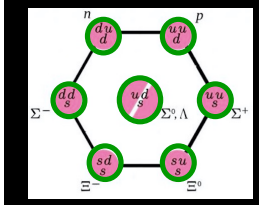


Tensor force

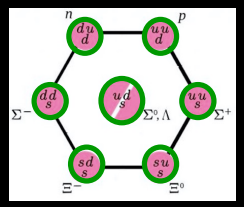


Flavor SU(3) Classification of BB system

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



x



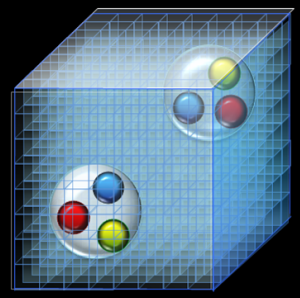
$$8 \times 8 = 27 + 8_s + 1 + 10^* + 10 + 8_a$$

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

Jaffe (1977)

D_{pn} (J=1)

S=-2 BB interactions : $V_C(r)$



a = 0.085 fm

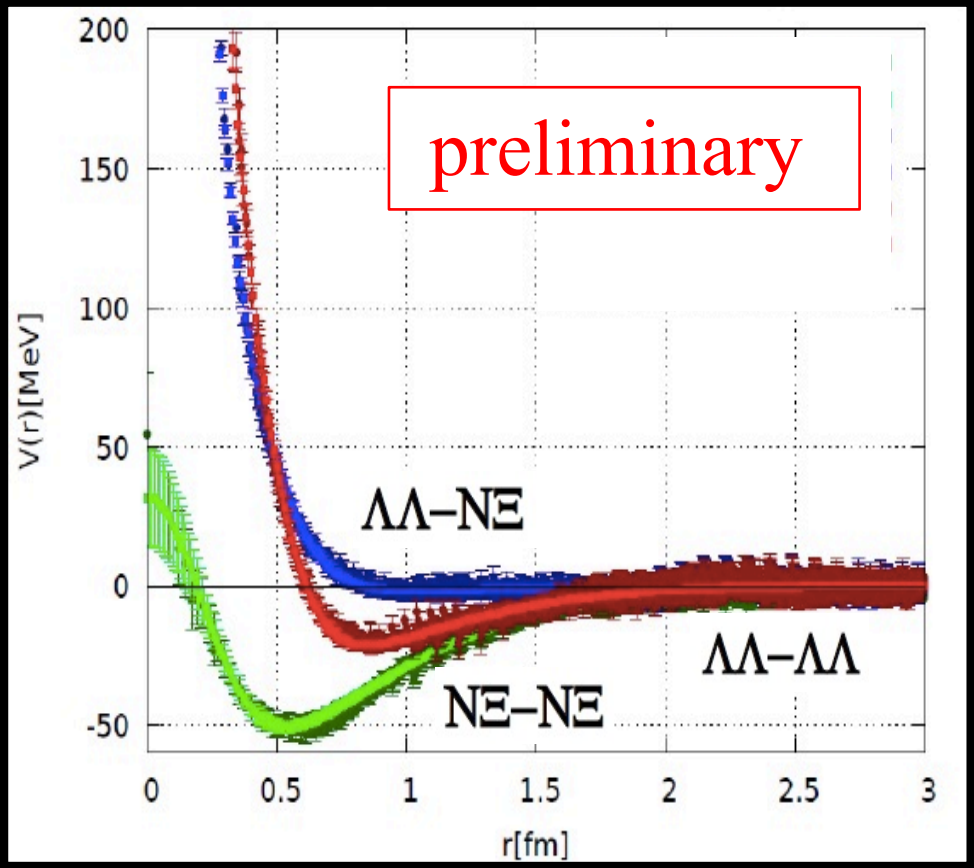
L = 8.1 fm

m_π = 146 MeV

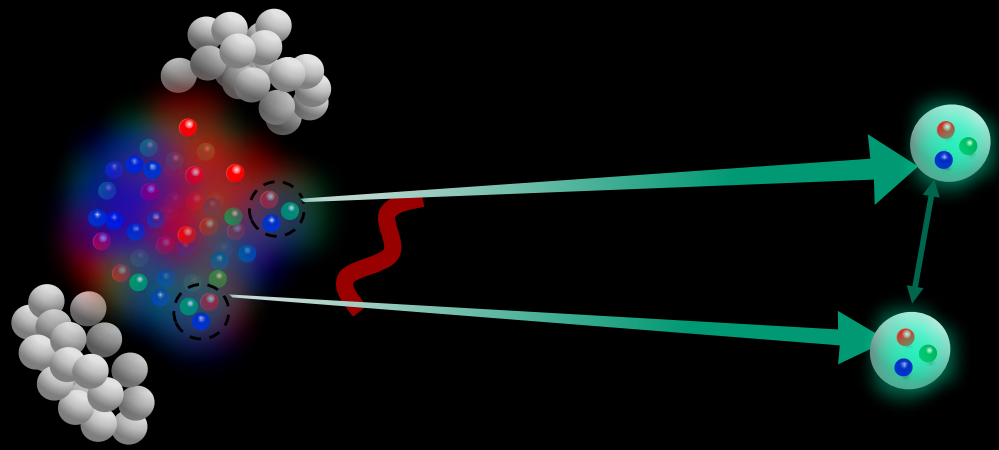
M_K = 525 MeV

K. Sasaki

K. Sasaki et al. [HAL QCD Coll.]



ALICE Coll., arXiv:1805.12455



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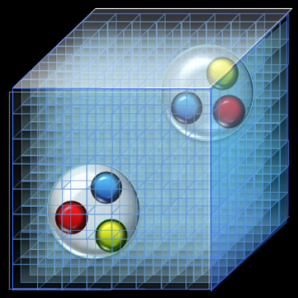

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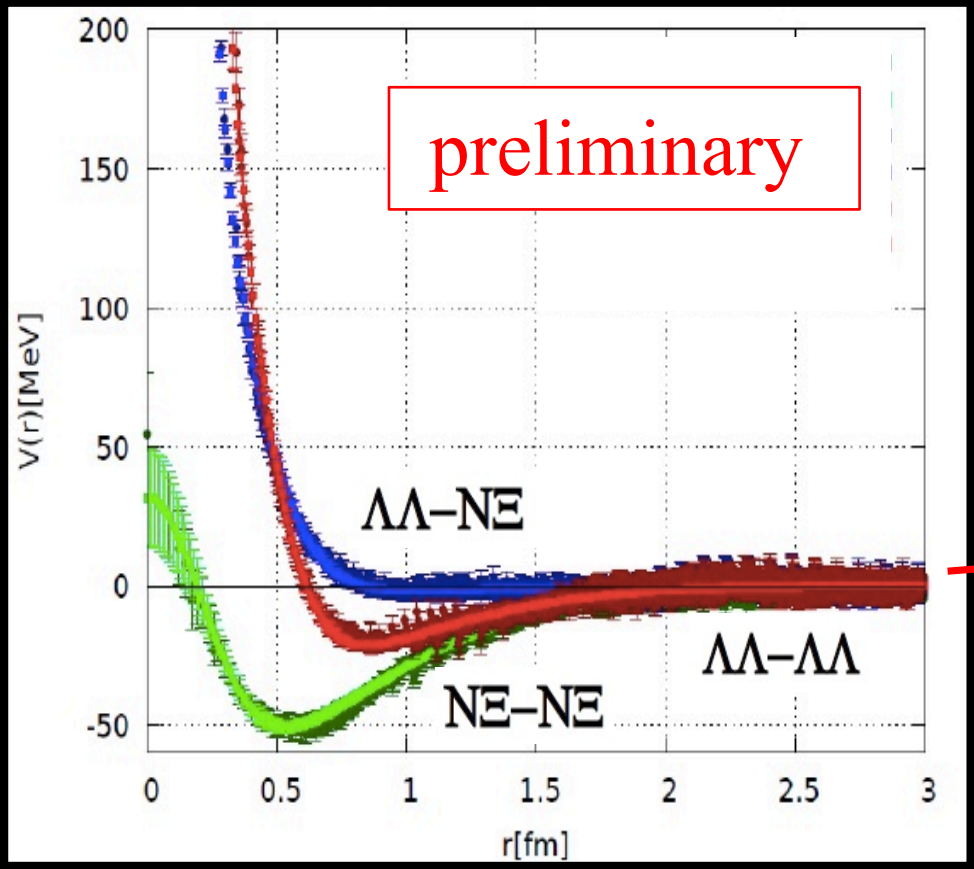

