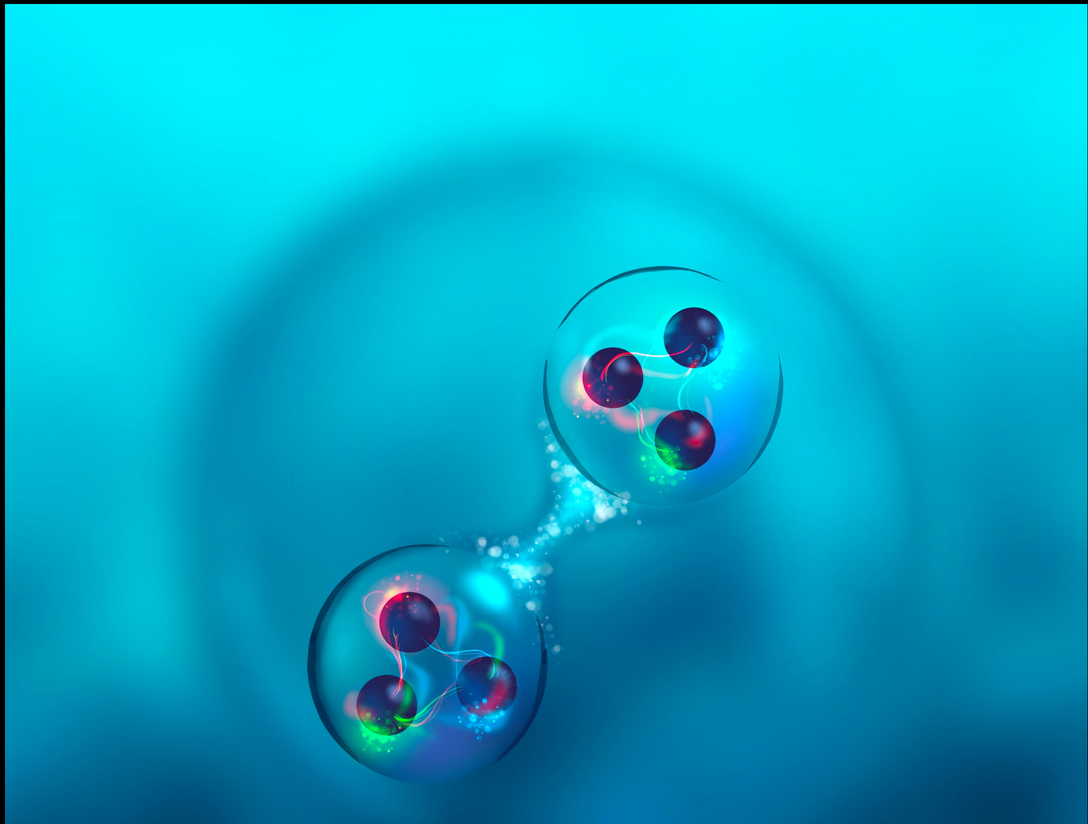
Hadron Interactions from Lattice QCD
- Theory Meets Experiments -



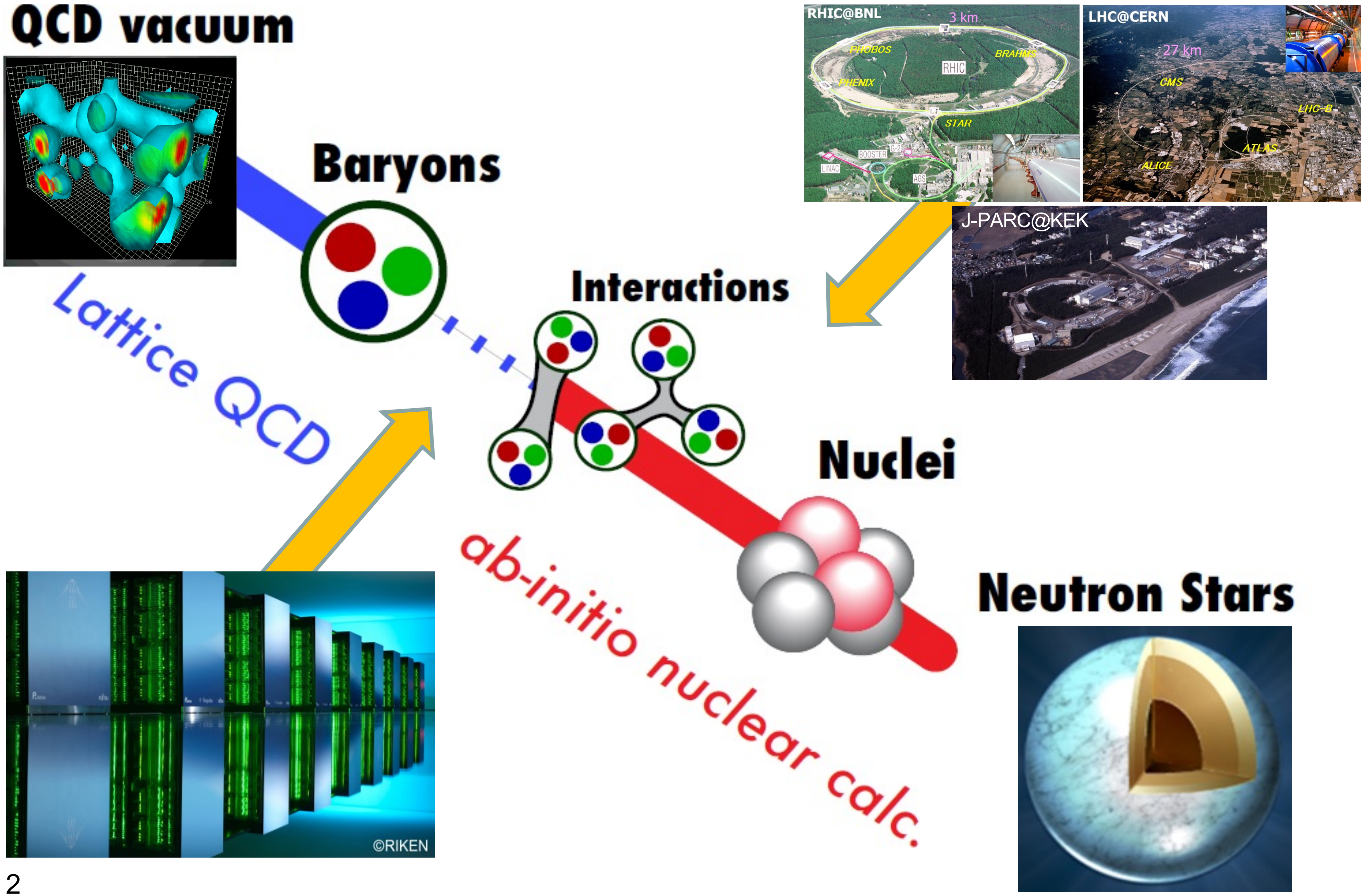
1. Introduction
2. LQCD for hadron interactions
3. LQCD vs. Expt. (RHIC/LHC/J-PARC)
4. Summary

Tetsuo Hatsuda
(RIKEN iTHEMS)

iTHEMS
RIKEN interdisciplinary Theoretical & Mathematical Sciences

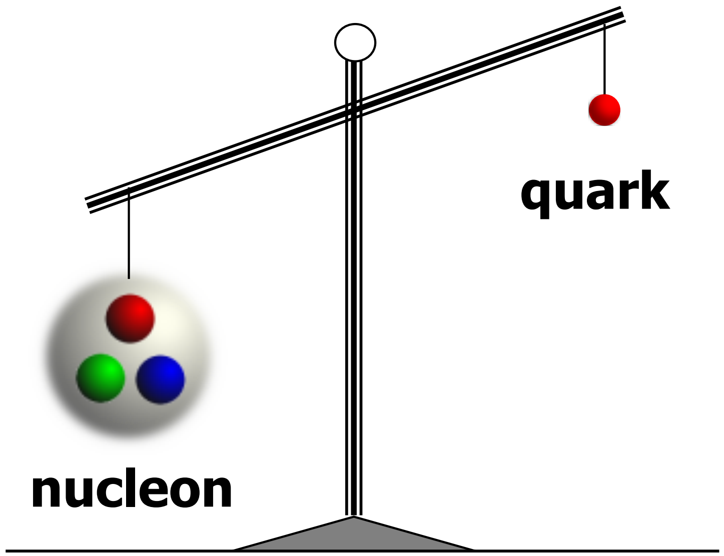
RHIC-BES Seminar
(Nov.15, 2022)

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



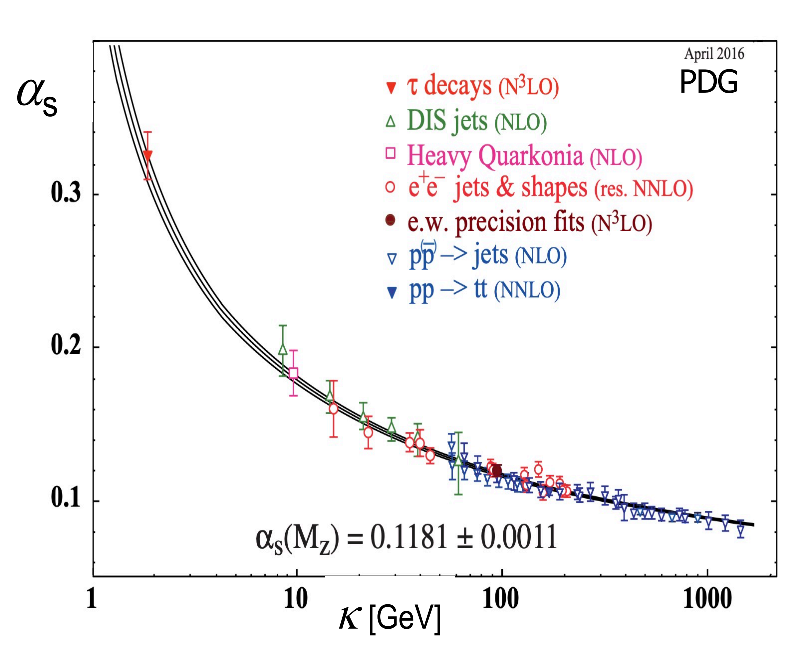
QCD is non-perturbative

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



Quark mass ~ 3 MeV

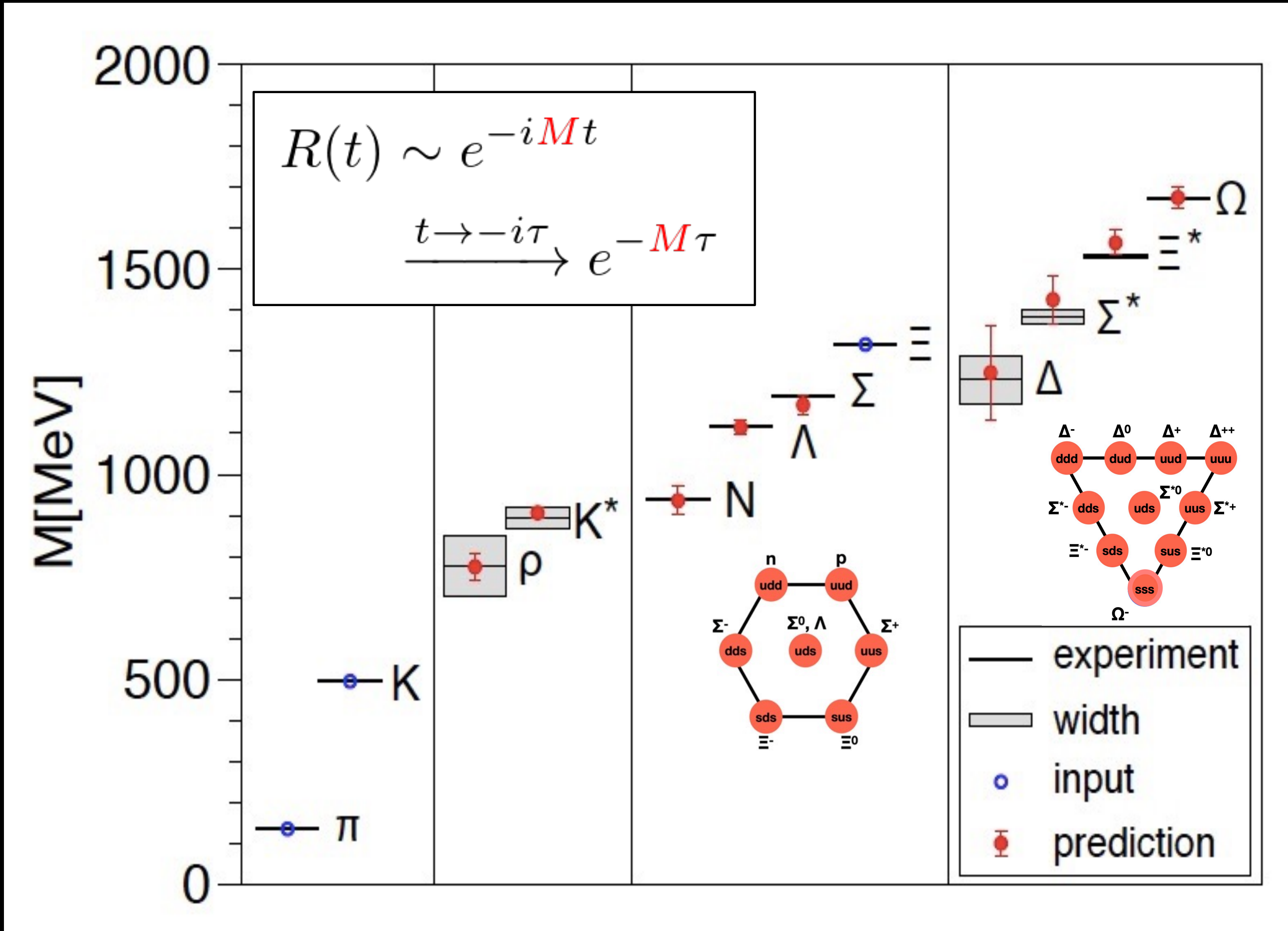
Nucleon mass ~ 940 MeV



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

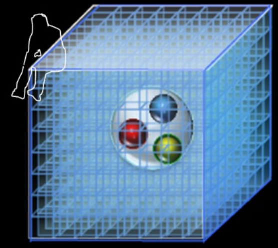
FLAG (Flavor-Lattice Averaging Group) http://flag.unibe.ch/

