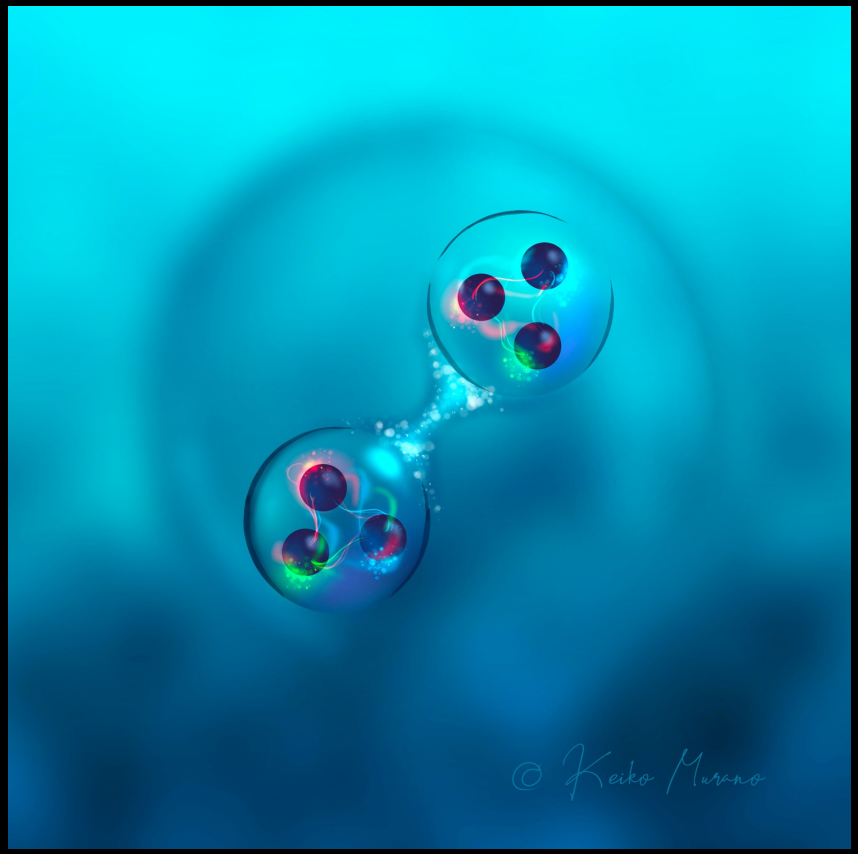
Hadron Interactions from Lattice QCD



Tetsuo Hatsuda
(RIKEN iTHEMS)

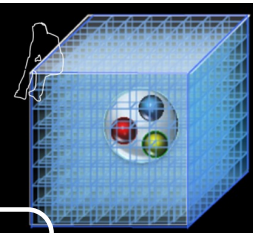
iTHEMS
RIKEN interdisciplinary Theoretical & Mathematical Sciences

Hadrons to Atomic nuclei
HAL
from Lattice QCD

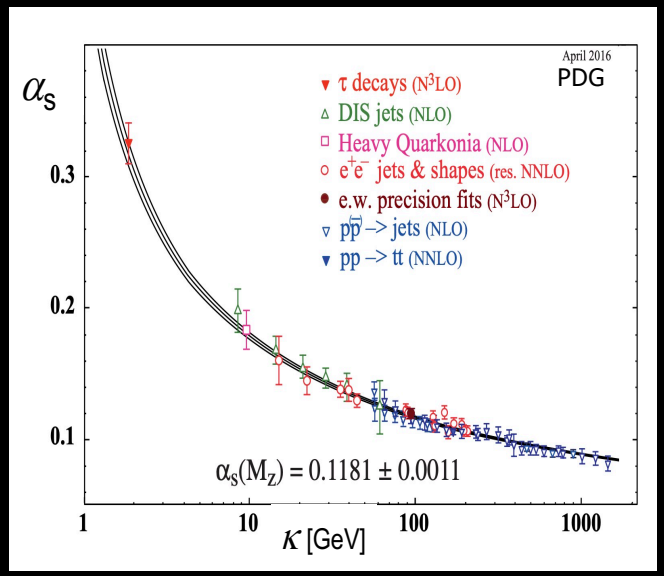
ExHIC WS (Sept. 29, 2022)

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

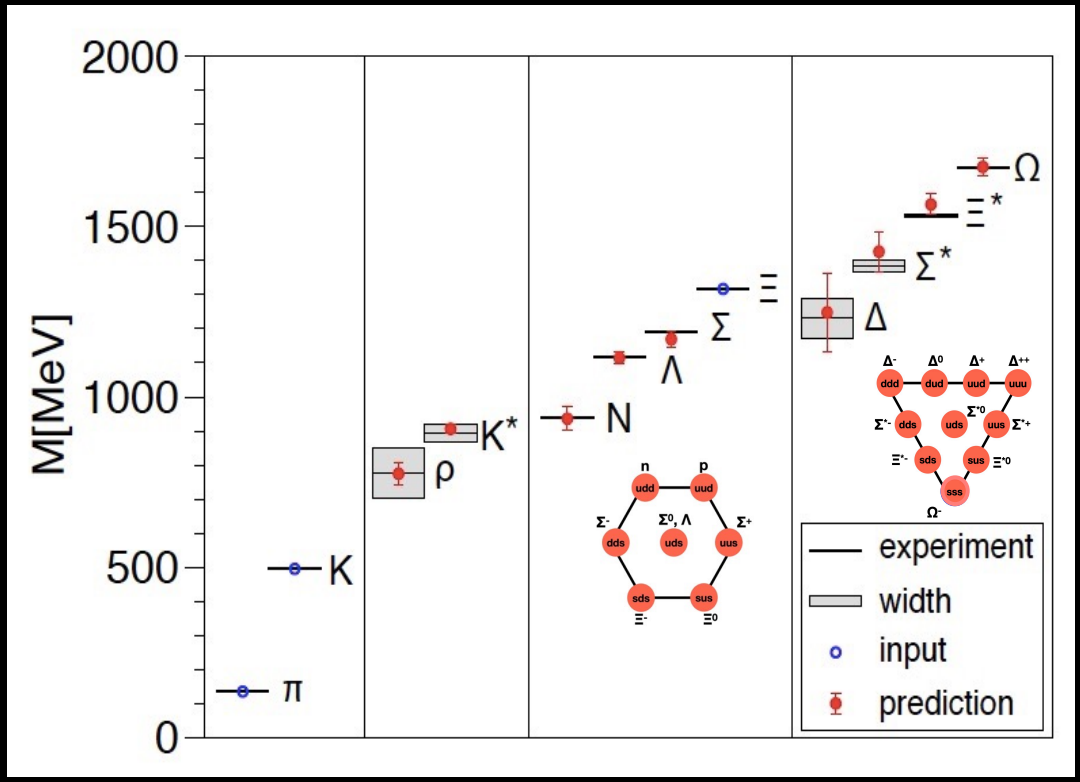
Lattice QCD



$$Z_{\rm QCD} = \int [dU][dqd\bar{q}] e^{-[S_{\rm glue}(U) + \bar{q}F(U)q]}$$



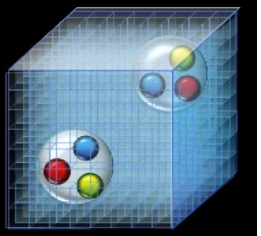
light quarks	MS-bar mass at 2GeV
m_u	2.27(9) MeV
m_d	4.67(9) MeV
m_s	92.0(1.1) MeV