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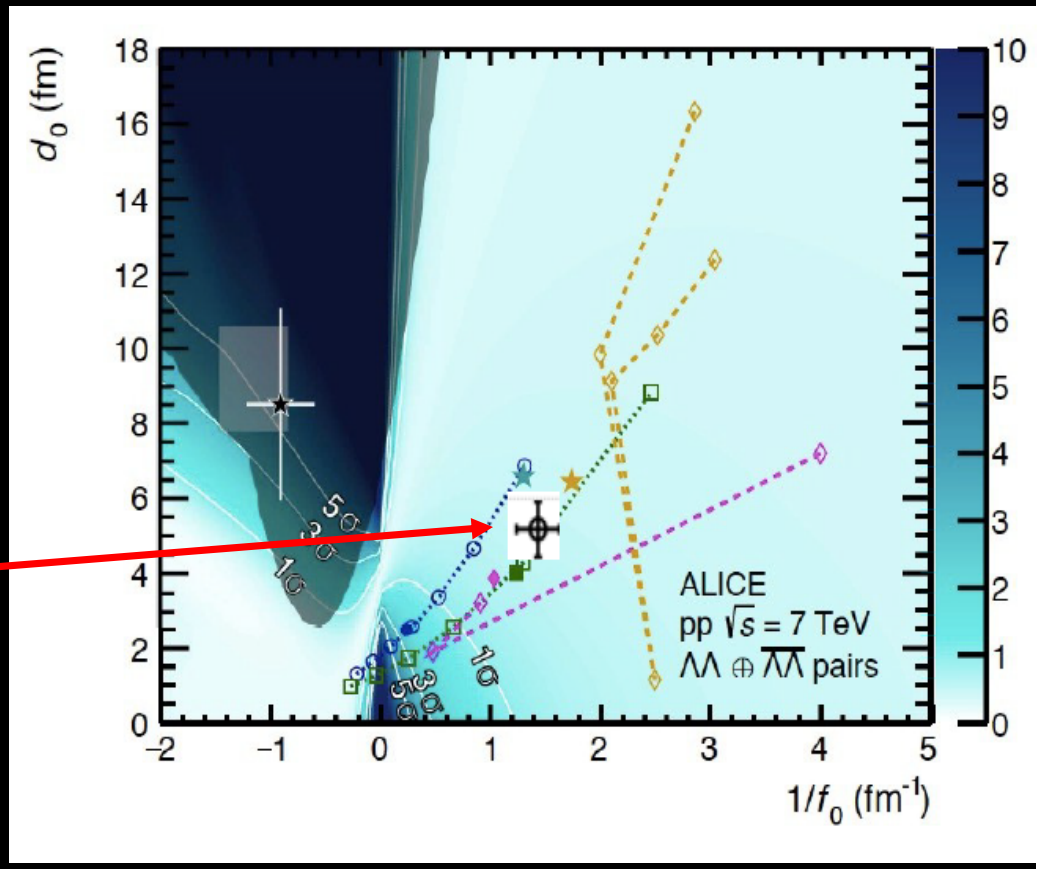