Hadron masses from LQCD

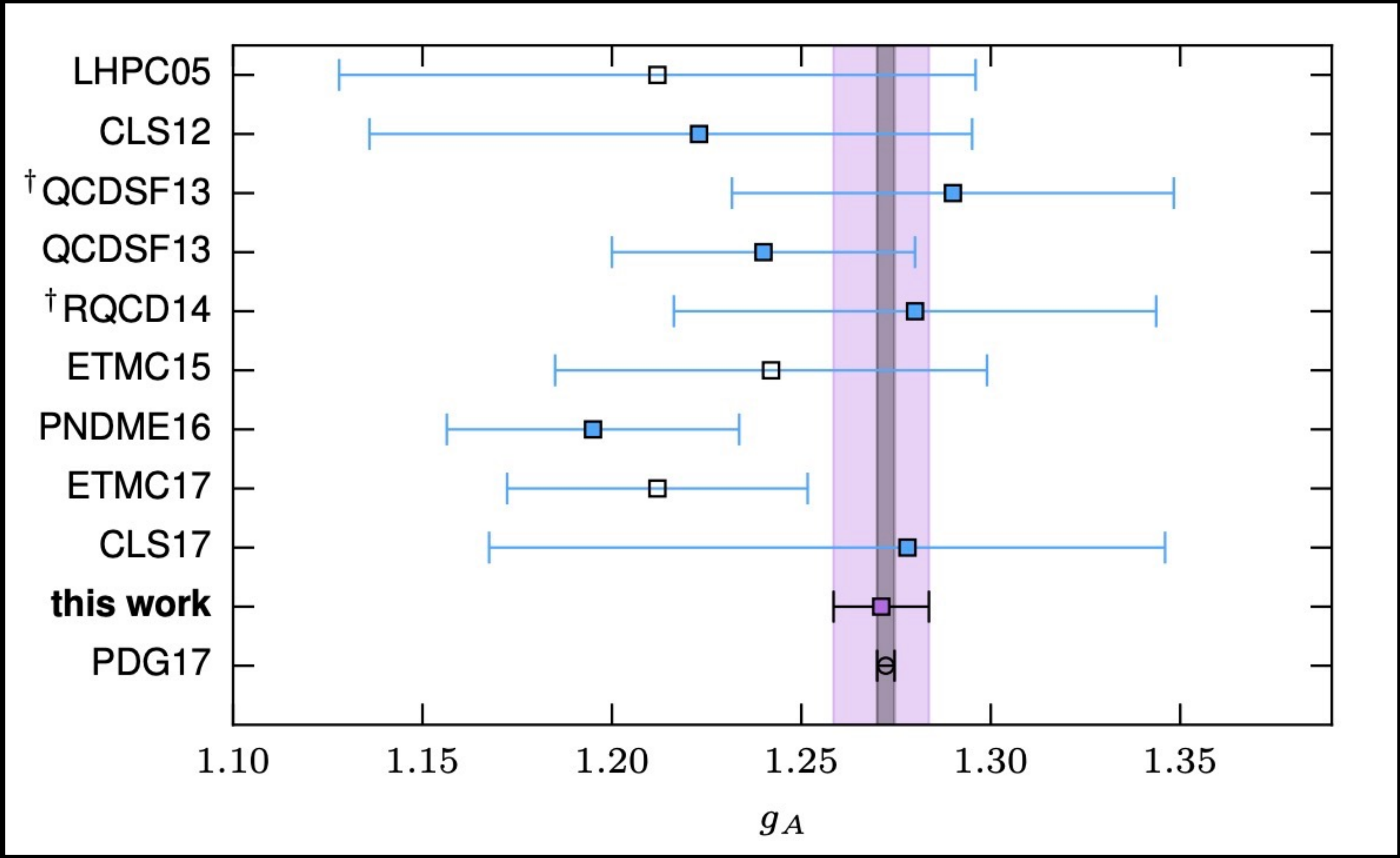


Review: Fodor and Hoelbling, Rev. Mod. Phys. 84 (2012) 449

Percent-level determination of g_A from LQCD



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

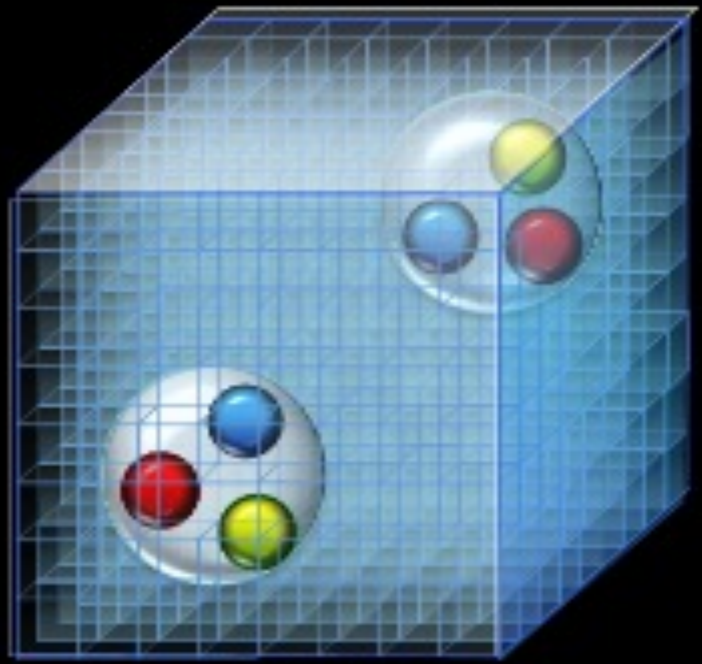


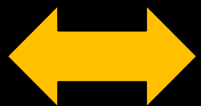
$(g_A)_{LQCD} = 1.271(13)$
$(\tau_n)_{LQCD} = 884(15)$ s

⟺

$(g_A)_{expt} = 1.272(2)$
$(\tau_n)_{PDG} = 880.2(1.0)$ s

Baryon Interactions





Exotic hadrons
Hypernuclei
Hyperons in neutron star

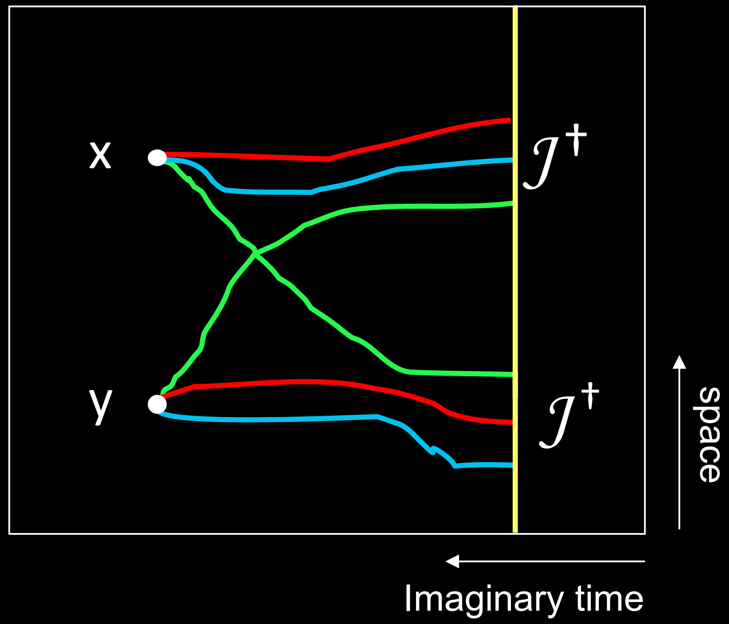
Interaction between compositive particles in QFT

Foundation: Haag, Nishijima, Zimmermann (1957), Borchers (1961)

Luscher's Method: Luscher, NPB <u>354</u> (1991) 531

HAL QCD Method: Ishii, Aoki, Hatsuda, PRL <u>99</u> (2007) 022001
HAL QCD Coll., PLB <u>712</u> (2012) 437

Recent eview: Aoki & Doi, Front. Phys. <u>8</u> (2020) 307



$$F^J(\mathbf{r},t) = \sum_n a_n^J \psi_n(\mathbf{r}) e^{-E_n t}$$

t >t* ~1fm

Time-dependent HAL QCD Equation

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

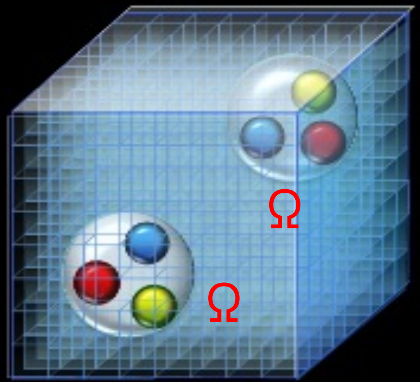
1. Derived from QCD
2. Fully relativistic
3. Faithful to S-matrix
4. Insensitive to lattice volume
5. Applicable to BB, MM, MB, BBB etc
6. Applicable to coupled channel systems

$$U(\mathbf{r},\mathbf{r}') = V(\mathbf{r},\mathbf{v})\delta(\mathbf{r}-\mathbf{r}'),$$

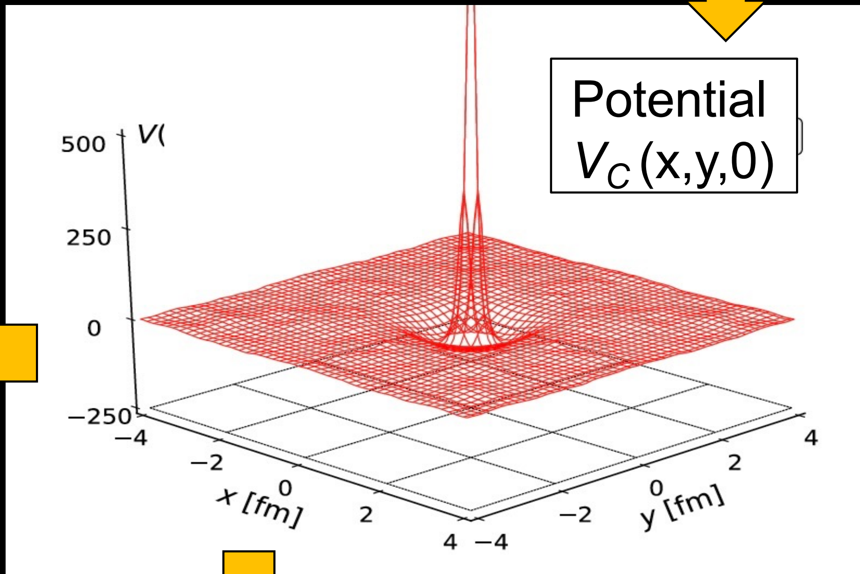
$$V(\mathbf{r},\mathbf{v}) = \underbrace{V_C(r) + V_T(r)S_{12}}_{\text{LO}} + \underbrace{V_{LS}(r)\mathbf{L}\cdot\mathbf{S}}_{\text{NLO}} + \underbrace{O(\mathbf{v}^2)}_{\text{N}^2\text{LO}} + \cdots$$

HAL QCD Procedure: an example
($\Omega\Omega$ at m_π=146MeV)

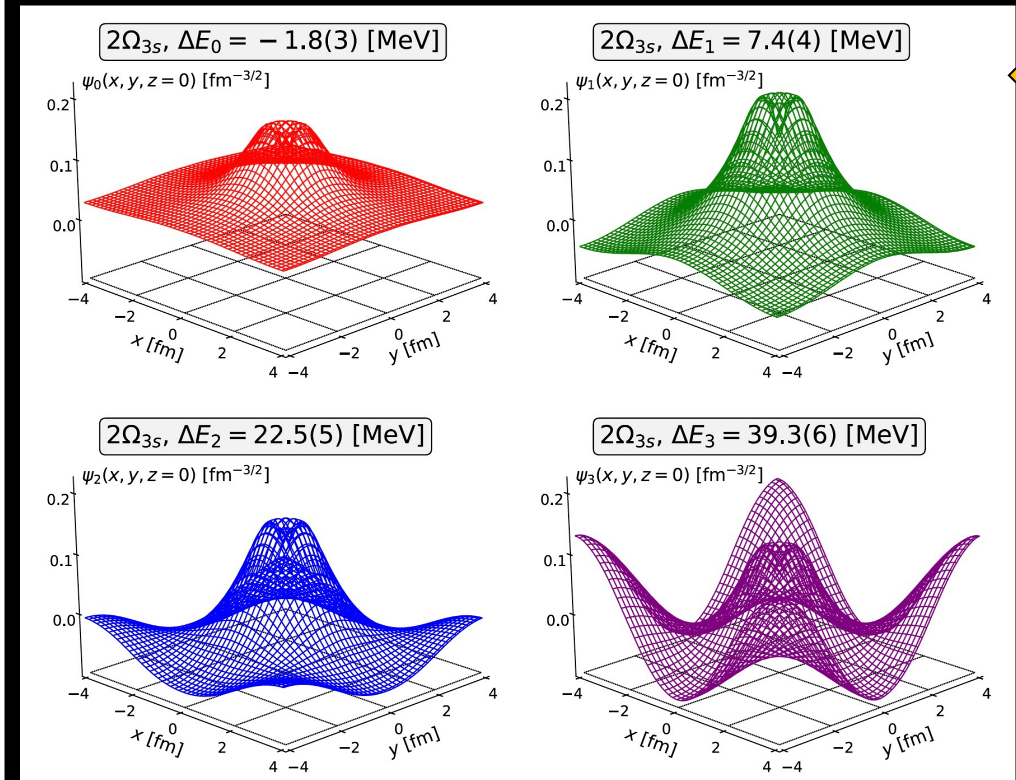
Gongyo+ [HAL QCD], PRL 120 (2018) 212001
Lyu+ [HAL QCD], PRD 105 (2022) 074512

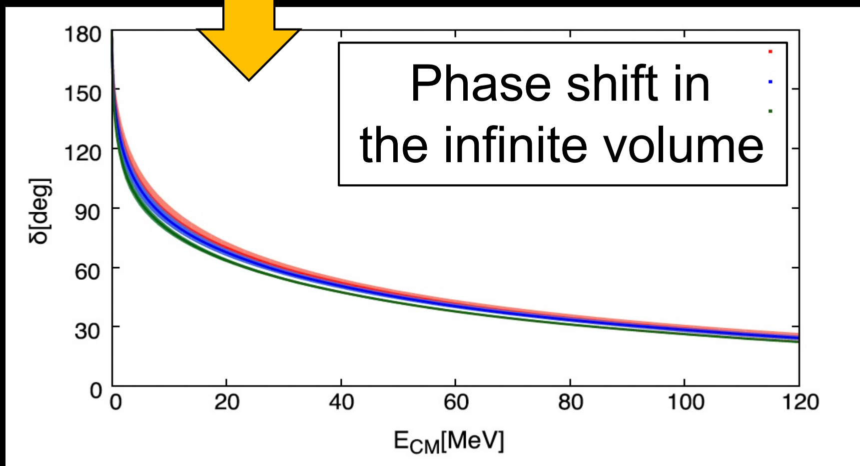


$$F^J(\mathbf{r},t) = \sum_n a_n^J \psi_n(\mathbf{r}) e^{-E_n t} \rightarrow V_C(r)$$