FLAG (Flavor-Lattice Averaging Group) http://flag.unibe.ch/

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

Interaction between compositive particles in QFT

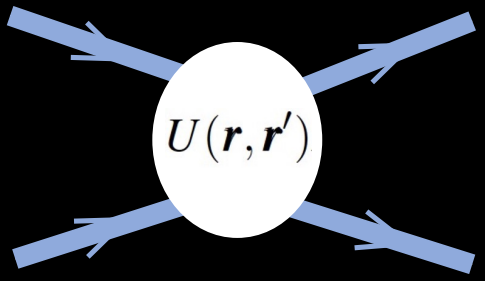


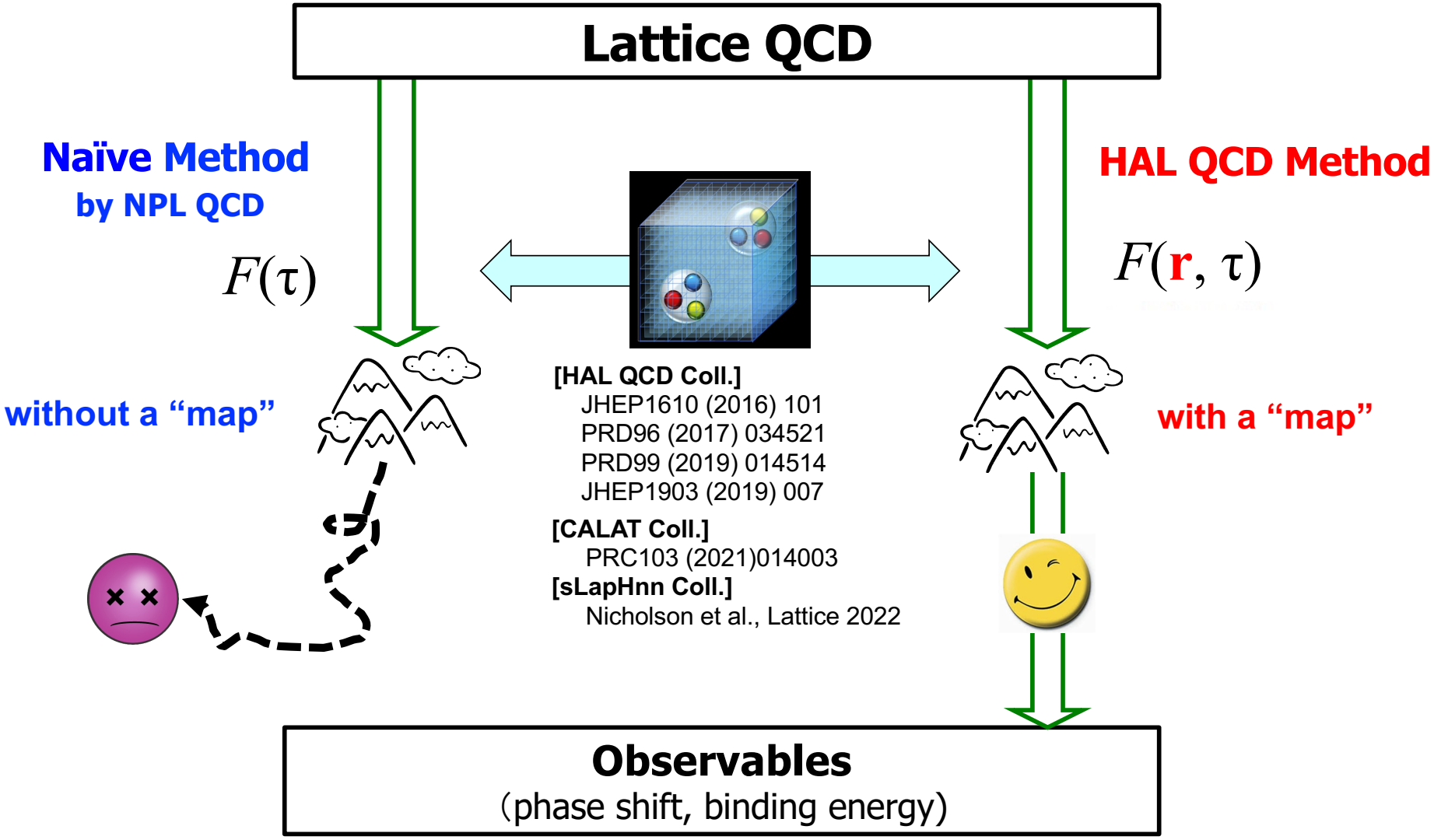
Foundation:	Haag, Nishijima, Zimmermann reduction formula (1957) Borchers' theorem (1961)	
Luscher's Method:	Luscher, Nucl. Phys. B354 (1991) 531	
HAL QCD Method:	Ishii, Aoki, Hatsuda,	Phys. Rev. Lett. 99 (2007) 022001
	HAL QCD Coll.,	Phys. Lett. B712 (2012) 437
Review:	Aoki & Doi,	Front. Phys. 8 (2020) 307

Time-dependent HAL QCD Equation

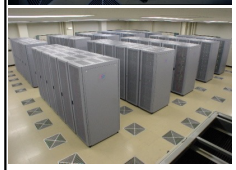
$$(\nabla^2 + \partial_{2t}^2 - m^2)F^J(\mathbf{r},t) = m\int d^3r\, U(\mathbf{r},\mathbf{r}')F^J(\mathbf{r}',t)$$

1. Derived from QCD
2. Fully relativistic equation
3. Faithful to S-matrix
4. Insensitive to lattice volume
5. Applicable to BB, MM, MB, BBB etc
6. Applicable to coupled channel systems




Lattice QCD
Naïve Method
by NPL QCD
$F(\tau)$
HAL QCD Method
$F(\mathbf{r}, \tau)$
without a "map"
with a "map"
[HAL QCD Coll.]
JHEP1610 (2016) 101
PRD96 (2017) 034521
PRD99 (2019) 014514
JHEP1903 (2019) 007
[CALAT Coll.]
PRC103 (2021)014003
[sLapHnn Coll.]
Nicholson et al., Lattice 2022
Observables
(phase shift, binding energy)

HAL QCD Lattice data



CP-PACS @Tsukuba
0.6 Tflops
(1996-2005)

PACS-CS @Tsukuba
14 TFlops
(2006-2011)

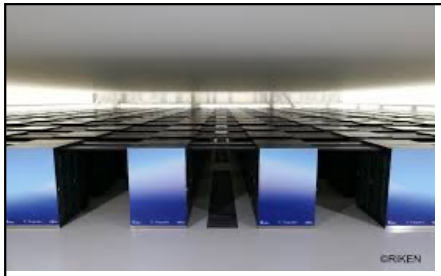
3-flavor & (2+1)-flavor
V~(3 fm)^3 , m_π > 400 MeV

BB	Inoue+, PTP 124 ('10)
H	Inoue+, PRL 106 ('11)
	NPA 881 ('12)
BB	Sasaki+, PTEP 2015 ('15)
NΩ	Etminan+, NPA 928 ('14)
ΩΩ	Yamada+, PTEP 2015 ('15)
KN, $\pi\Sigma$	Ikeda+, PoS Lat ('11)
KN	Murakami+, PTEP 2020 ('20)
T_{cc}	Ikeda+, PLB 729 ('14)
Z_c	Ikeda+, PRL 117 ('16)
D^{bar}-N	Ikeda+, HAL internal rep. ('16)
J/ψ-N	Sugiura+, PoS Lat ('18)
Λ_c-N	Miyamoto+, NPA 971 ('18)

K computer
@ RIKEN
10 PFlops
(2011-2019)

(2+1)-flavor
V=(8.1 fm)^3 , m_π=146 MeV

S=-1 (ΛN, ΣN)	Nemura+, EPJ conf. 175 ('18)
S=-3 (ΞΣ, ΞΛ-ΞΣ)	Ishii+, EPJ conf. 175 ('18)
S=-4 (ΞΞ)	Doi+, EPJ conf, 175 ('18)
SU(3) basis	Inoue+, AIP conf. 2130 ('19)
S=-2 (ΛΛ, NΞ)	Sasaki+, NPA 998 ('20)
S=-3 (NΩ)	Iritani+, PLB 792 ('19)
S=-6 (ΩΩ)	Gongyo+, PRL 120 ('18)
C=+6 ($\Omega_{ccc}\Omega_{ccc}$)	Tong+, PRL 127 ('21)
ϕN	Lyu+, 2205.10544 ('22)



Fugaku
@RIKEN
440 PFlops
(2020-)

(2+1)-flavor
V=(8.1 fm)^3 , m_π=138 MeV

BB: Octet x Octet
BB: Octet x Decuplet
BB: Octet x Charmed

BB: LS force

MB: KN, ϕN , DN, J/ψ-N, ⋯

MM: $\pi\pi$, πK, DD*, J/ψ-J/ψ, ⋯

BBB

Phase I: exploratory studies → **Phase II: almost physical point** → **Phase III: physical point**