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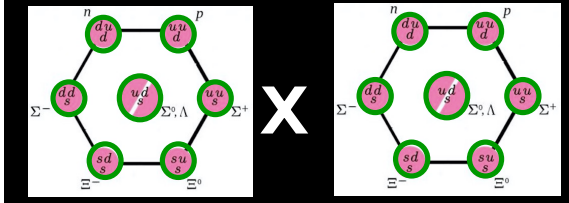
c.f. Dyson & Xoung, PRL 14 (1965)

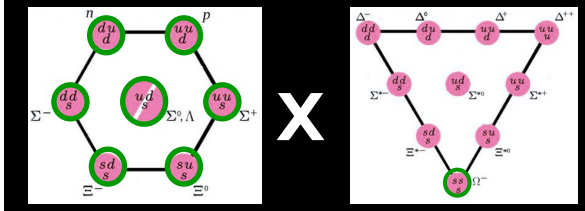


$$8 \times 8 = 27 + 8_s + 1 + 10^* + 10 + 8_a$$

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

Jaffe (1977)

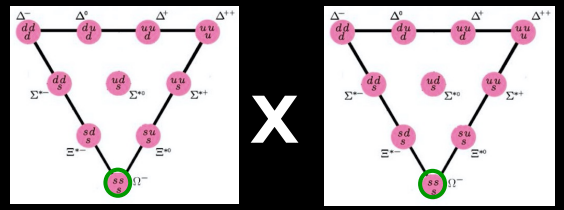
D_{pn} (J=1)



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

$N\Omega$ (J=2)

Goldman et al (1987)



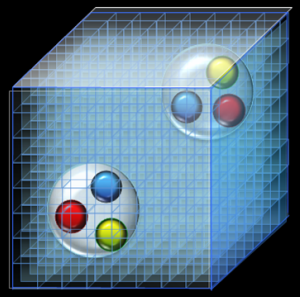
$$10 \times 10 = 28 + 27 + 35 + 10^*$$

$\Omega\Omega$(J=0)

Zhang et al (1997)