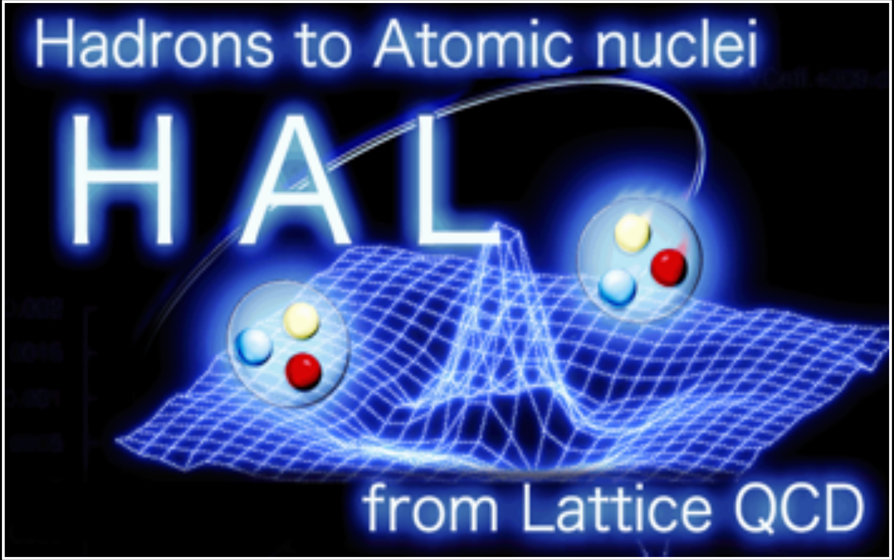


Ψ_n (r) and E_n in a finite volume

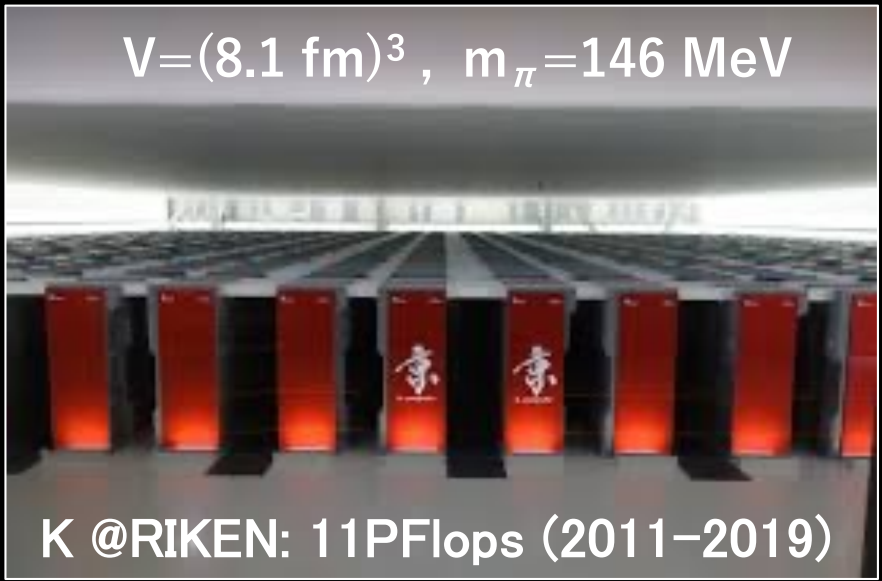


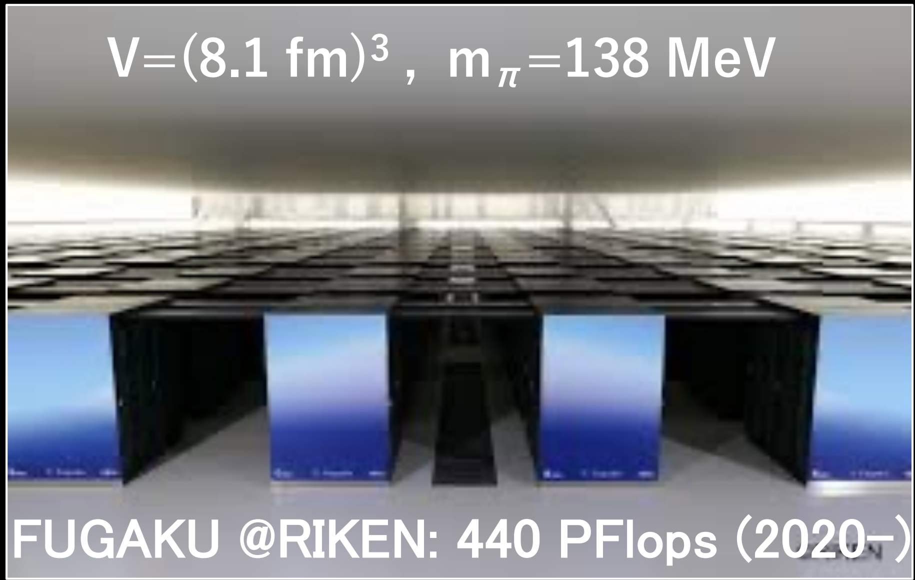


Large scale LQCD simulations for BB interactions

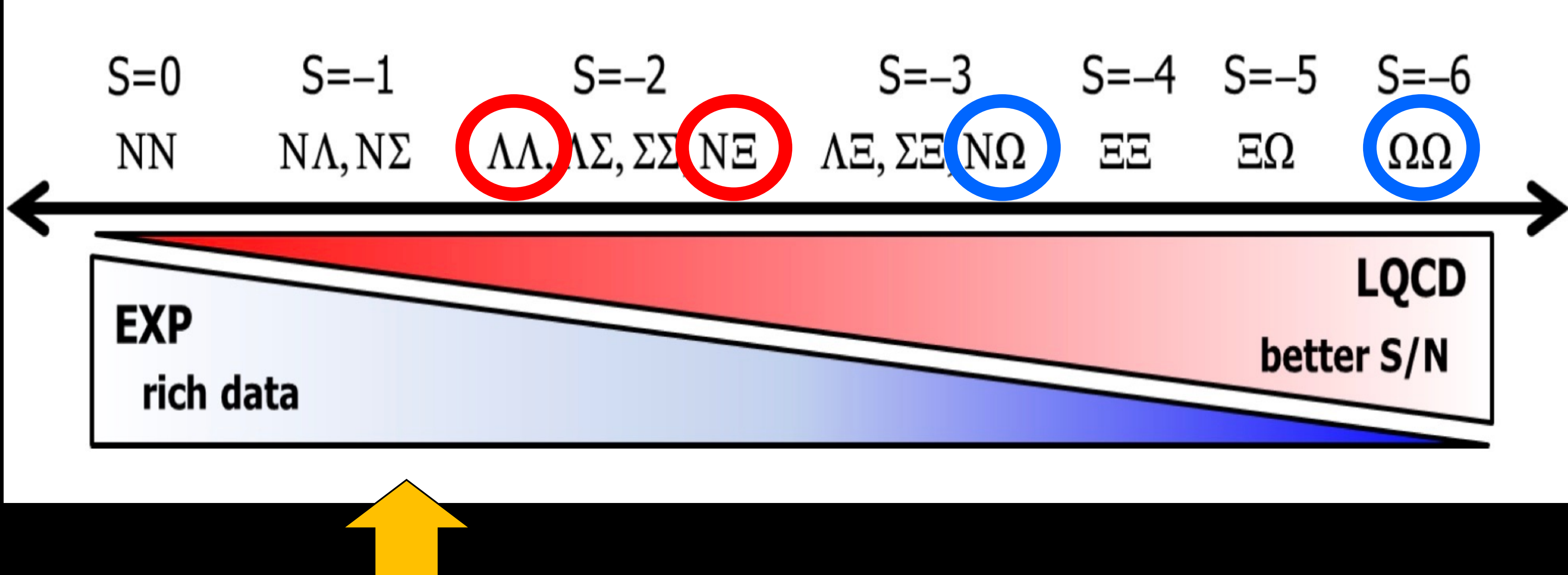


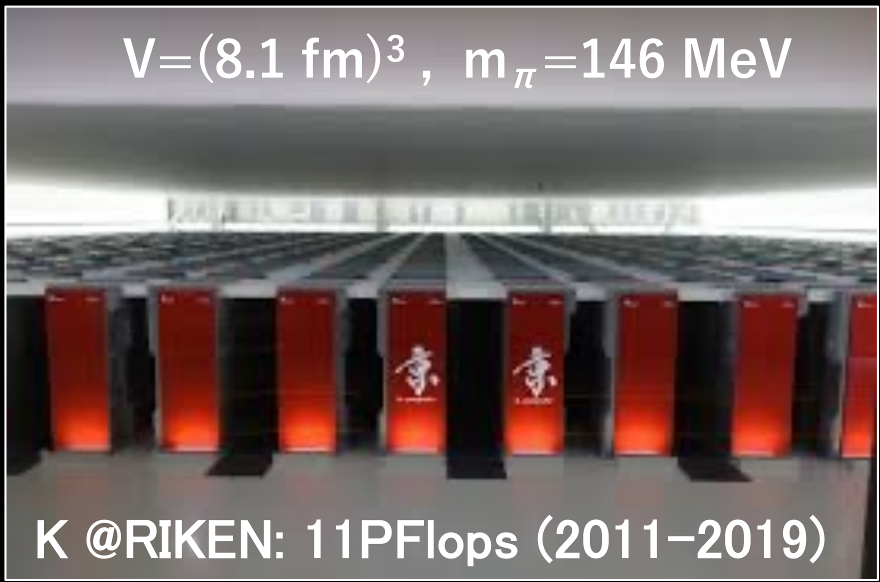
(KEK) T. Aoyama
(RIKEN) T. Doi, T. Hatsuda, T. Sugiura
(Nihon) T. Inoue
(YITP) Y. Akahoshi, S. Aoki, K. Murakami
(RCNP) T. M. Doi, N. Ishii, K. Murano, H. Nemura
(Osaka) Y. Ikeda, K.Sasaki
(Birjand) F. Etminan
(Beijing) Y. Liu, H. Tong

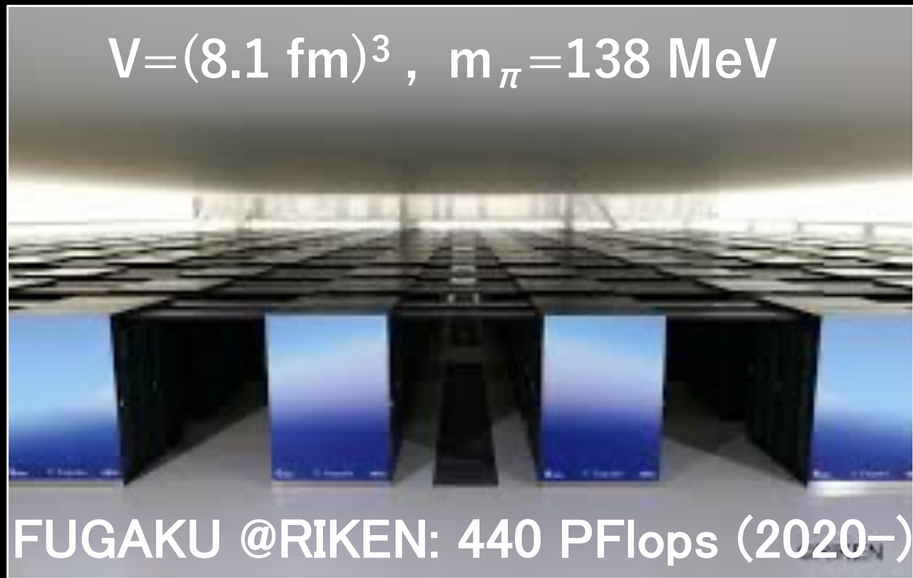




Large scale LQCD simulations for BB interaction

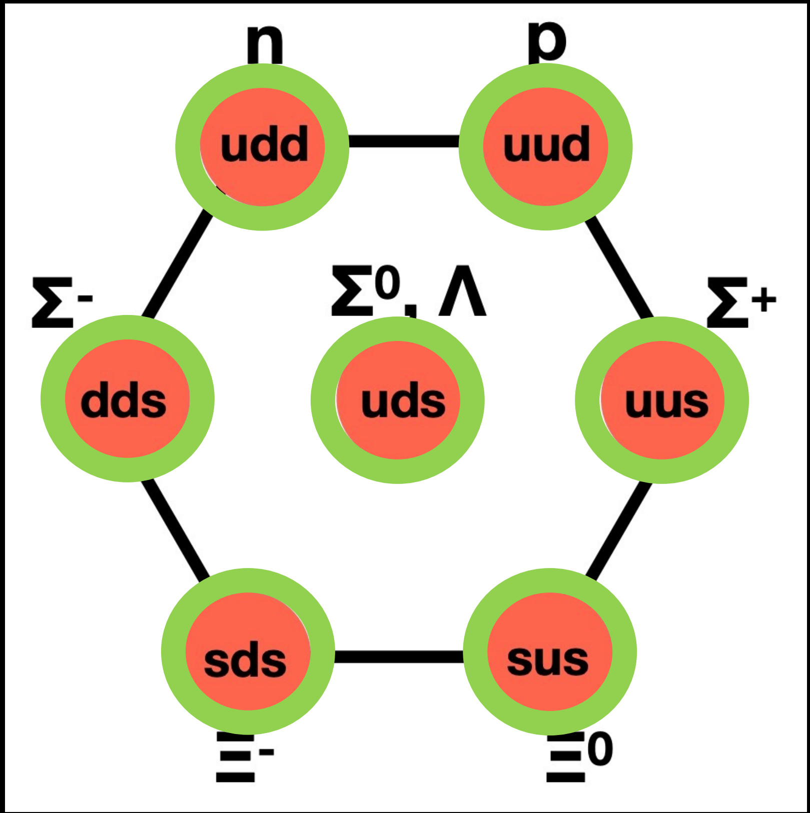




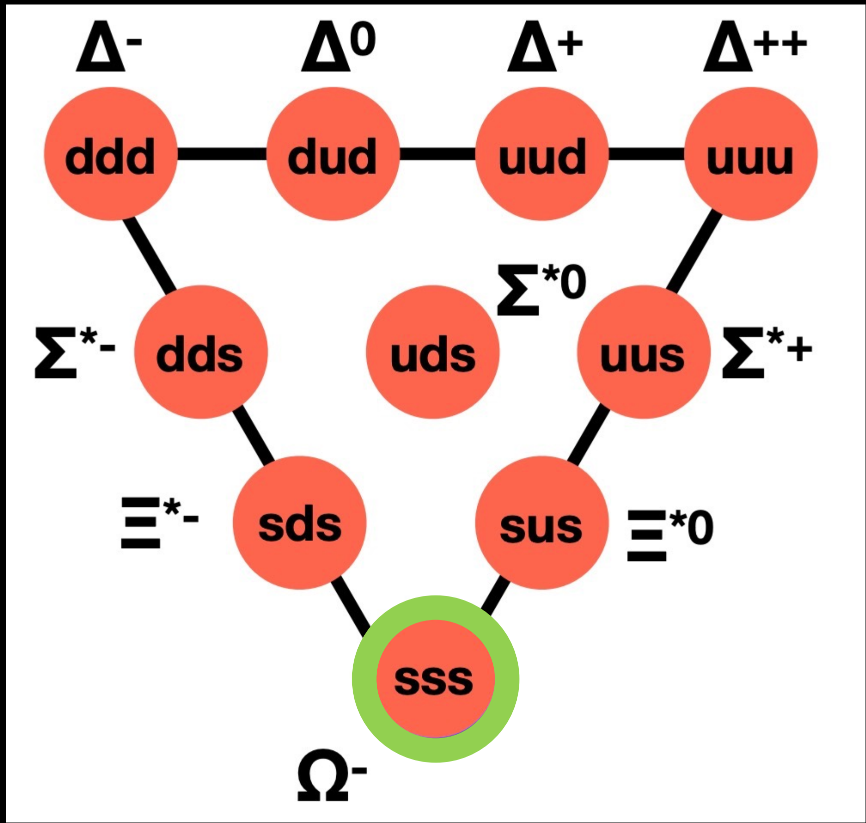


Flavor SU(3) classification

8 (Octet)

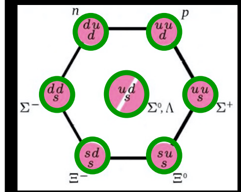


10 (Decuplet)

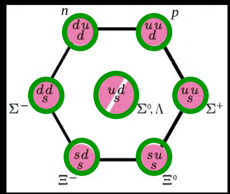


Stable against strong decays

SU(3)$_F$ classification of BB system



x



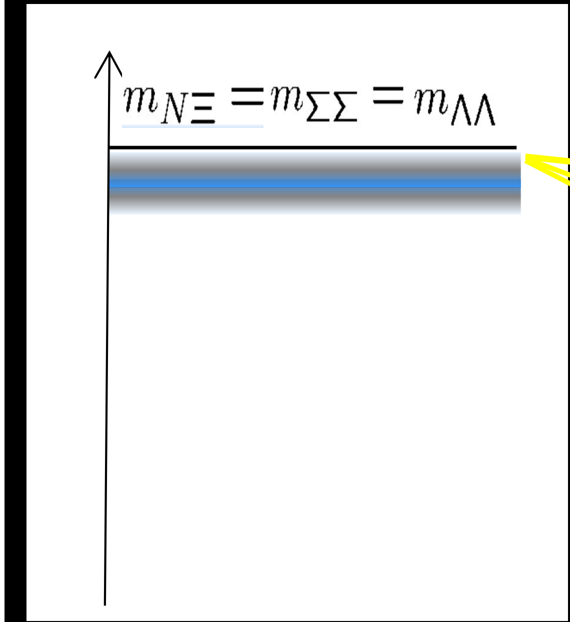
$$8 \times 8 = 27 + 8_s + 1 + 10^* + 10 + 8_a$$

$NN(^1S_0)$ → 27

$H(^1S_0)$ → 1
Jaffe (1977)

$NN(^3S_1)$ → 10*
deuteron

Fate of "H (uuddss)" dibaryon from LQCD

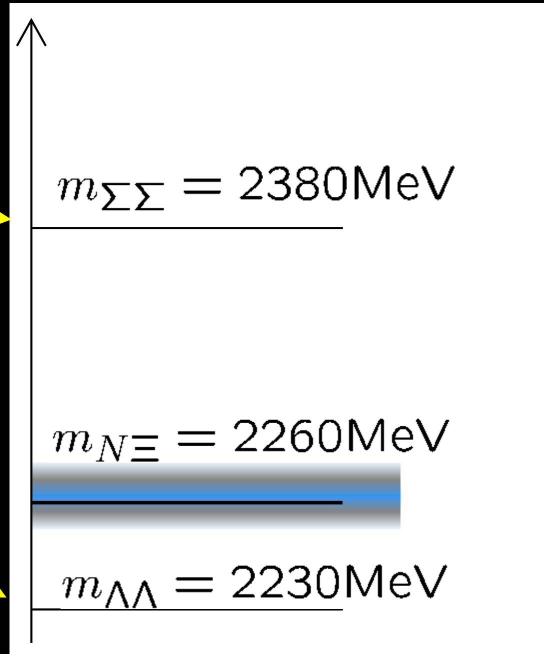


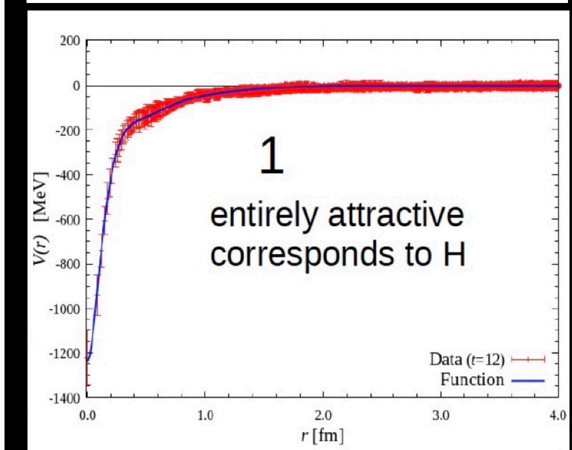
$m_{ud}=m_s$

(~ 100 MeV)

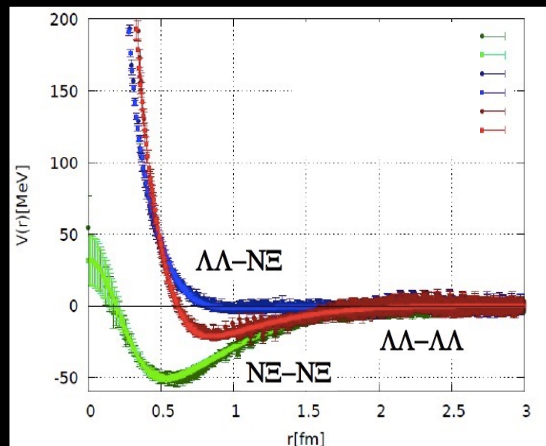
$m_{ud} < m_s$

(~10MeV) (~100MeV)