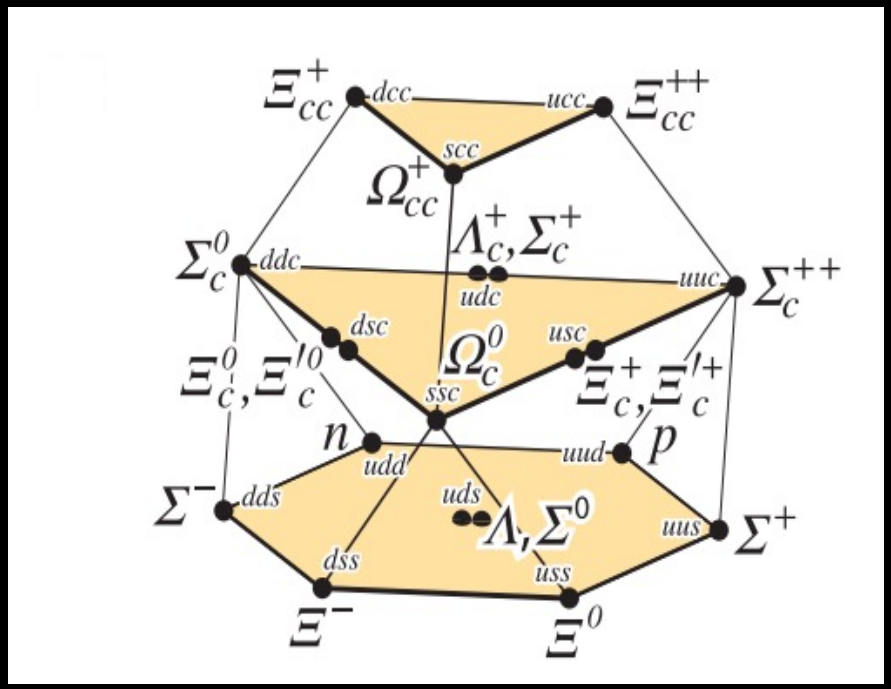
Phase II (almost physical point) Highlights

K computer
@ RIKEN
10 PFlops
(2011-2019)

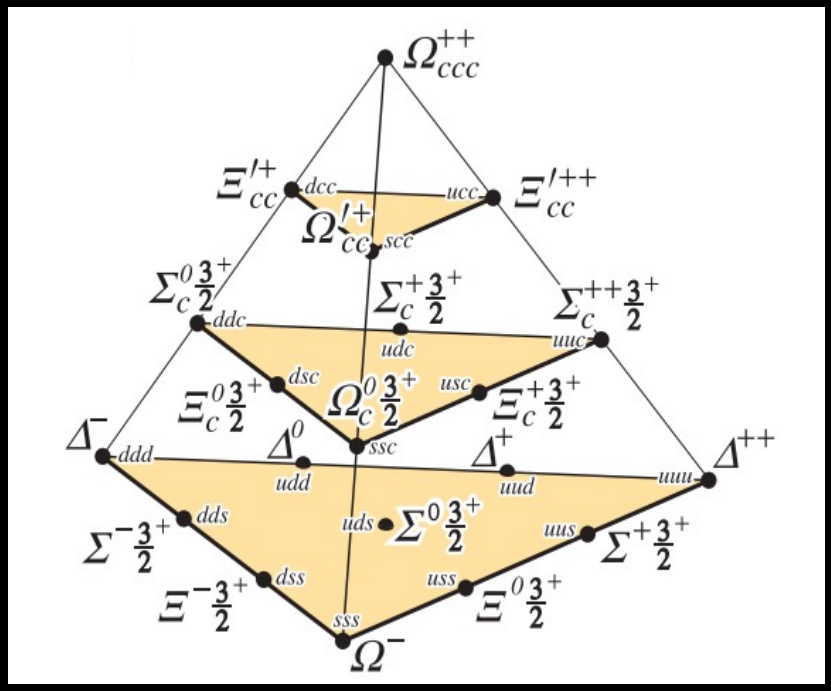
(2+1)-flavor
$V=(8.1\ \mathrm{fm})^3$, **m_π=146 MeV**

Baryons multiplet

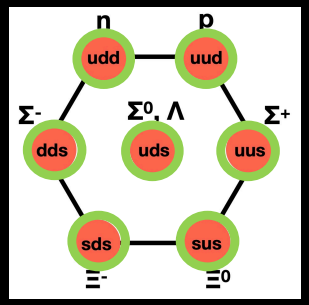
spin 1/2 **20-plet**



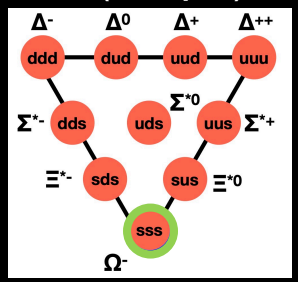
spin 3/2 **20-plet**



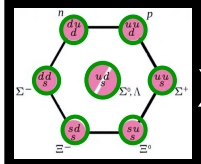
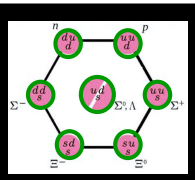
8 (Octet)



10 (Decuplet)



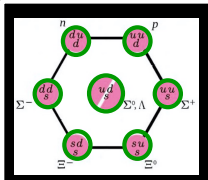
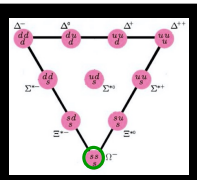
Baryon pairs in flavor SU(3)


x


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

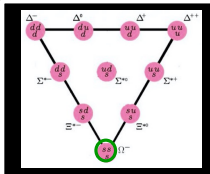
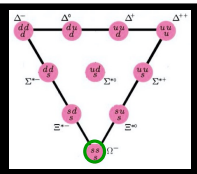
$NN(^1S_0)$ $H_{\Lambda\Lambda-N\Xi-\Lambda\Sigma}(^1S_0)$ $NN(^3S_1)$

Jaffe (1977)


x


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

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


x


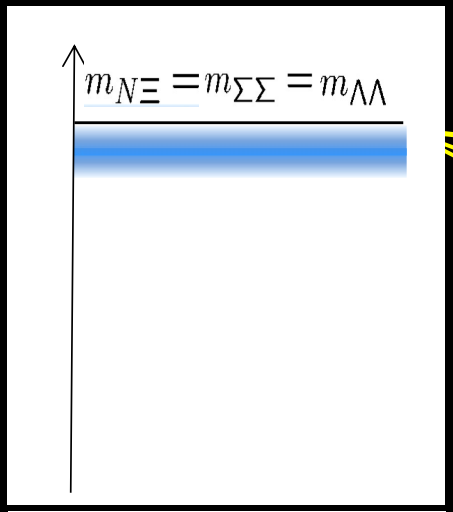
$10 \times 10 = 28 + 27 + 35 + 10^*$

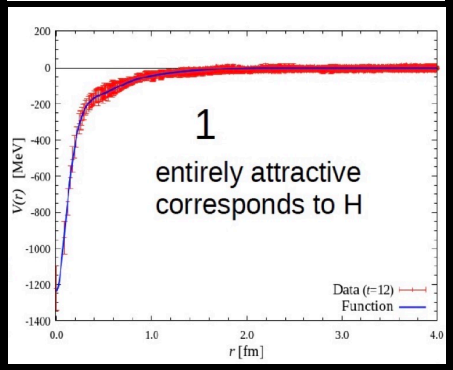
Kopeliovich+ (1990) $\Omega\Omega(^1S_0)$ $\Delta\Delta(^7S_3)$ Dyson+ (1964)

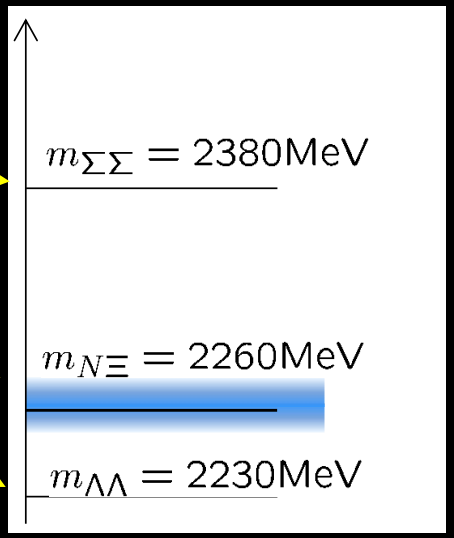
Fate of "H (uuddss)" dibaryon from LQCD

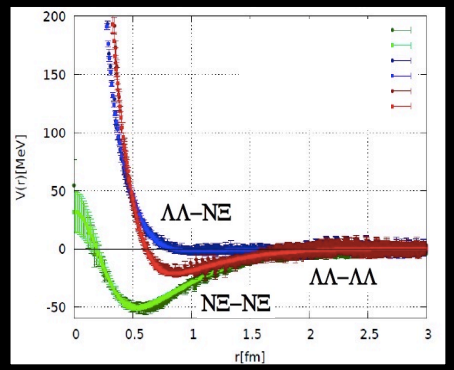
$m_{ud}=m_s$ (~ 100 MeV)