S=-6 BB interaction $V_C(r)$

Gongyo et al. [HAL QCD Coll.],
Phys. Rev. Lett. 120 (2018) 212001



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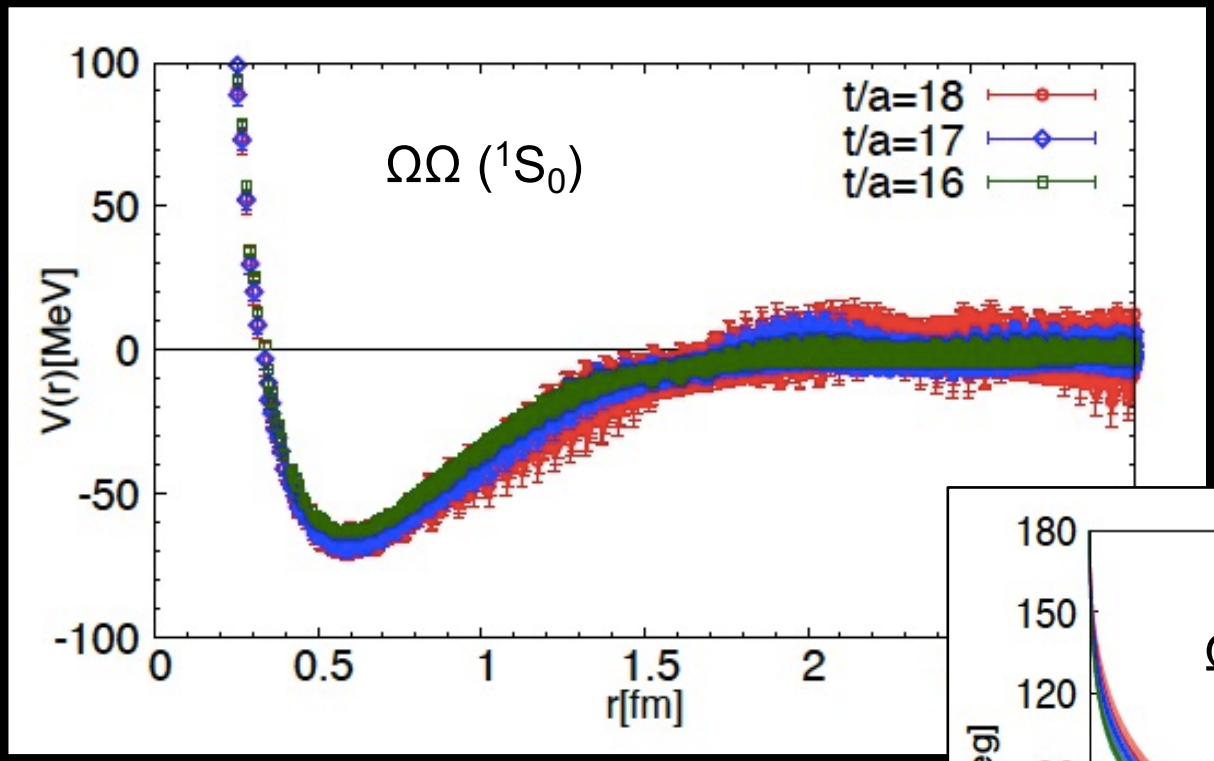
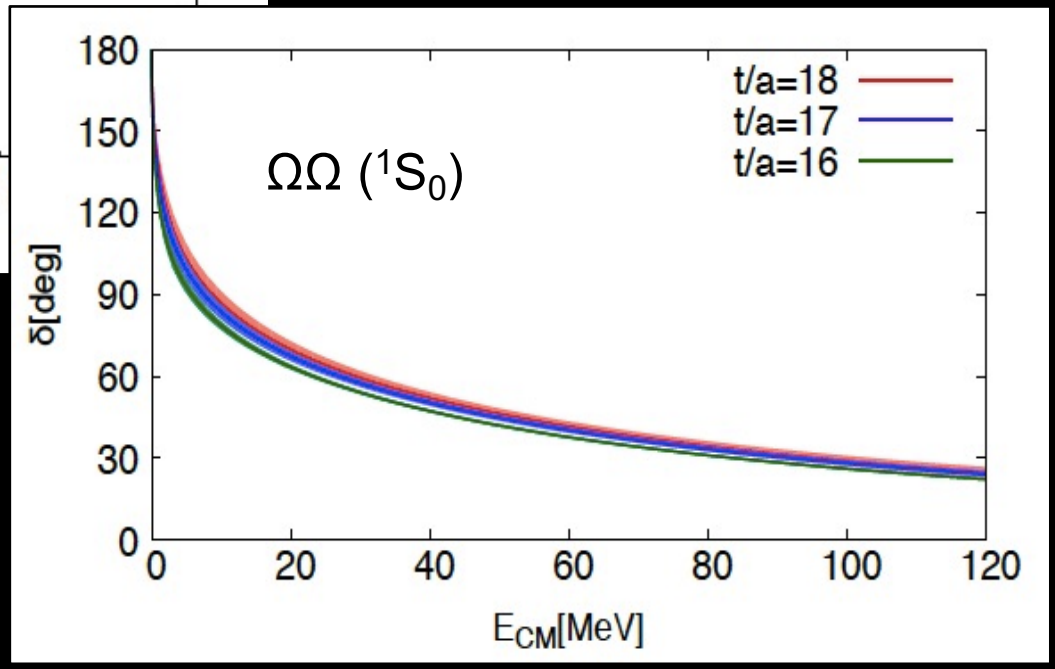
S. Gongyo