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



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 ($^{11}S_0$)

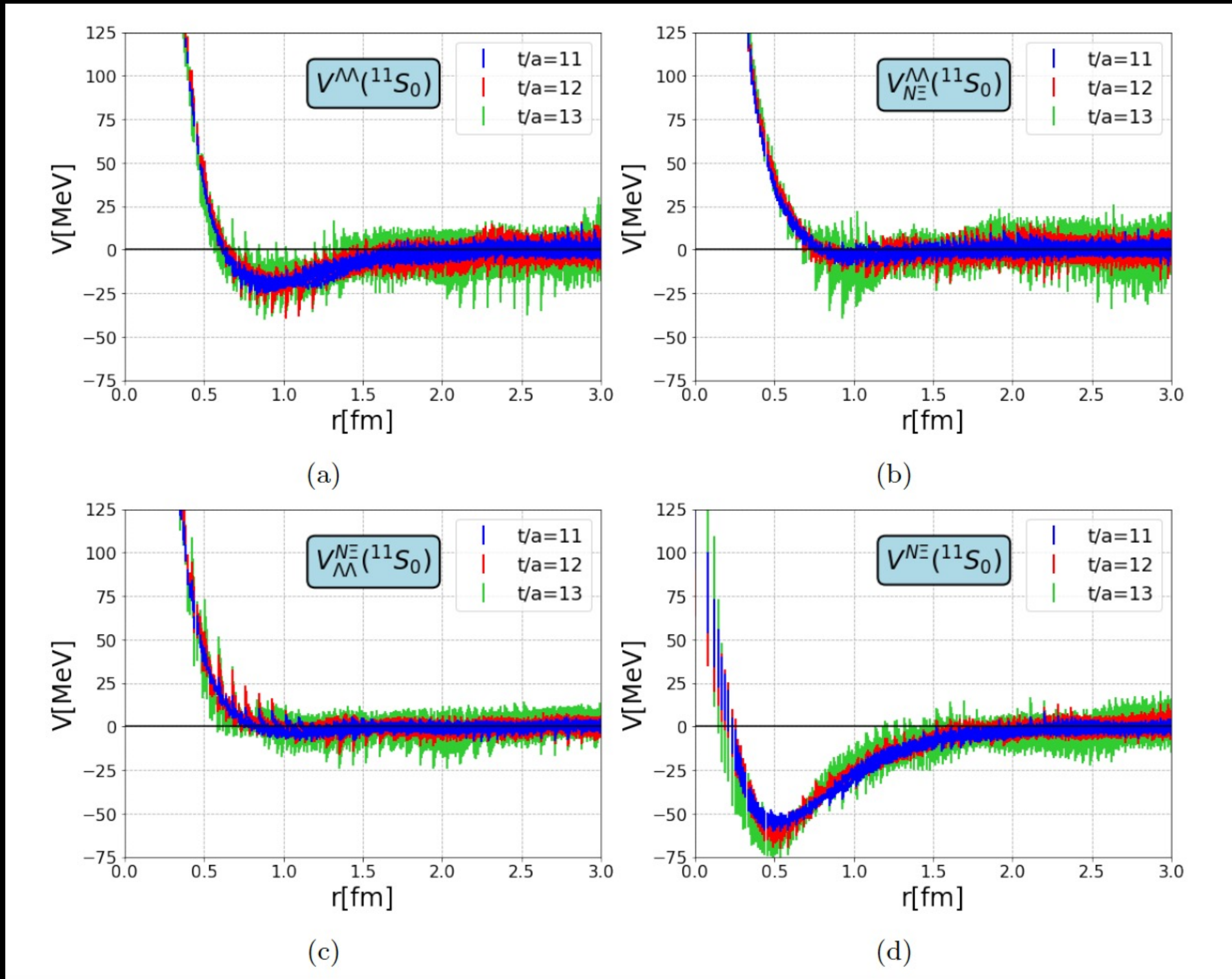
K. Sasaki+ [HAL QCD Coll.] Nucl. Phys. **A998** (2020)

Small ΛΛ attraction

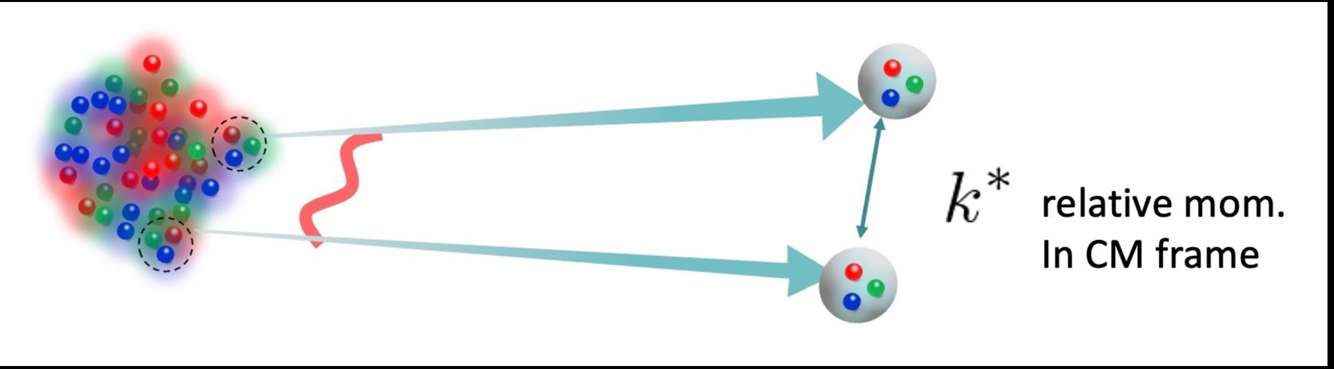
Short-range NΞ-ΛΛ coupling

Short-range NΞ-ΛΛ coupling

Large NΞ attraction

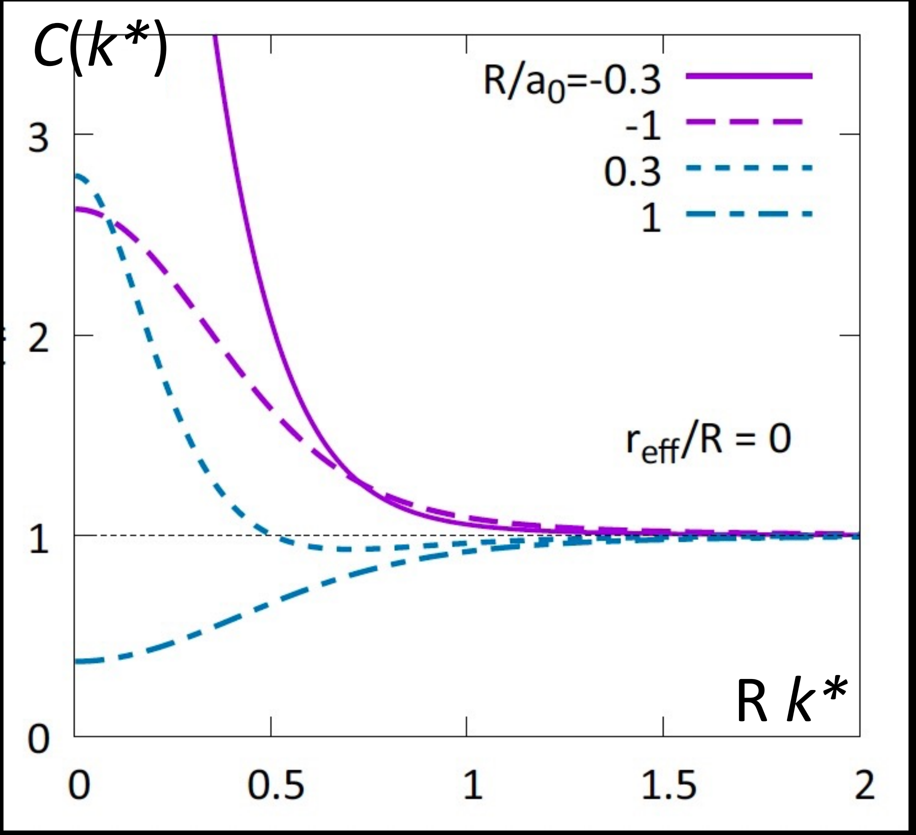


Femtoscopy : particle correlations in pp, pA and AA



$$C_{\rm expt}(k^*) = \frac{\xi(k^*) N_{\rm same}(k^*)}{N_{\rm mixed}(k^*)}$$

$$C_{\rm theo}(k^*)$$
$$= \int d^3r S(r,k^*) |\Psi(r,k^*)|^2$$
$$= 1 + \int d^3r S(r,k^*) [|\Psi_0(r,k^*)|^2 - |j_0(k^* r)|^2]$$

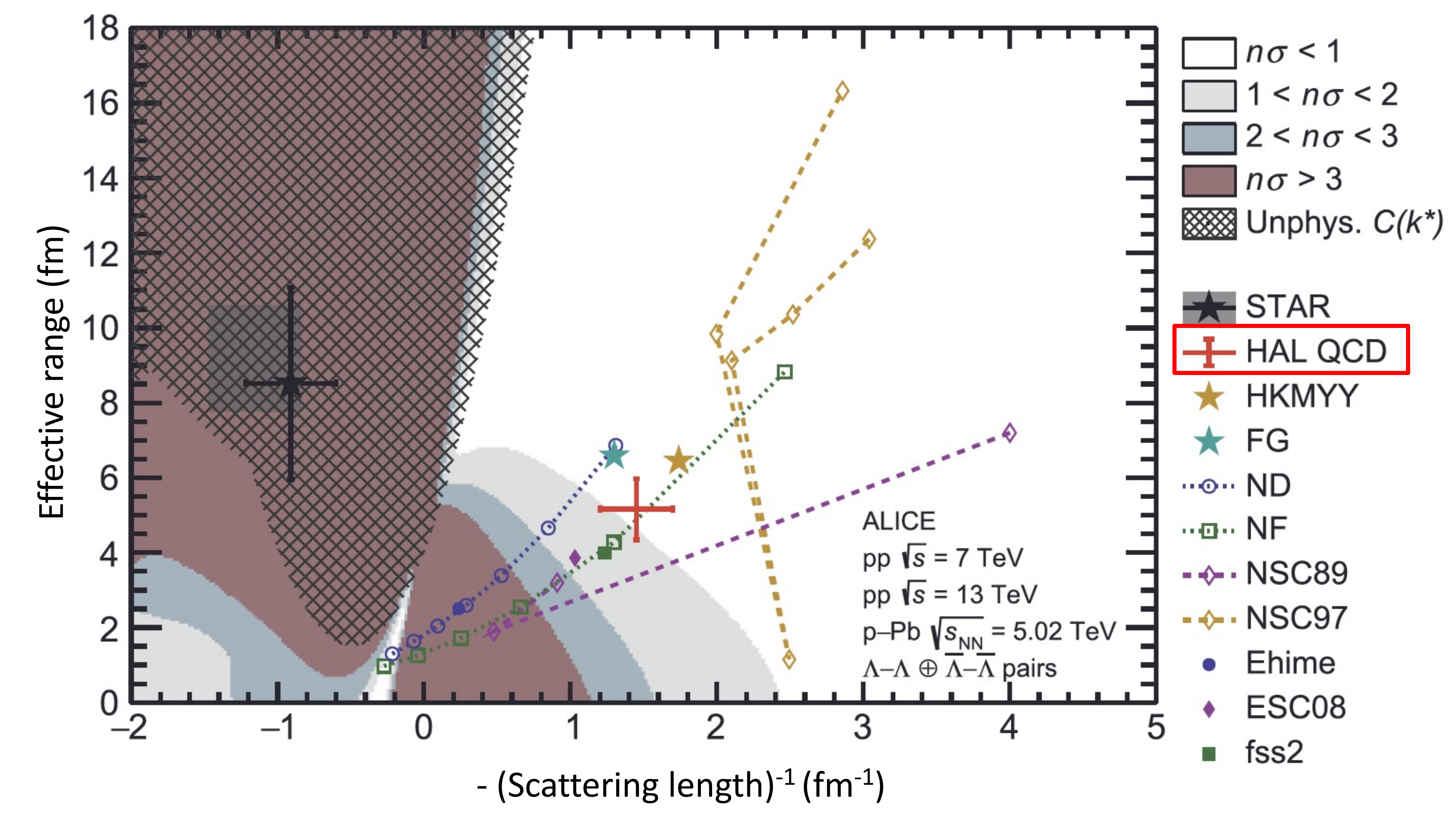


Koonin, Phys. Lett. B 70, 43 (1977).
Lednicky and Lyuboshits, Yad. Fiz. 35, 1316 (1981).
Pratt, Phys. Rev. D 33, 1314 (1986).
Anchishkin, Heinz, and Renk, Phys. Rev. C 57, 1428 (1998).
Lednicky, Lyuboshits, and Lyuboshits, Phys. At. Nucl. 61, 2950 (1998).
Haidenbauer, Nucl. Phys. A 981, 1 (2019).

Morita et al., Phys. Rev. C101 (2020) 015201

ΛΛ correlation in pp and pA

ALICE Coll., Phys. Lett. B797 (2019)

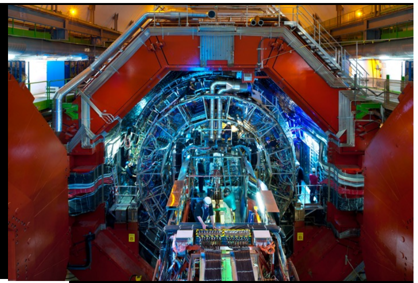


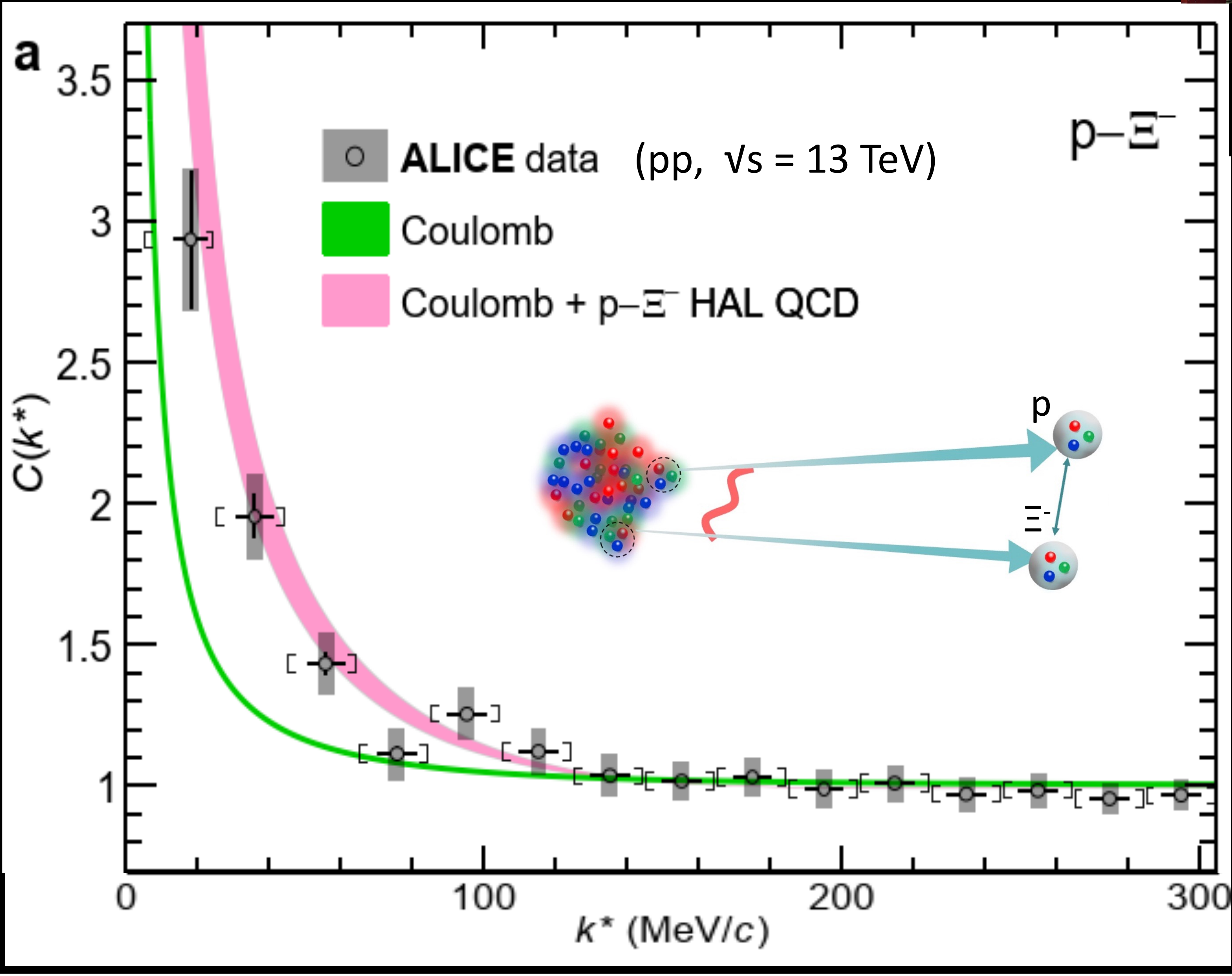
K. Sasaki+ [HAL QCD Coll.]
Nucl. Phys. **A998** (2020)

$$a_0^{(\Lambda\Lambda)} = -0.81 \pm 0.23^{+0.00}_{-0.13}\ [\text{fm}], \quad r_{\text{eff}}^{(\Lambda\Lambda)} = 5.47 \pm 0.78^{+0.09}_{-0.55}\ [\text{fm}],$$