$m_{ud} < m_s$ (~10MeV) (~100MeV)









Inoue et al., [HAL QCD Coll.]
Nucl. Phys. A881 (2012) 28

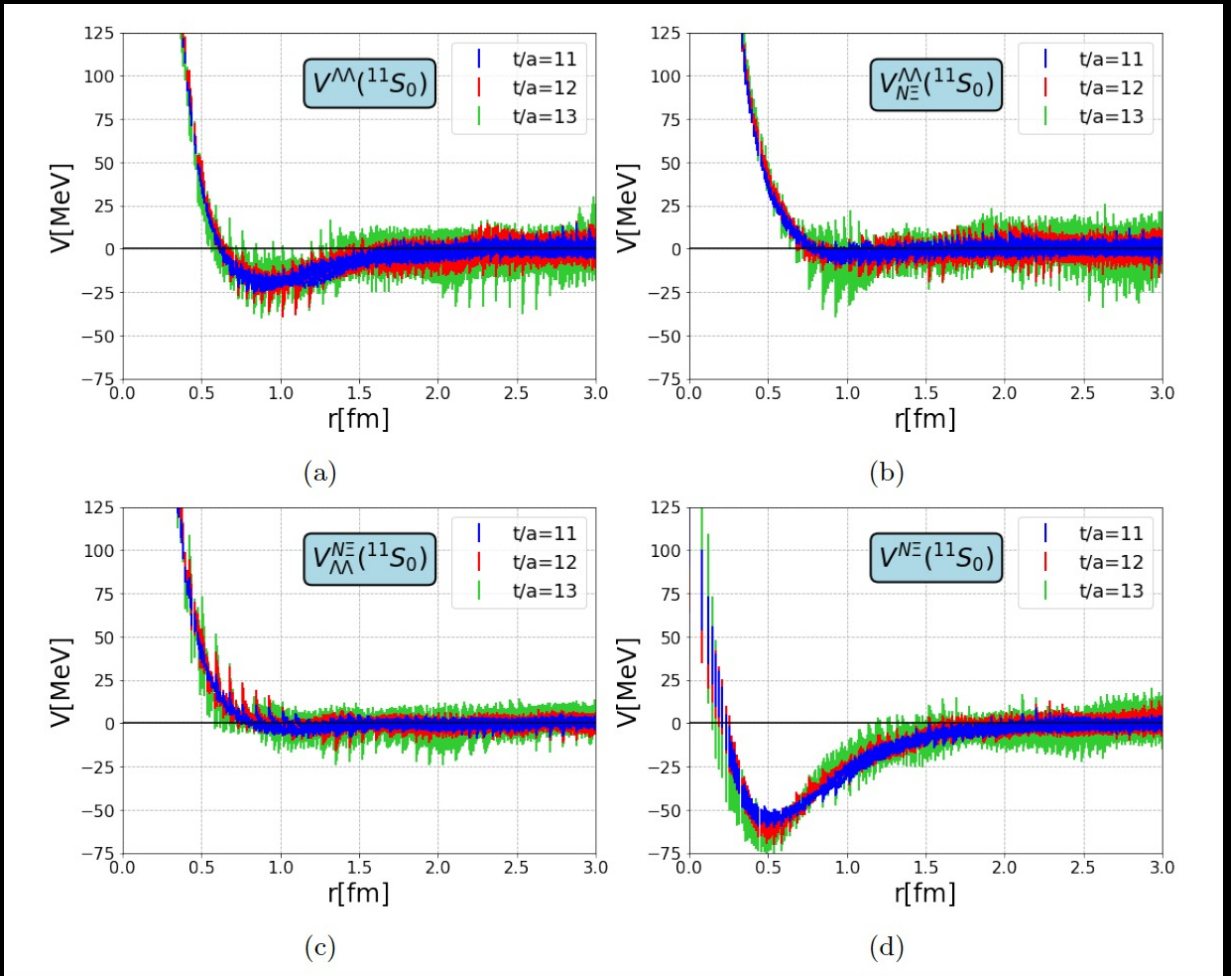
Sasaki et al., [HAL QCD Coll.]
Nucl. Phys. A998 (2020) 121737

Coupled Channel S=-2 system ($^{11}S_0$)