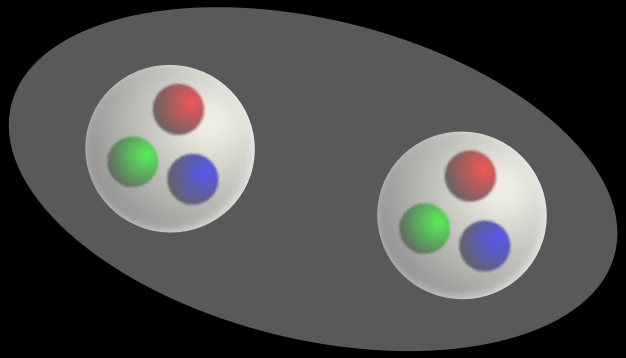




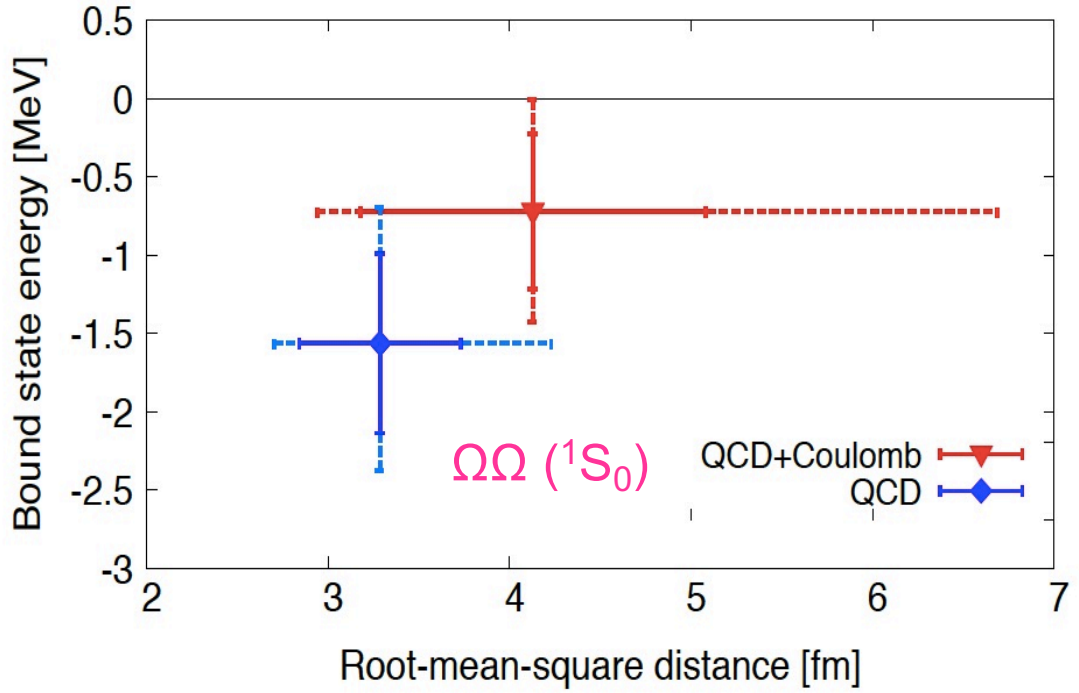
New “stable” dibaryon?

Gongyo et al. [HAL QCD Coll.],
Phys. Rev. Lett. 120 (2018) 212001

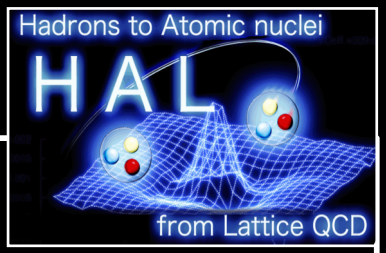
$$a_0^{(\Omega\Omega)} = 4.6(6)(^{+1.2}_{-0.5}) \quad \text{fm},$$
$$r_{\text{eff}}^{(\Omega\Omega)} = 1.27(3)(^{+0.06}_{-0.03}) \quad \text{fm}.$$



Deuteron (1931, Urey)
Di-Omega ΩΩ ?



Summary



BB interactions from LQCD

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

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

EXP rich data

LQCD better S/N

Hypernuclear levels
FSI at RHIC, LHC

FSI in
Future HIC

Backup slide

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