NΞ correlation in pp

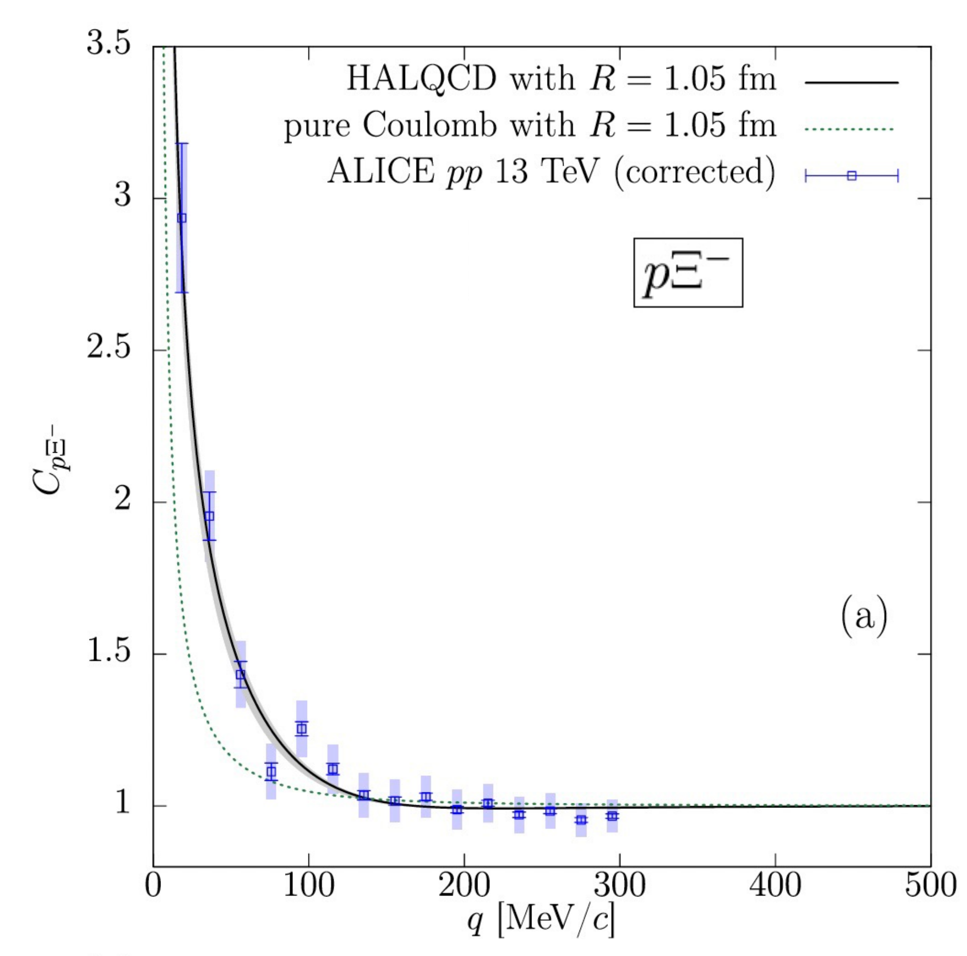
ALICE Coll., Nature 588 (2020) 232

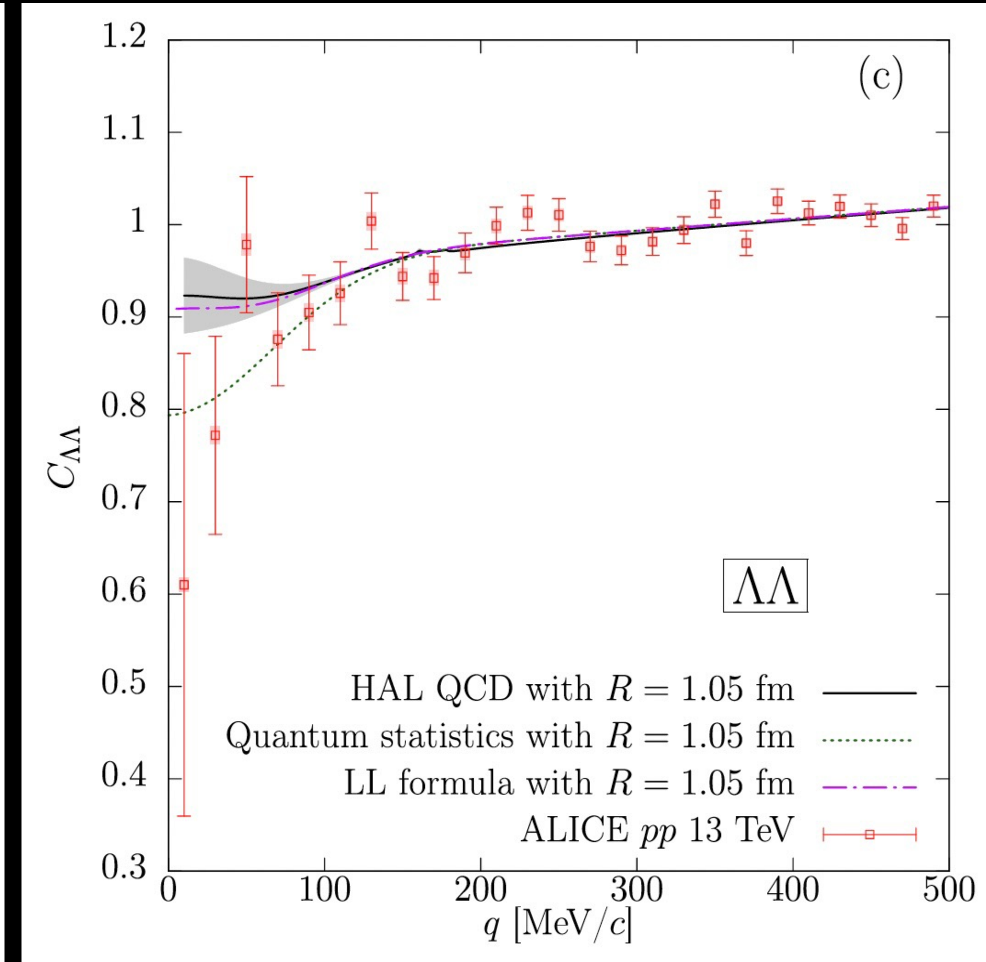




Fully coupled channel analysis

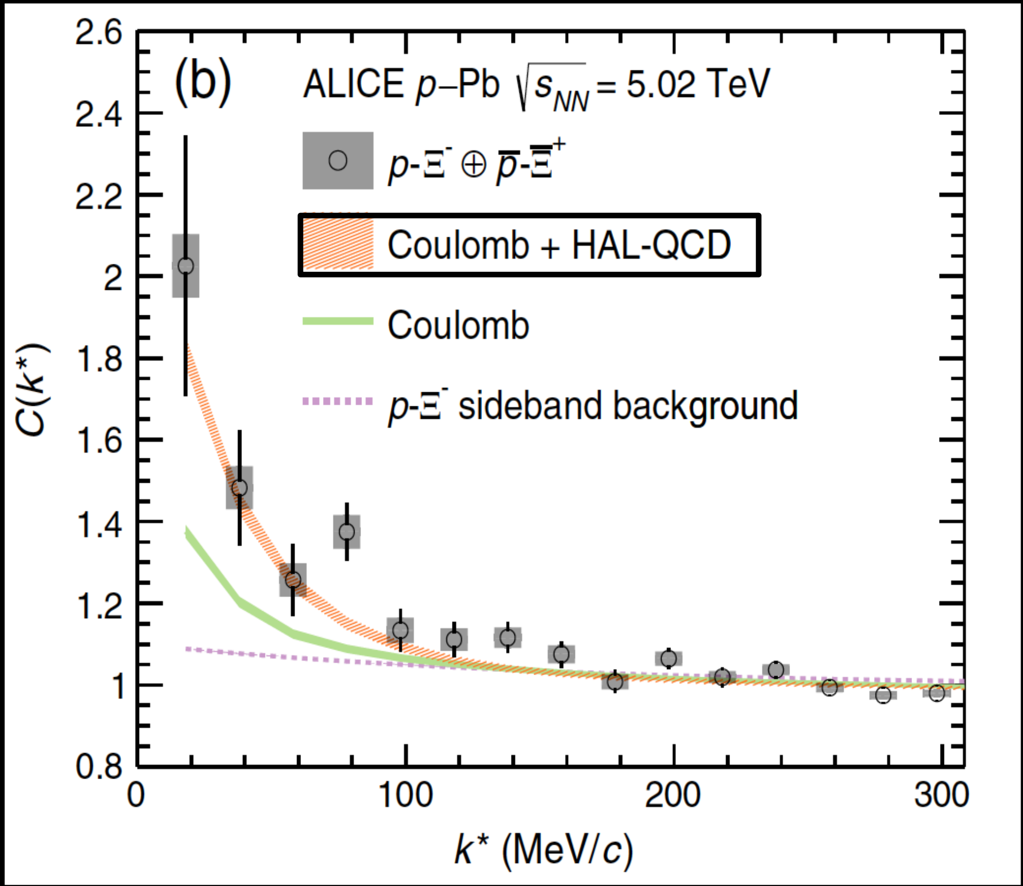
Kamiya+, Phys. Rev. C 105 (2022) 014915

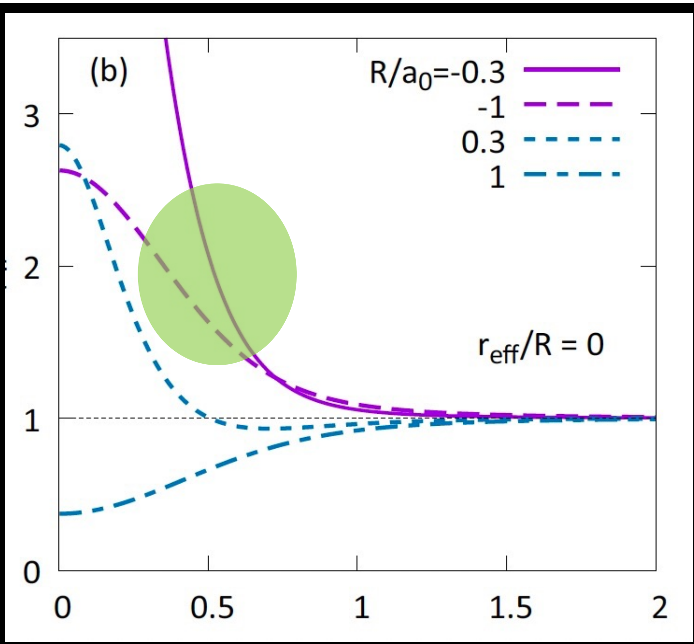




NΞ correlation in pA and AA

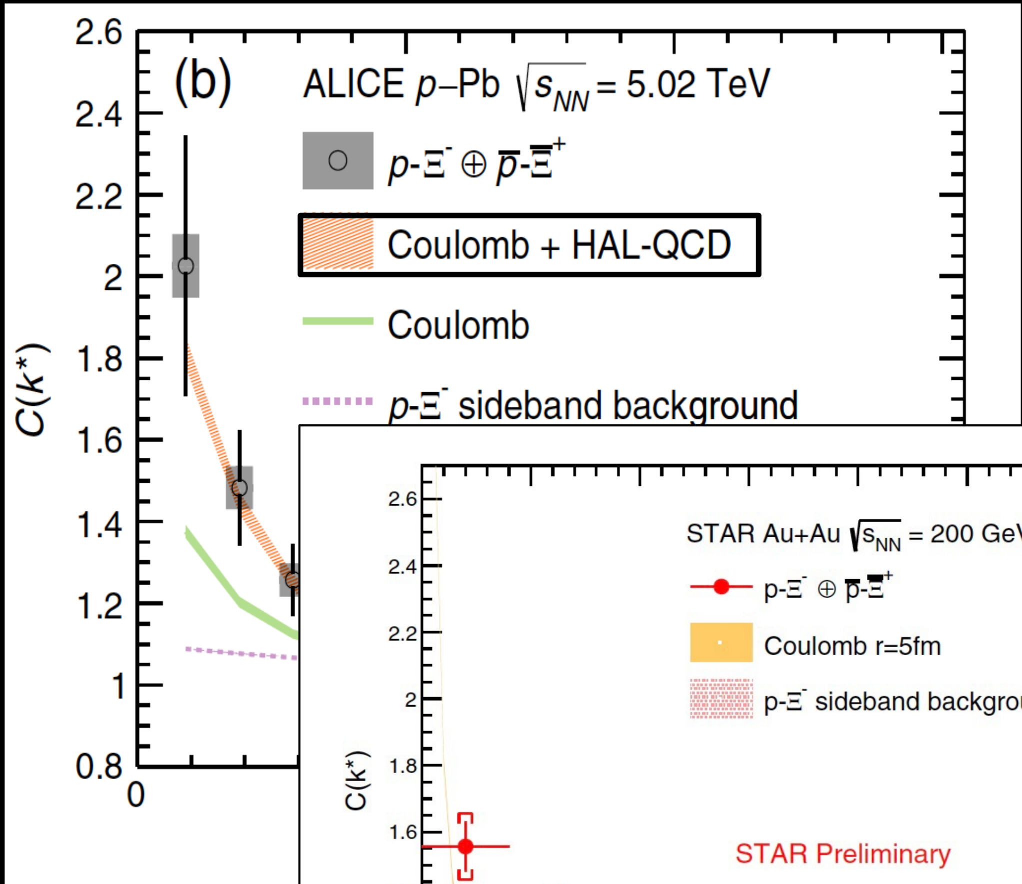
ALICE Coll., Phys.Rev.Lett. 123 (2019)