K. Sasaki+ [HAL QCD Coll.]
Nucl. Phys. **A998** (2020)

Weak
ΛΛ attraction

Short-range
(weak)
NΞ-ΛΛ coupling

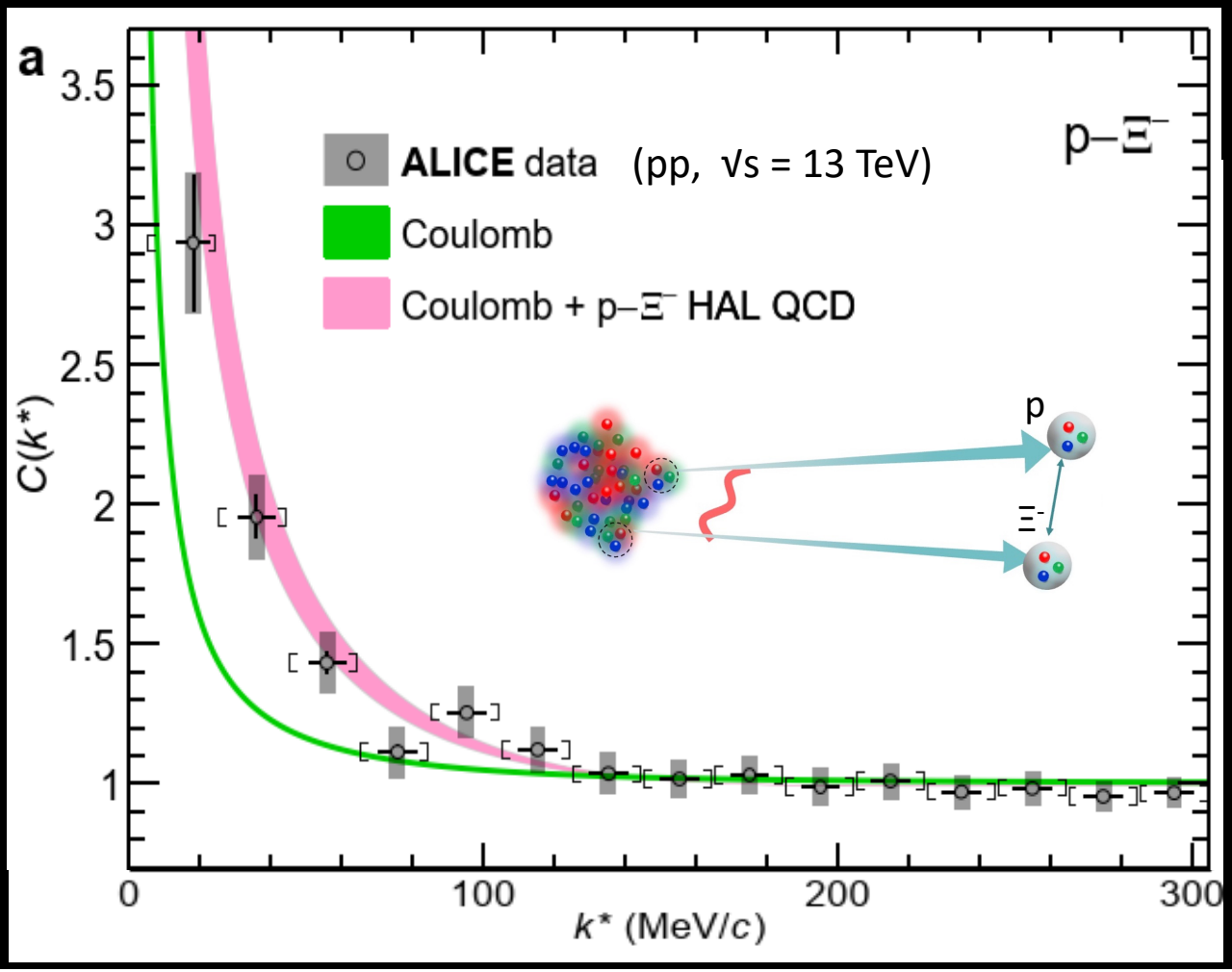


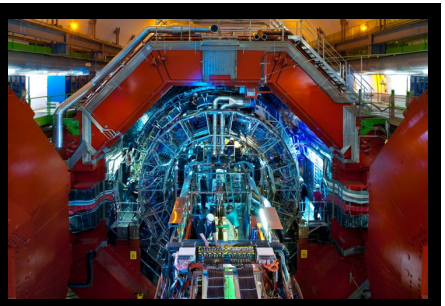
Short-range
(weak)
NΞ-ΛΛ coupling

Strong
NΞ attraction

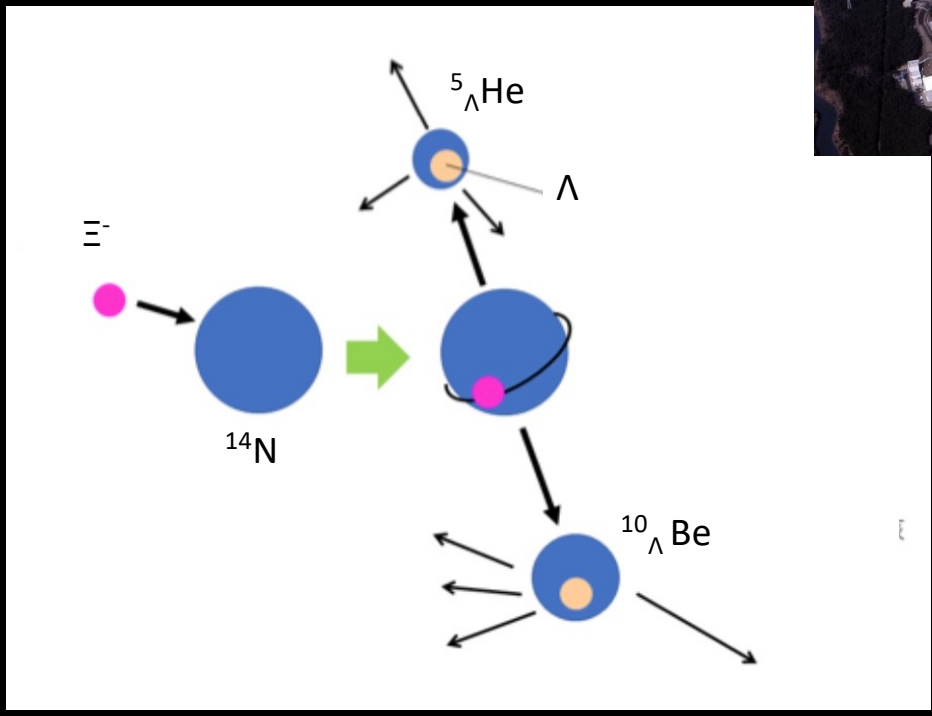
Femtoscopy: NΞ pair in pp collisions

LHC ALICE Coll., Nature 588 (2020) 232





Discovery of Ξ hypernuclei (J-PARC)

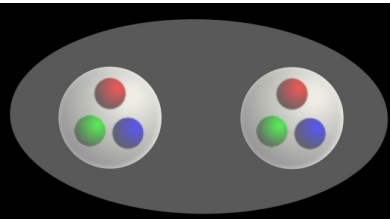


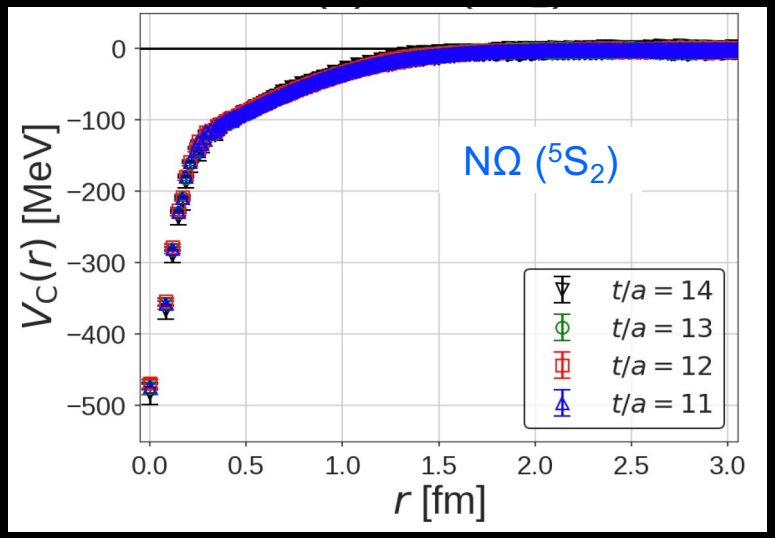
Event	Target	Decay mode	B_{Ξ^-} [MeV]
KISO [9,10]	^{14}N	$^{10}_{\Lambda}$Be $^{5}_{\Lambda}$He	3.87 ± 0.21
	^{14}N	$^{10}_{\Lambda}$Be* $^{5}_{\Lambda}$He	1.03 ± 0.18
IBUKI (present data)	^{14}N	$^{10}_{\Lambda}$Be $^{5}_{\Lambda}$He	1.27 ± 0.21

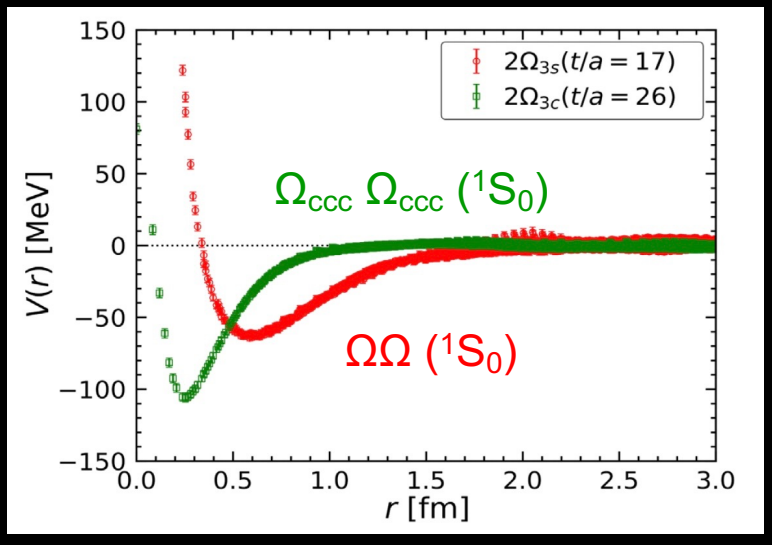
J-PARC E07 Coll.,
Phys.Rev.Lett.
126 (2021) 062501