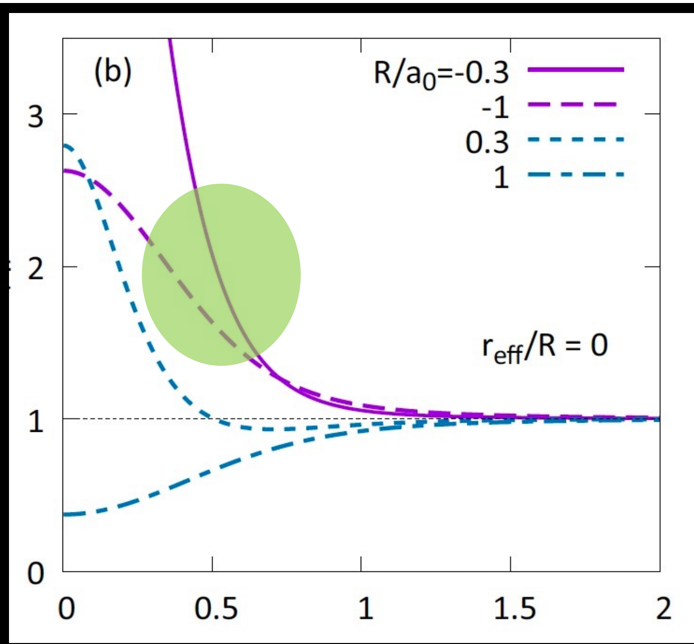


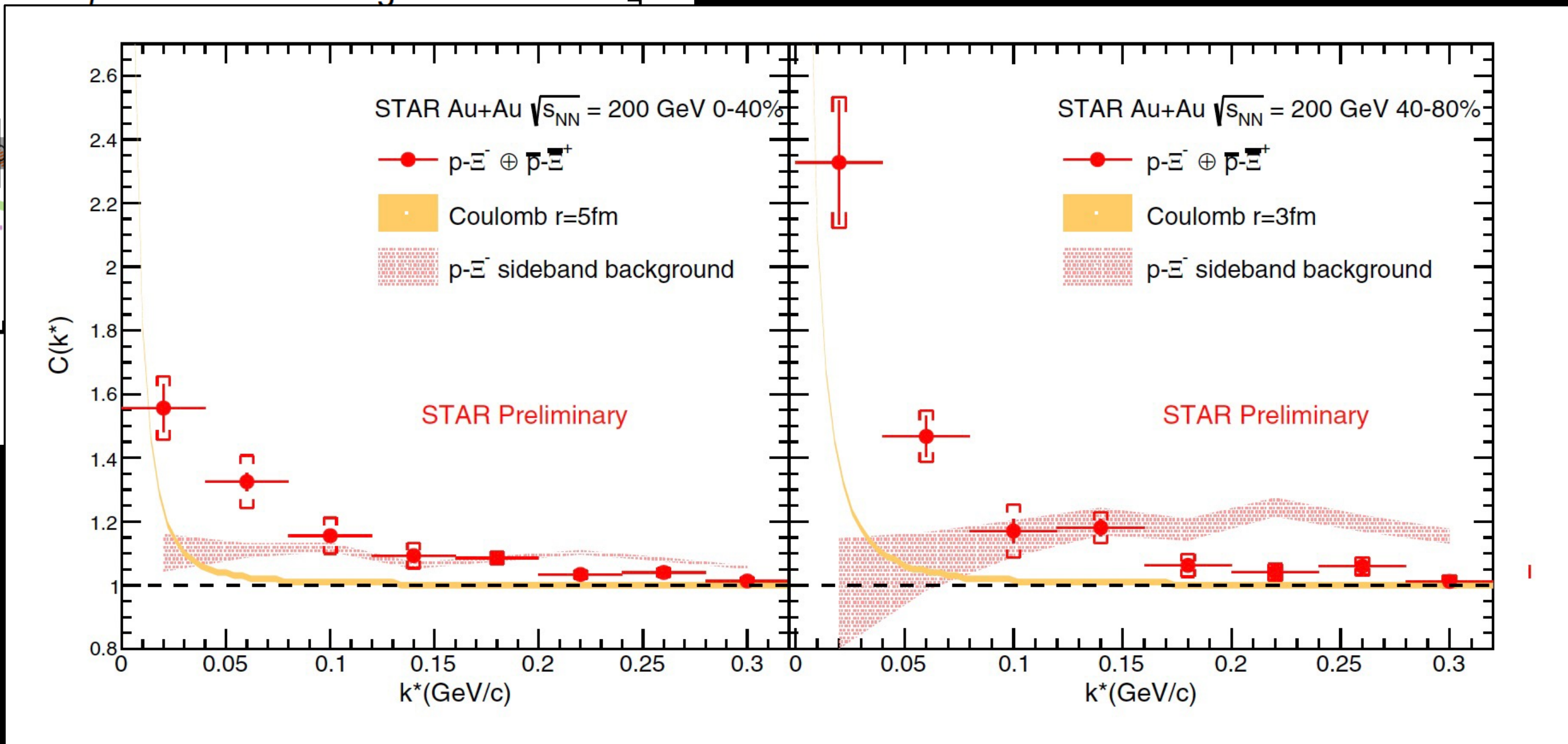


NΞ correlation in pA and AA

ALICE Coll., Phys.Rev.Lett. 123 (2019)





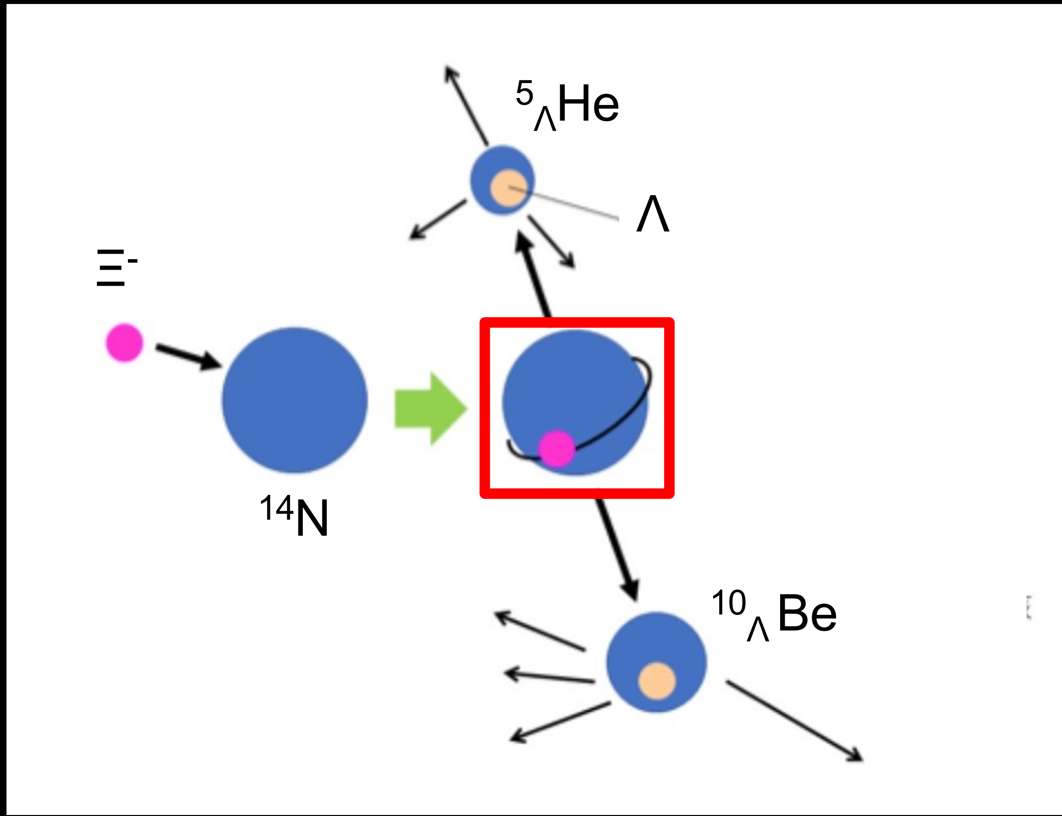


No bound NΞ ?

STAR Coll., EPJ Web of Conf. 259 (2022)

Ξ hypernuclei at J-PARC

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

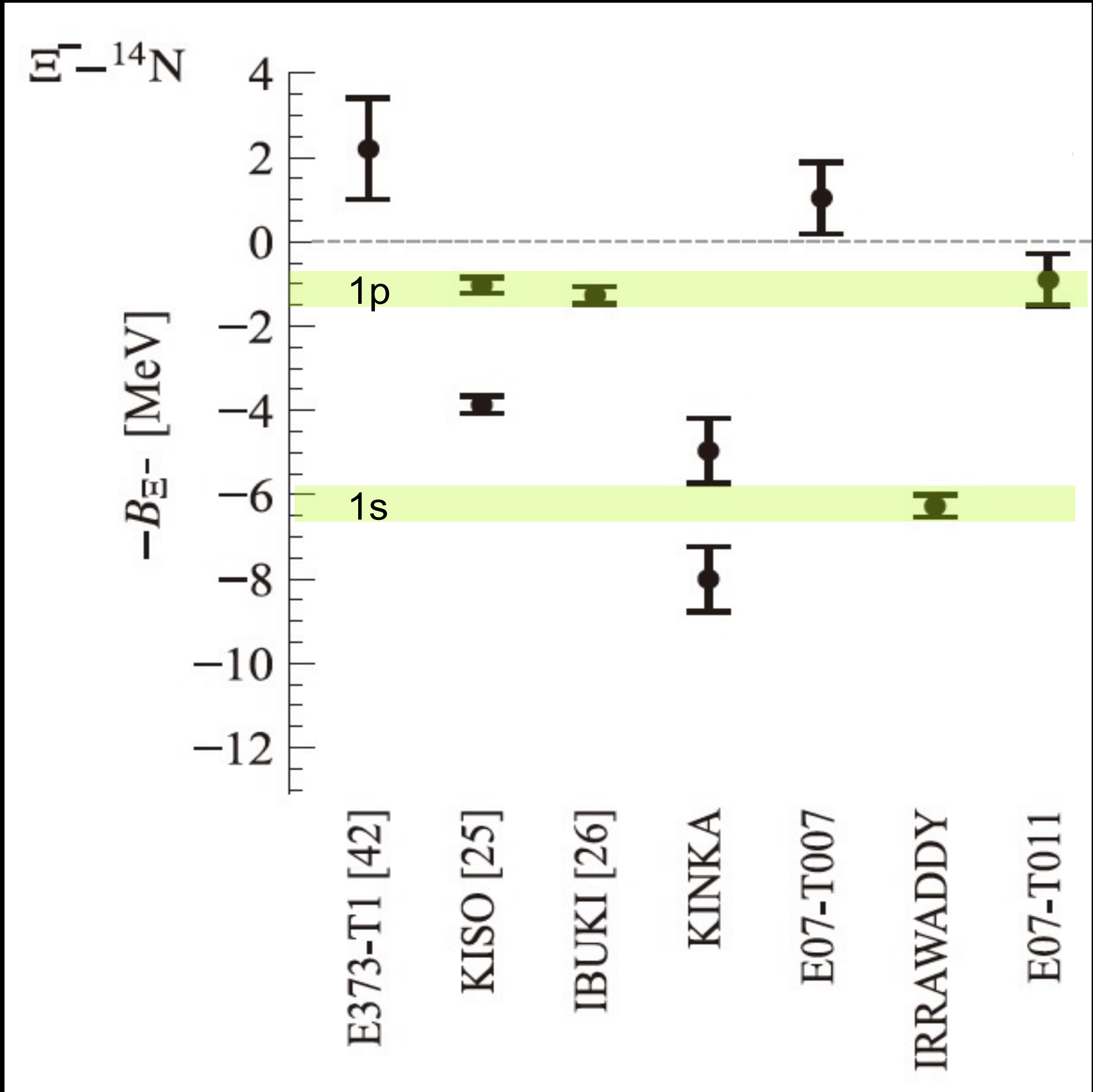


Attraction in NΞ
Weak NΞ- ΛΛ coupling

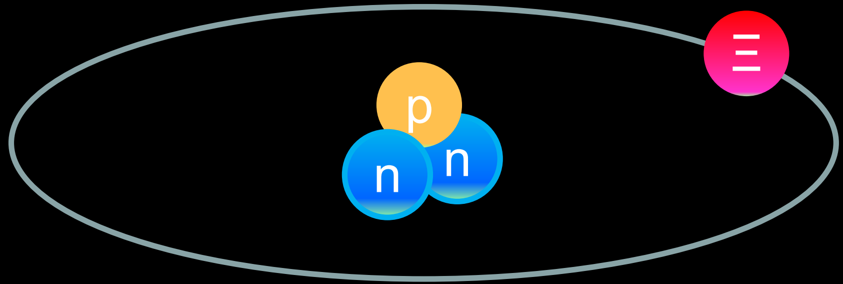
Consistent with HAL QCD prediction

Ξ hypernuclei found so far

Yoshimoto+, PTEP 2021 (2021) 073D02

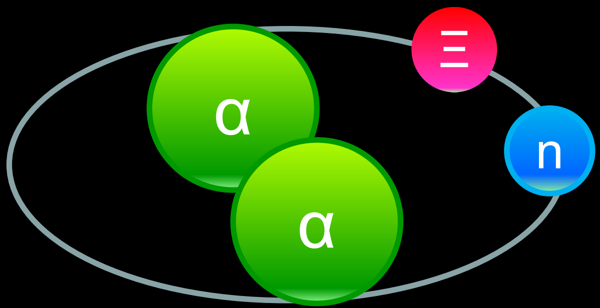


Q1. What is the lightest Ξ hypernuclei?



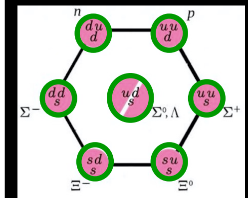
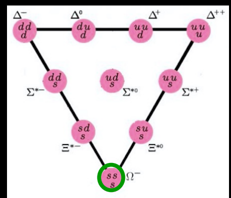
Hiyama, Sasaki, Miyamoto, Doi, Hatsuda, Yamamoto, Rijken, Phys.Rev.Lett.124 (2020) 092501

Q2. Can we test the spin-isospin dependence of ΞN int.?



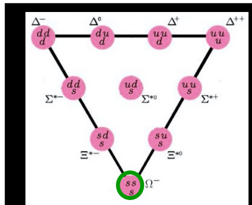
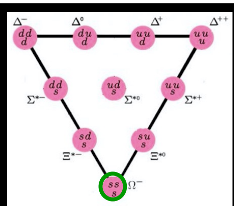
Hiyama, Isaka, Doi, Hatsuda, arXiv:2209.06711 [nucl-th]

SU(3)$_F$ classification of BB system

 x 

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

NΩ ($^5S_2$) Goldman+ (1987), Oka (1988)

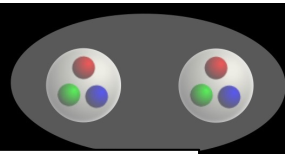
 x 

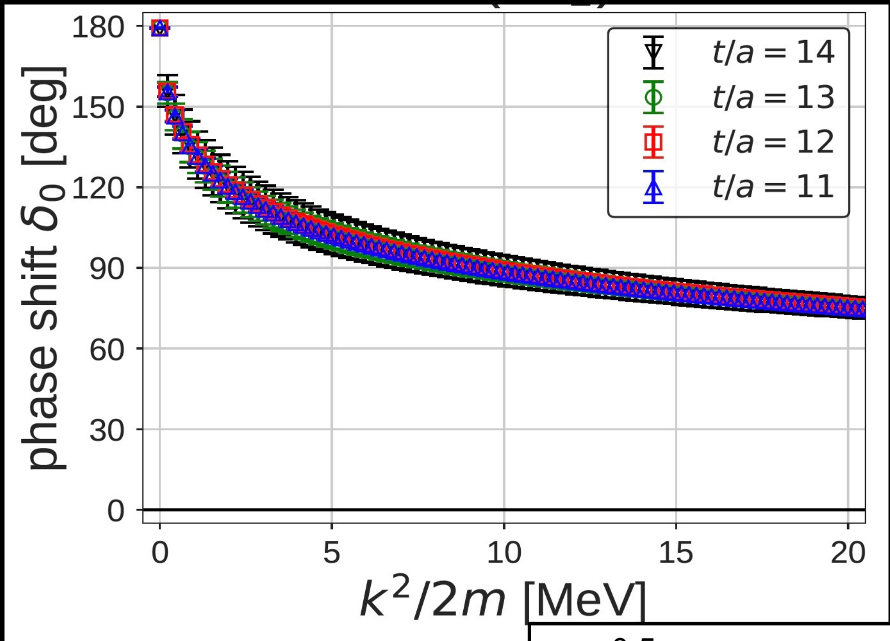
$10 \times 10 = 28 + 27 + 35 + 10^*$

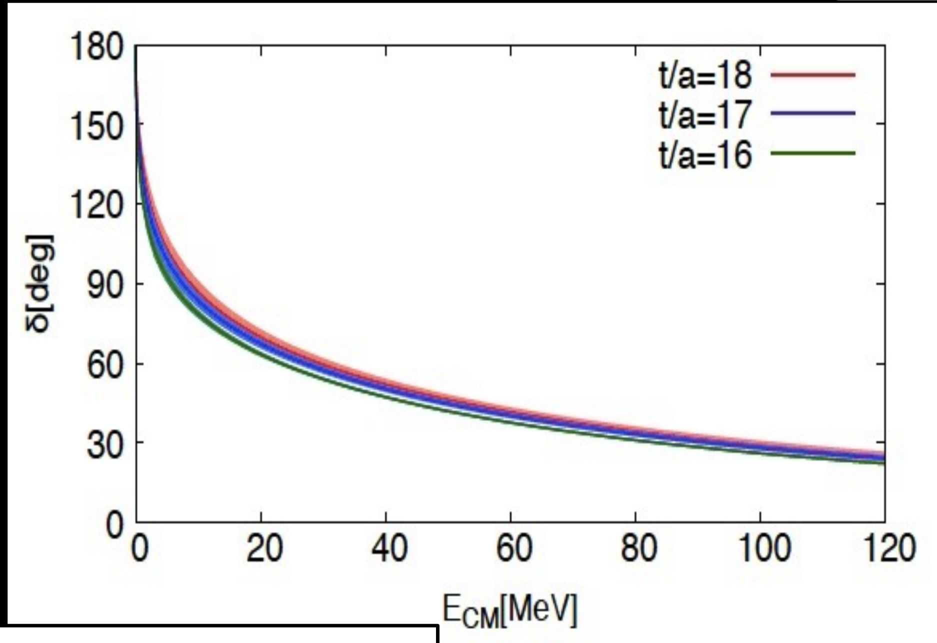
Kopeliovich+ (1990) $\Omega\Omega(^1S_0)$

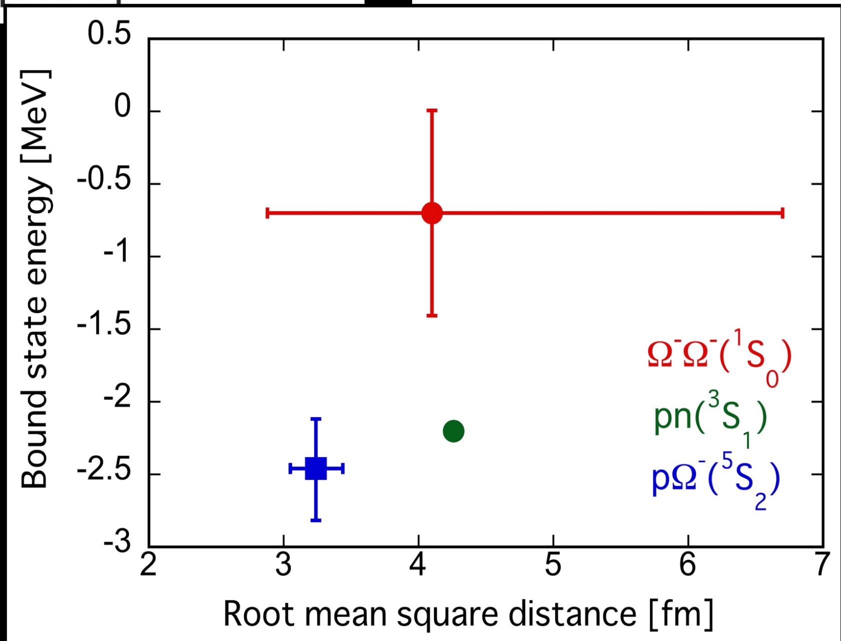
$\Delta\Delta(^7S_3)$ Dyson+ (1964)

quasi-bound NΩ and bound ΩΩ ?







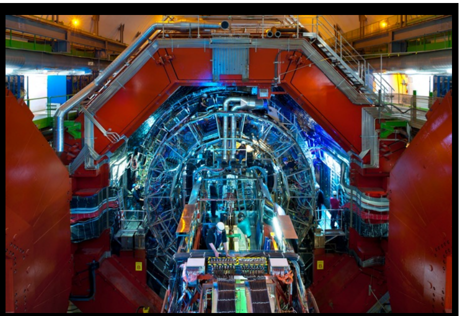


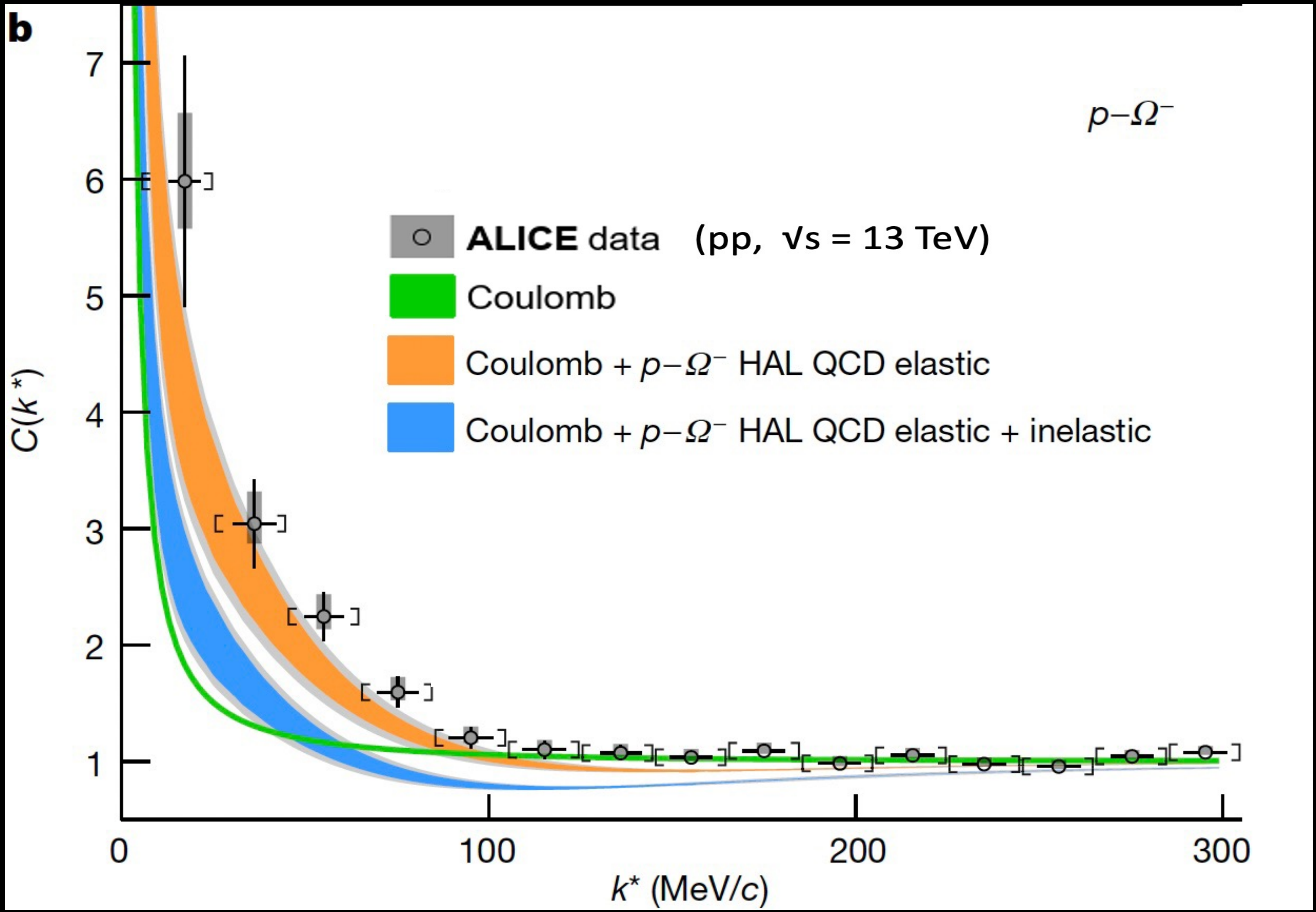
Iritani+ [HAL QCD Coll.], PLB 792 (2019) 284

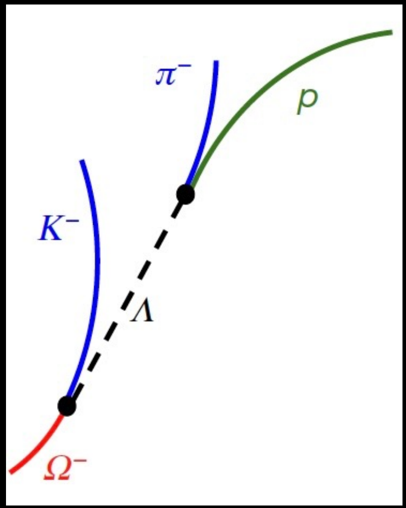
Gongyo+ [HAL QCD Coll.], PRL 120 (2018) 212001
Tong+ [HAL QCD Coll.], PRL 127 (2021) 072003