Attraction in NΞ, Weak NΞ- ΛΛ coupling

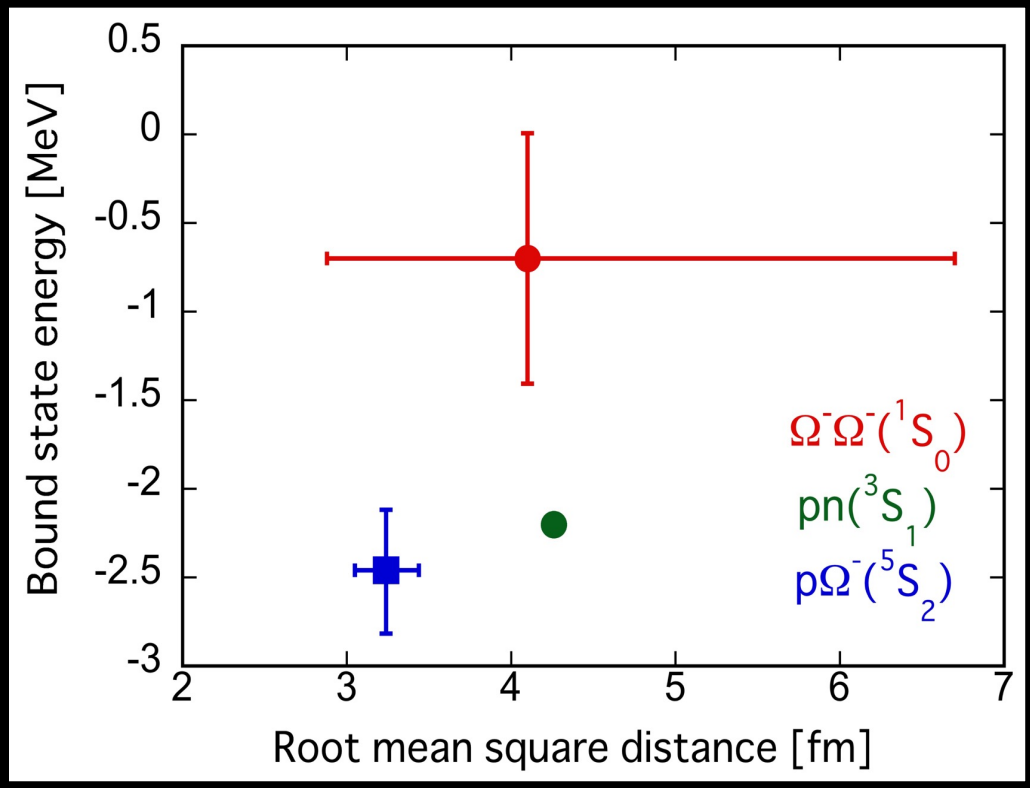
Baryon pair with S=-3, S=-6, C=+6





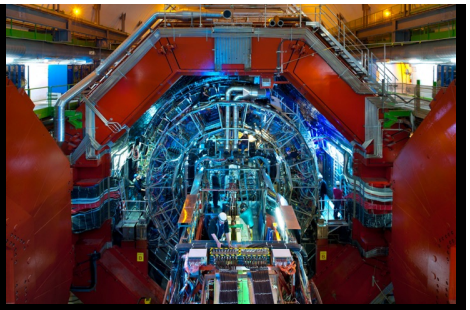


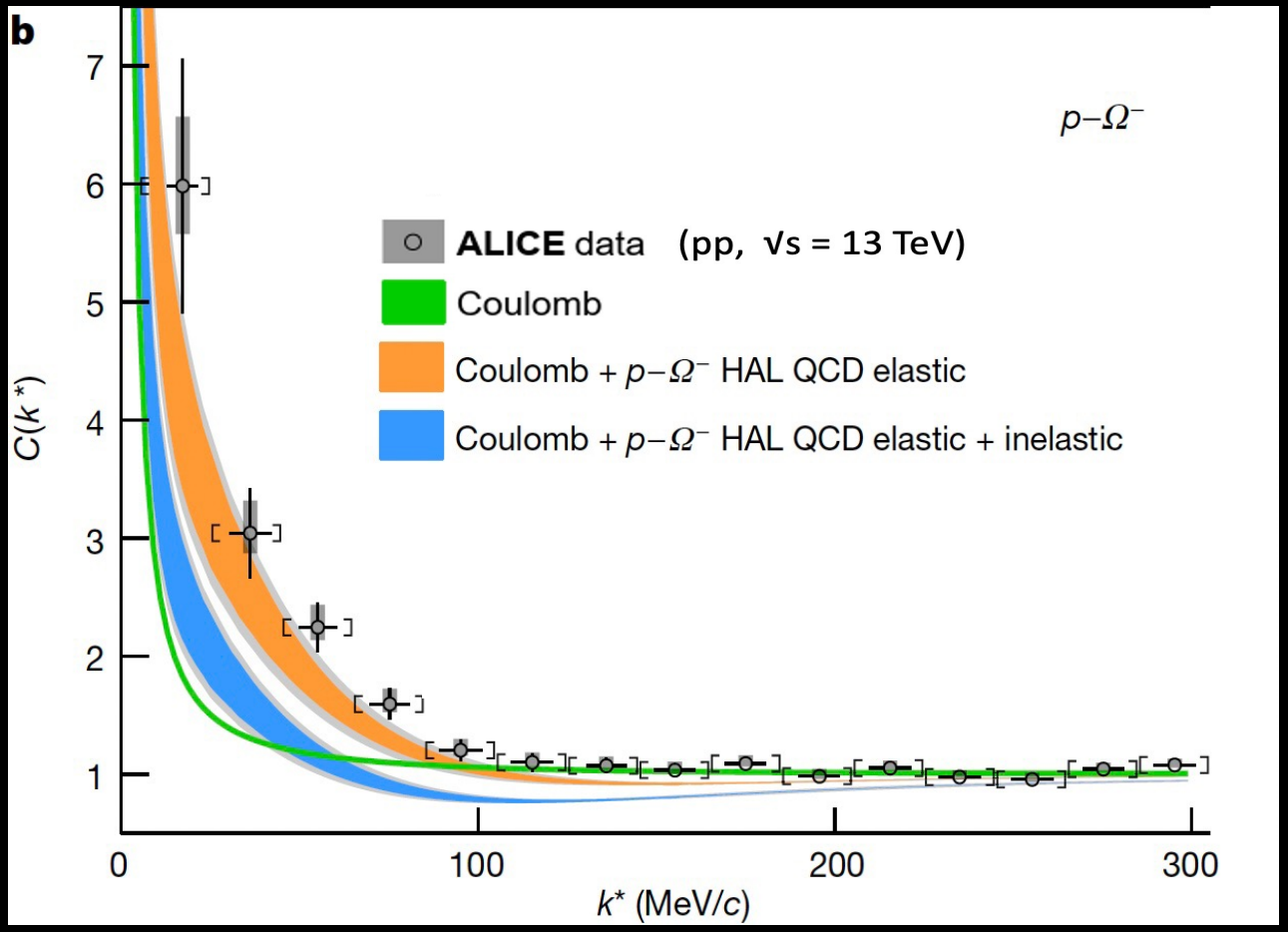
Gongyo+ [HAL QCD Coll.], PRL 120 (2018) 212001
Iritani+ [HAL QCD Coll.], PLB 792 (2019) 284
Tong+ [HAL QCD Coll.], PRL 127 (2021) 072003

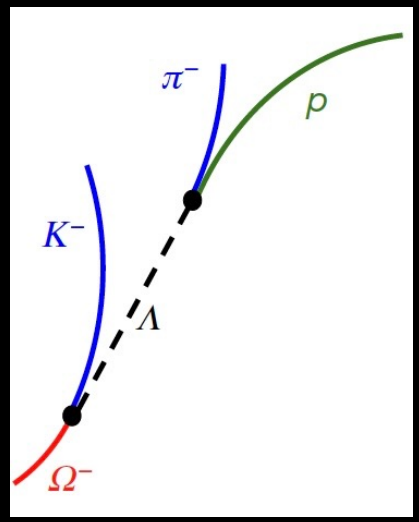


Femtoscopy: NΩ pair in pp collisions

LHC ALICE Coll., Nature 588 (2020) 232

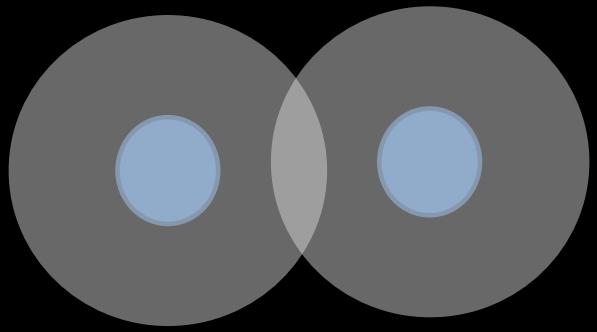






Question:

What is the force between
"neutral particles" at long range ?



Answer:

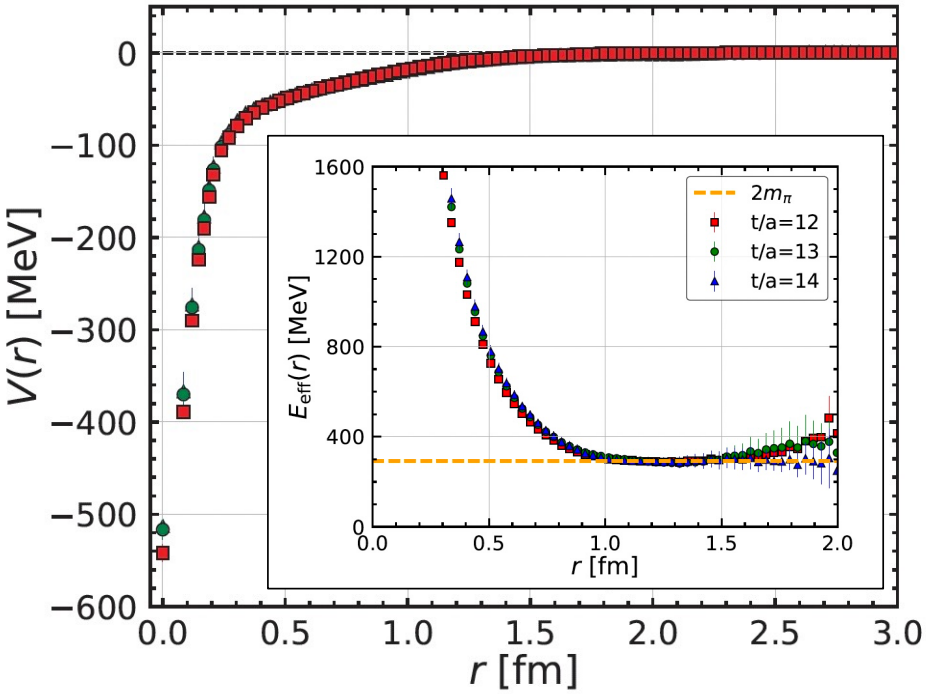
Atoms
2-photon exchange force
= van der Waals (Casimir-Polder) force → $-1/r^7$

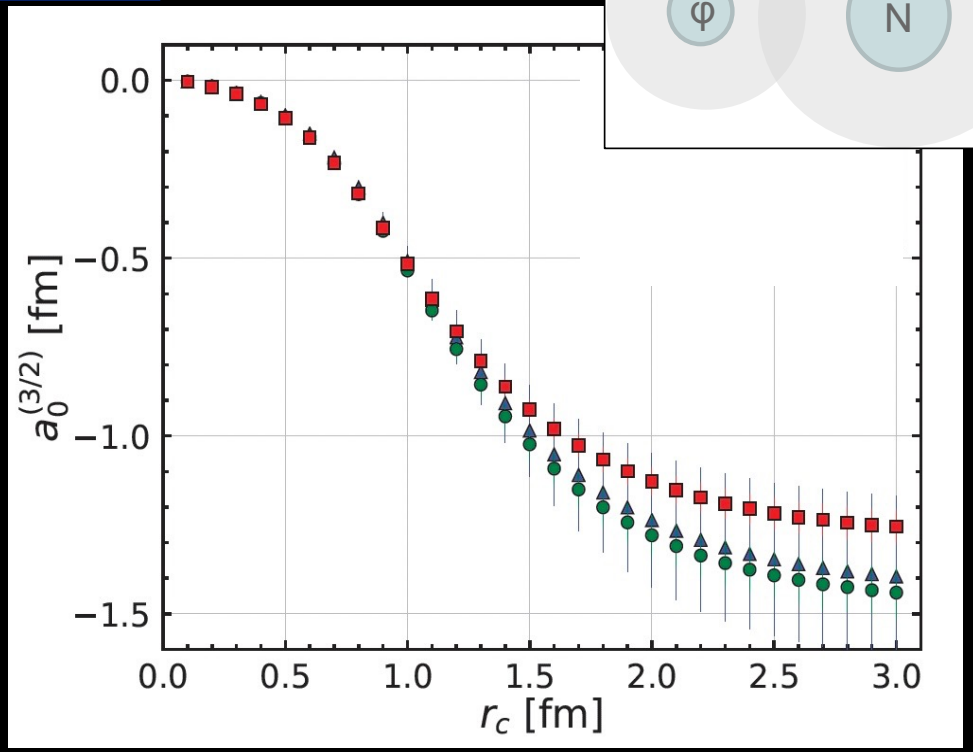
QCD
2-pion exchange force

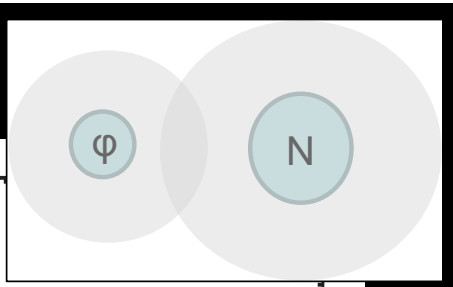
Bhanot and Peskin, Nucl. Phys. B156 (1979) 391
Fujii and Kharzeev, Phys. Rev. D60 (1999) 114039
Brambilla et al., Phys. Rev. D93 (2006) 054002

First evidence of two-pion exchange in LQCD

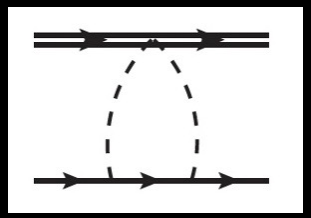
Lyu+ [HAL QCD Coll.], 2205.10544 [hep-lat]







Two-pion Tail at r > $(2m_\pi)^{-1}$



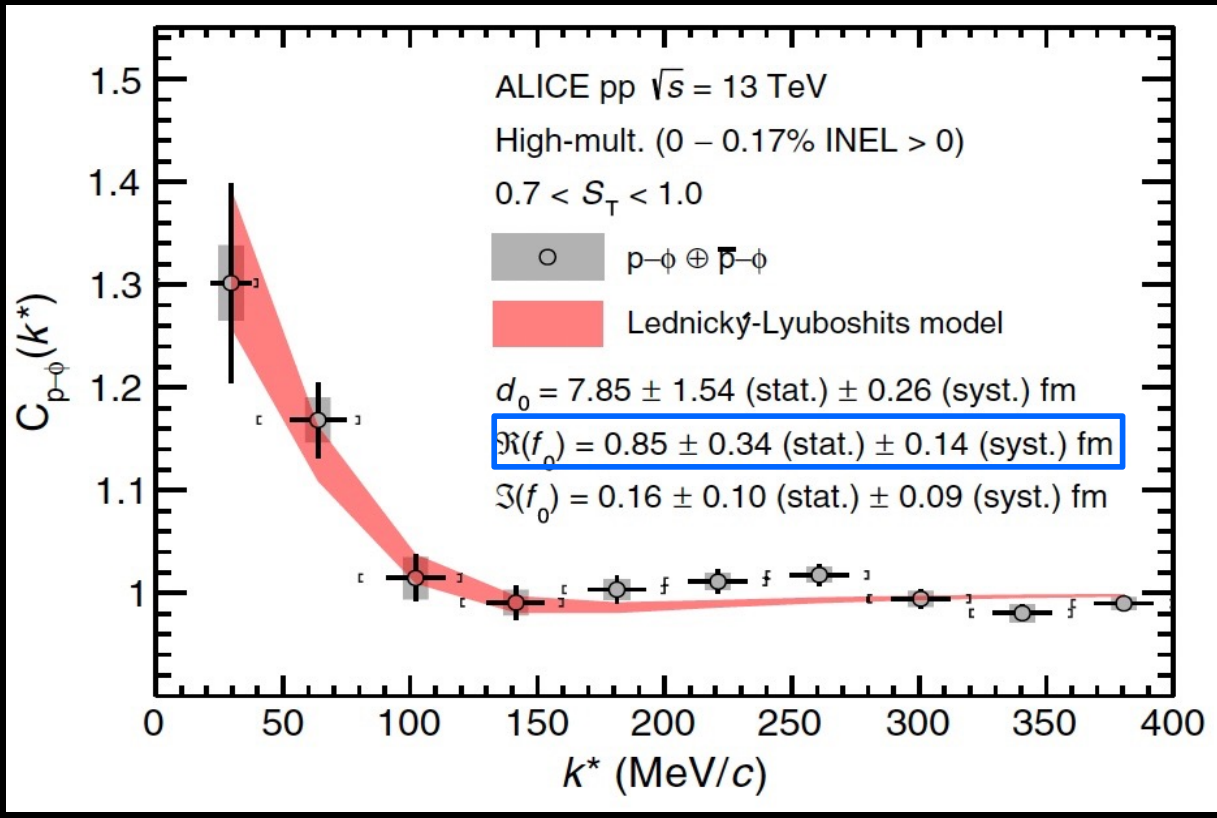
$$V(\boldsymbol{r}) = \frac{3g_A^2 m_\pi^4 (c_{di} + c_m)}{128\pi^2 F^2} \frac{e^{-2m_\pi r}}{r^2}.$$

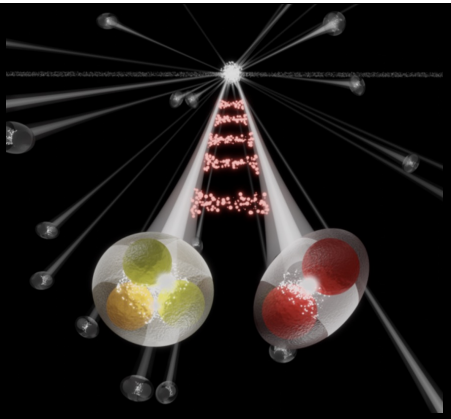
Krein and Casttela , Phys. Rev. D98 (2018) 0140289.

PHYSICAL REVIEW LETTERS **127,** 172301 (2021)

Experimental Evidence for an Attractive *p*-ϕ Interaction

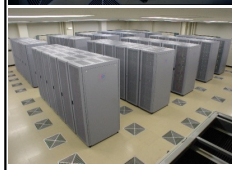
S. Acharya *et al.*[*]
(ALICE Collaboration)





https://home.cern/news/news/physics/alice-takes-next-step-understanding-interaction-between-hadrons

HAL QCD Lattice data



CP-PACS @Tsukuba
0.6 Tflops
(1996-2005)

PACS-CS @Tsukuba
14 TFlops
(2006-2011)

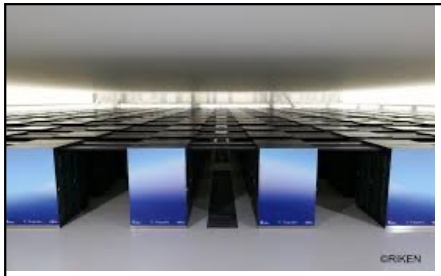
3-flavor & (2+1)-flavor
V~(3 fm)^3 , m_π > 400 MeV

BB	Inoue+, PTP 124 ('10)
H	Inoue+, PRL 106 ('11)
	NPA 881 ('12)
BB	Sasaki+, PTEP 2015 ('15)
NΩ	Etminan+, NPA 928 ('14)
ΩΩ	Yamada+, PTEP 2015 ('15)
KN, $\pi\Sigma$	Ikeda+, PoS Lat ('11)
KN	Murakami+, PTEP 2020 ('20)
T_{cc}	Ikeda+, PLB 729 ('14)
Z_c	Ikeda+, PRL 117 ('16)
D^{bar}-N	Ikeda+, HAL internal rep. ('16)
J/ψ-N	Sugiura+, PoS Lat ('18)
Λ_c-N	Miyamoto+, NPA 971 ('18)

K computer
@ RIKEN
10 PFlops
(2011-2019)

(2+1)-flavor
V=(8.1 fm)^3 , m_π=146 MeV

S=-1 (ΛN, ΣN)	Nemura+, EPJ conf. 175 ('18)
S=-3 (ΞΣ, ΞΛ-ΞΣ)	Ishii+, EPJ conf. 175 ('18)
S=-4 (ΞΞ)	Doi+, EPJ conf, 175 ('18)
SU(3) basis	Inoue+, AIP conf. 2130 ('19)
S=-2 (ΛΛ, NΞ)	Sasaki+, NPA 998 ('20)
S=-3 (NΩ)	Iritani+, PLB 792 ('19)
S=-6 (ΩΩ)	Gongyo+, PRL 120 ('18)
C=+6 ($\Omega_{ccc}\Omega_{ccc}$)	Tong+, PRL 127 ('21)
ϕN	Lyu+, 2205.10544 ('22)



Fugaku
@RIKEN
440 PFlops
(2020-)

(2+1)-flavor
V=(8.1 fm)^3 , m_π=138 MeV

BB: Octet x Octet
BB: Octet x Decuplet
BB: Octet x Charmed

BB: LS force

MB: KN, ϕN , DN, J/ψ-N, ⋯

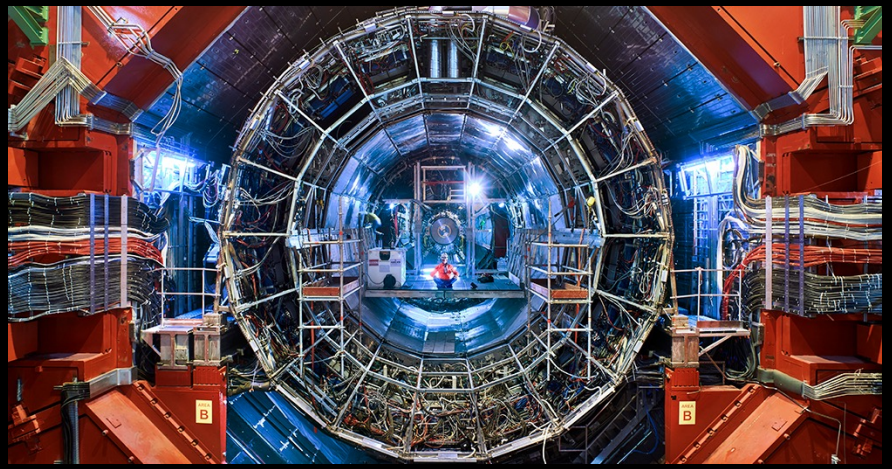
MM: $\pi\pi$, πK, DD*, J/ψ-J/ψ, ⋯

BBB

WE ARE HERE !

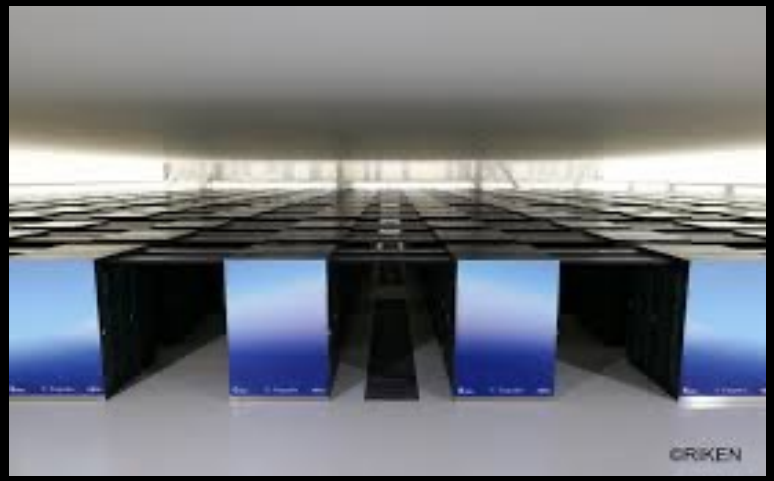
Summary

Laboratory Data



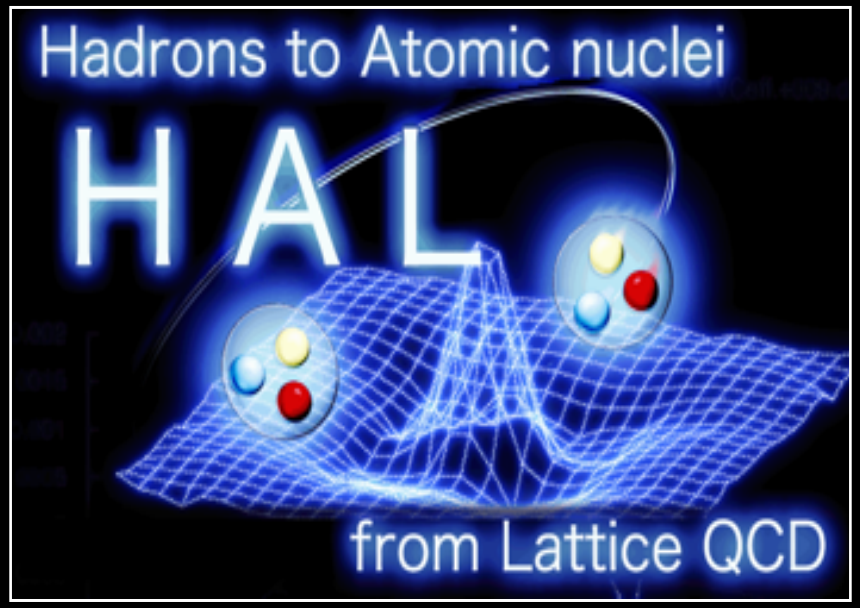
HAL QCD Method

Lattice Data



HAL QCD Method applied to charm sector.
→ Takuya Sugiura's talk (Sept. 30, 17:30-)

Collaborators are very much welcome!
- lattice analysis, applications -



(KEK) T. Aoyama

(RIKEN) T. Doi, T. Hatsuda, T. Sugiura

(Nihon) T. Inoue

(YITP) Y. Akahoshi, S. Aoki, K. Murakami

(RCNP) T. M. Doi, N. Ishii, K. Murano, H. Nemura

(Osaka) Y. Ikeda, K.Sasaki

(Birjand) F. Etminan

(Beijing) Yan Liu, Hui Tong