NΩ correlation in pp

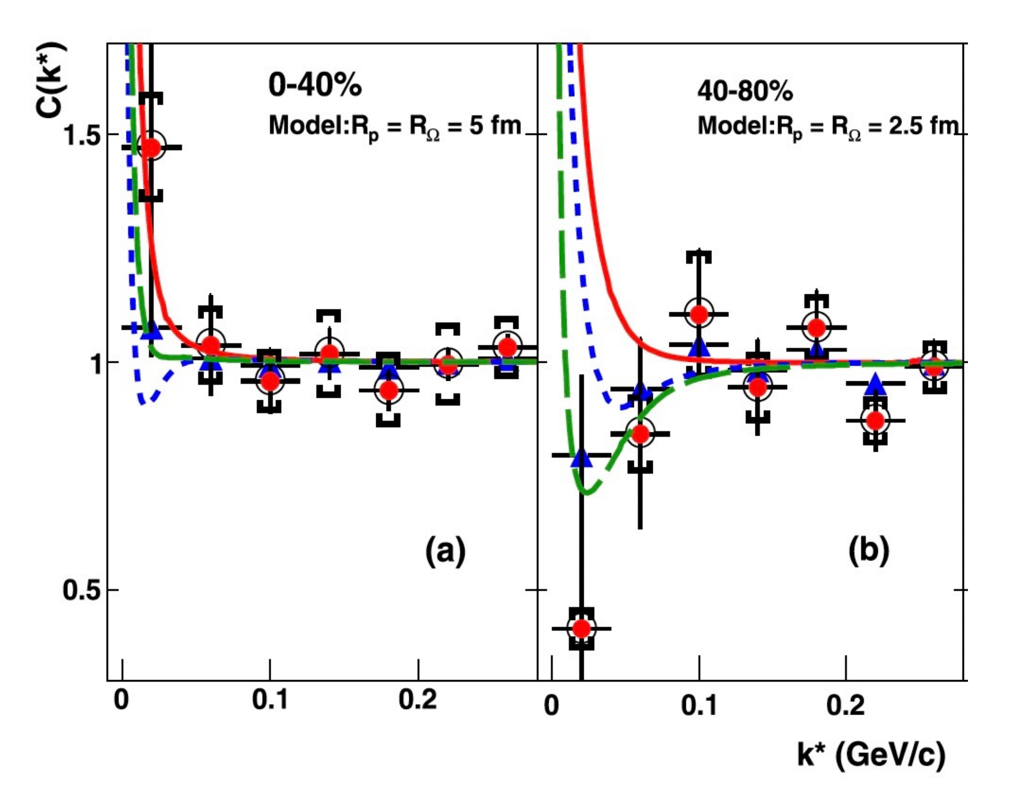
LHC ALICE Coll., Nature 588 (2020) 232



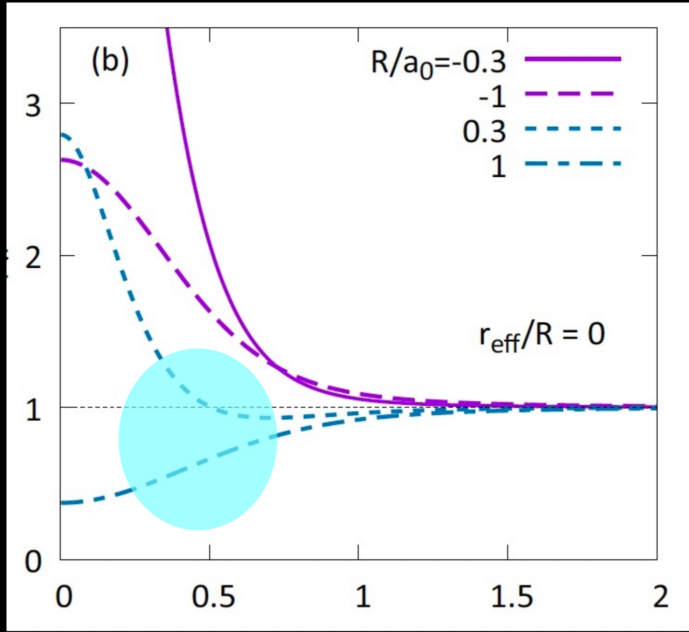




NΩ correlation in AA

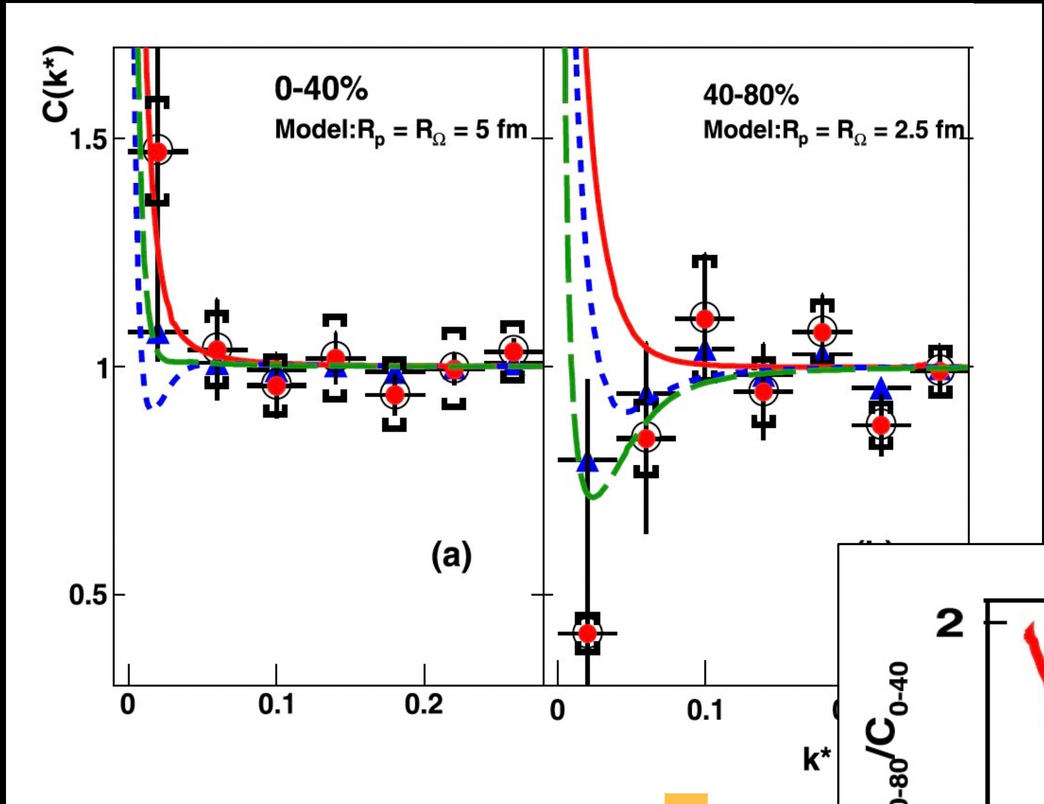


STAR Coll.,
Phys. Lett. 790 (2019) 490

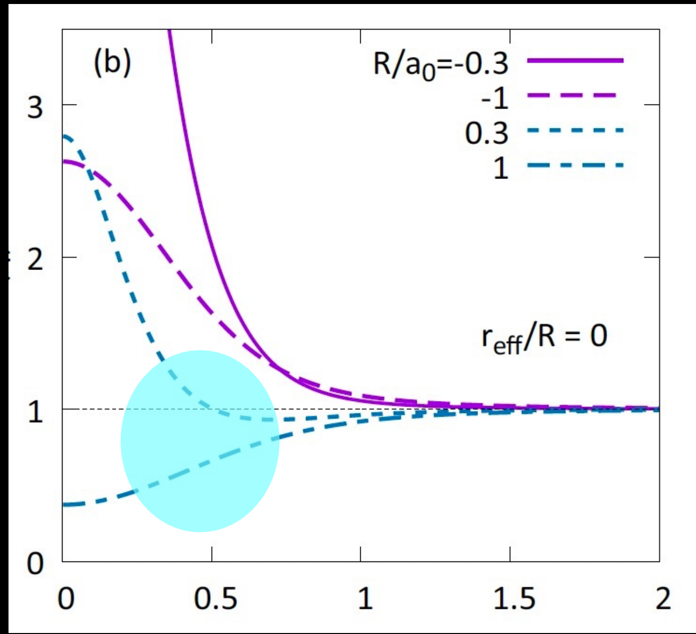


Morita et al., PRC101 (2020) 015201

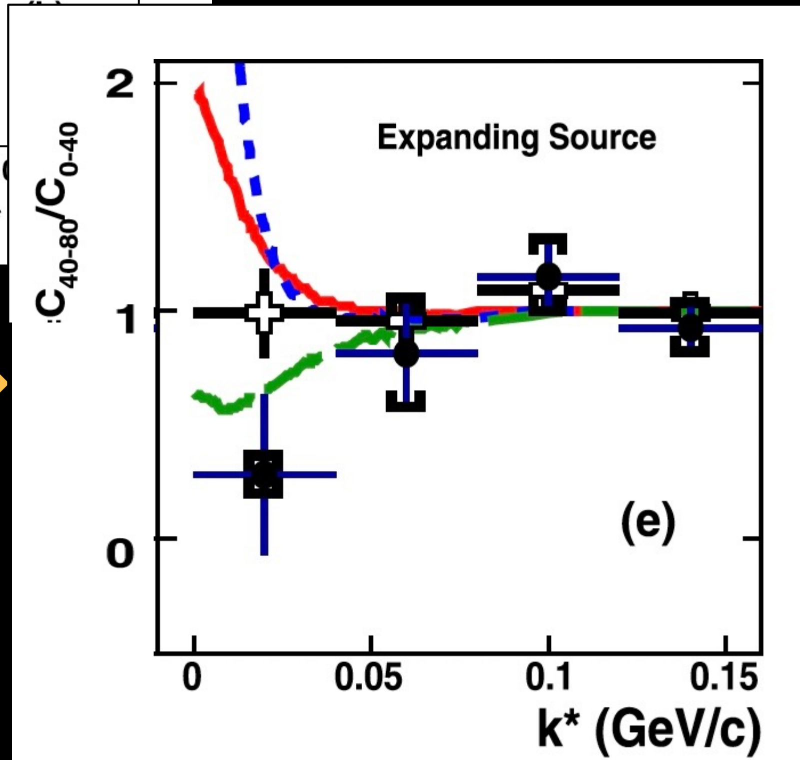
NΩ correlation in AA



STAR Coll.,
Phys. Lett. 790 (2019) 490

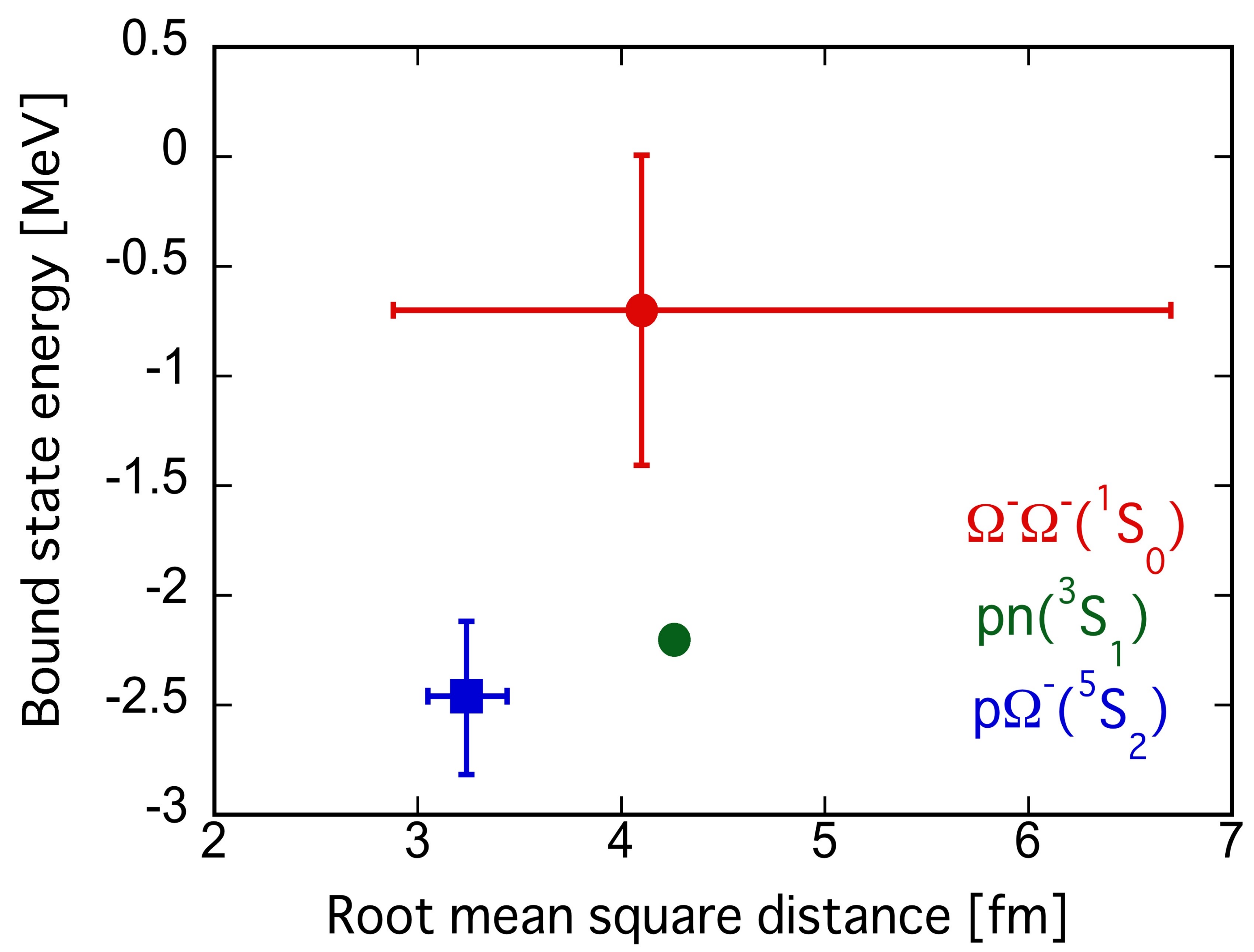


Morita et al., PRC101 (2020) 015201



Bound NΩ ???

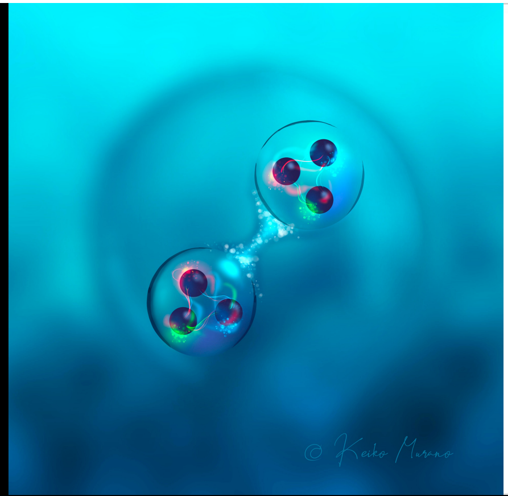
quasi-bound NΩ and bound ΩΩ ?



Iritani+ [HAL QCD Coll.], PLB 792 (2019) 284

Gongyo+ [HAL QCD Coll.], PRL 120 (2018) 212001
Tong+ [HAL QCD Coll.], PRL 127 (2021) 072003

e-mail from Freeman Dyson,
(Sep. 13, 2017)



Thank you very much for sending me your paper on the Omega-Omega calculation. This is a beautiful piece of work, and it will be a big step forward if the experimenters are able to confirm it.

Thank you also for referring to our 1964 paper. I am amazed that you remember that paper after 53 years. The predictions that we made in that paper turned out to be wrong, and the SU6 theory was soon abandoned. Luckily you did not assume SU6 symmetry when you made your prediction.

Now I wish you the joy of seeing it confirmed.

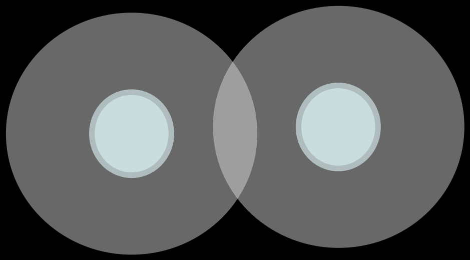
Yours sincerely,

Freeman Dyson.

Y=2 States in Su(6) Theory

Freeman J. Dyson and Nguyen-Huu Xuong
Phys. Rev. Lett. 13, 815 – Published 28 December 1964; Erratum Phys. Rev. Lett. 14, 339 (1965)

Question:



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

Answer:

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

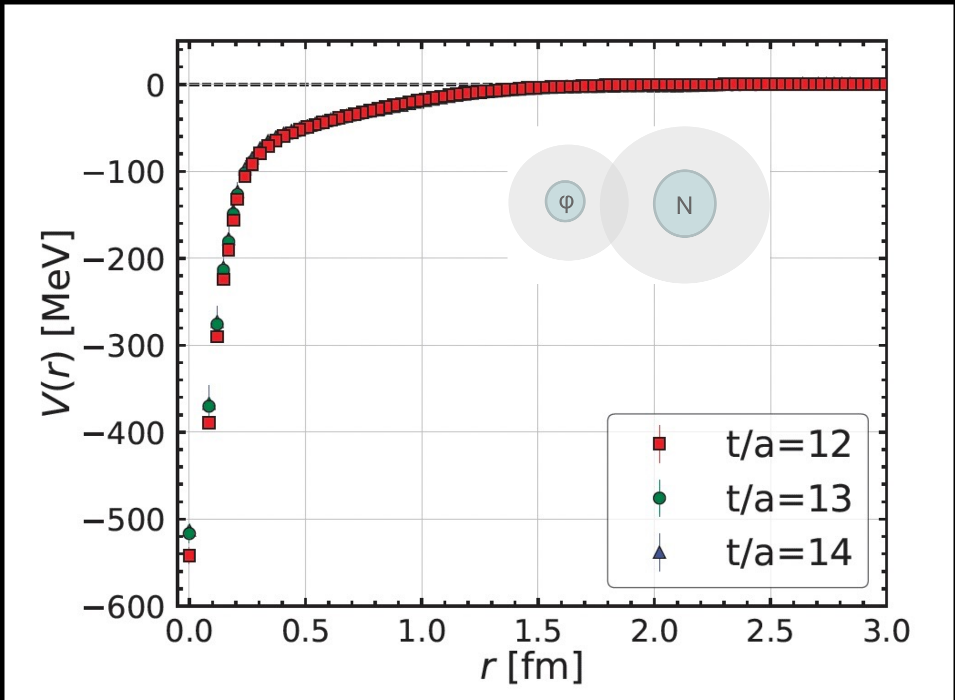
QCD
2-pion exchange force

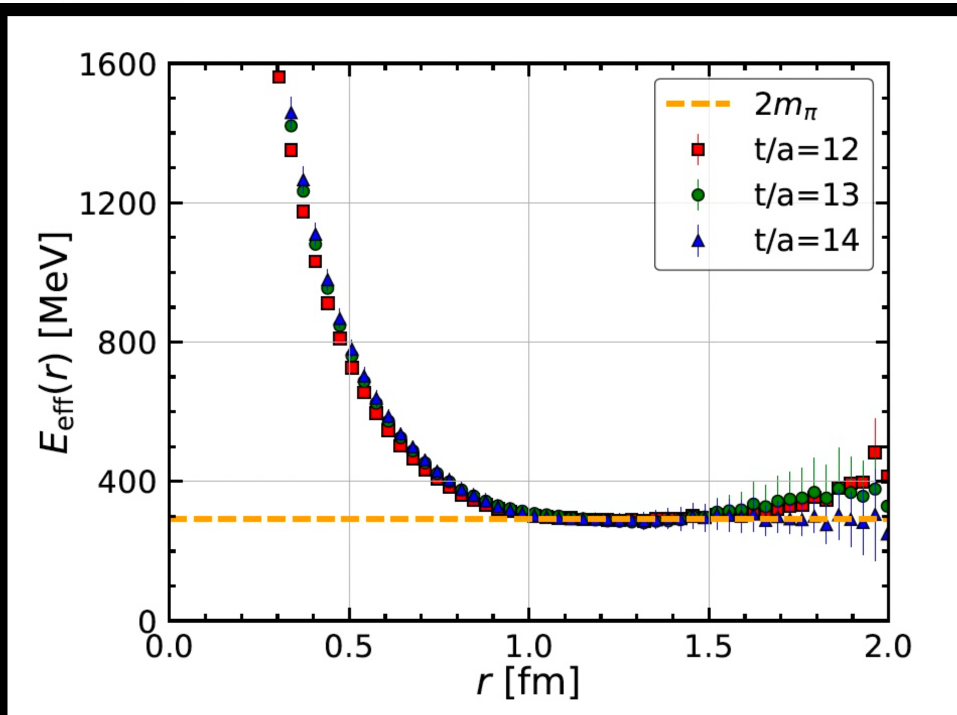
Bhanot and Peskin, Nucl. Phys. B156 (1979) 391
Fujii and Kharzeev, Phys. Rev. D60 (1999) 114039
Brambilla et al., Phys. Rev. D93 (2006) 054002

PHYSICAL REVIEW D **106,** 074507 (2022)

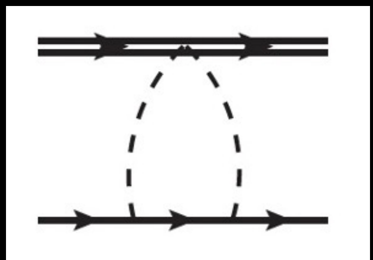
Attractive N-ϕ interaction and two-pion tail from lattice QCD near physical point

Yan Lyu,[1,2,*] Takumi Doi,[2,†] Tetsuo Hatsuda,[2,‡] Yoichi Ikeda,[3,§] Jie Meng,[1,4,‖]
Kenji Sasaki,[3,¶] and Takuya Sugiura[2,**]





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 D **106**, 074507 (2022)

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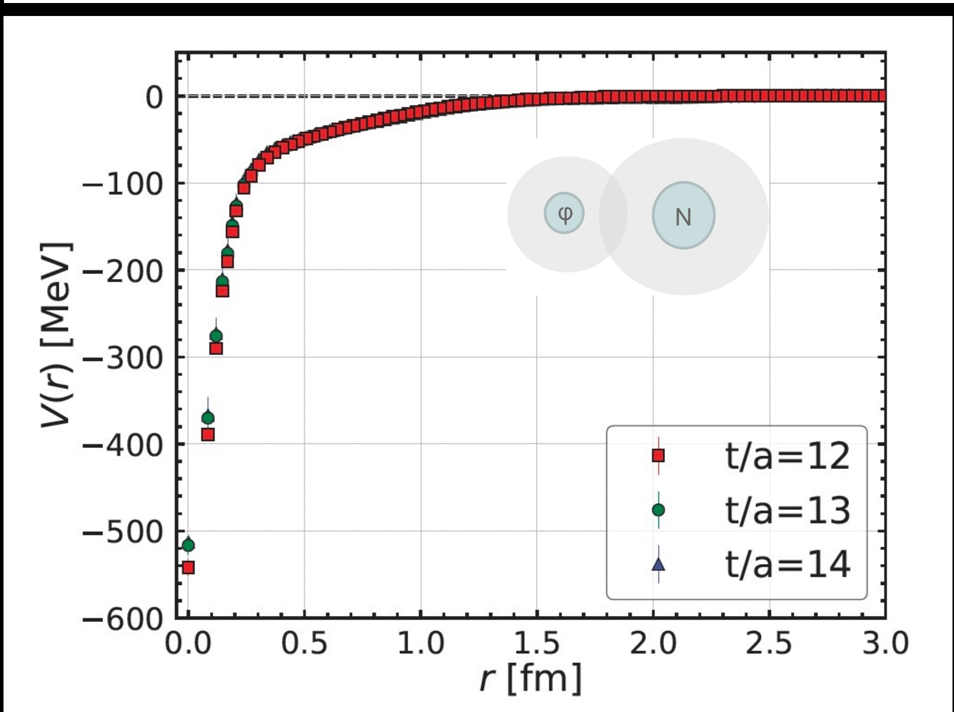

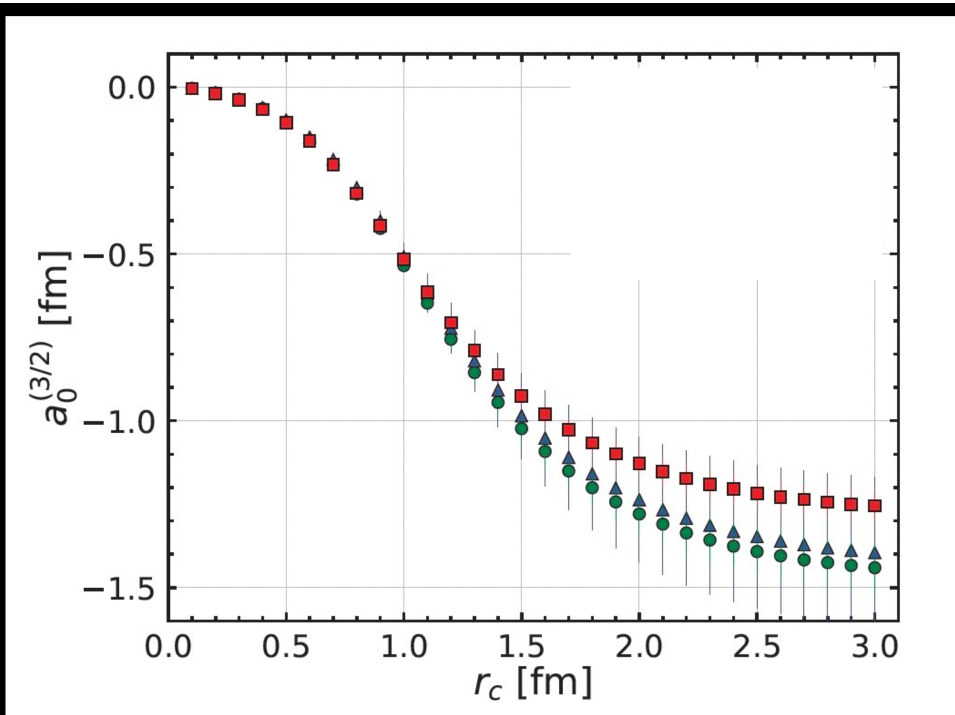

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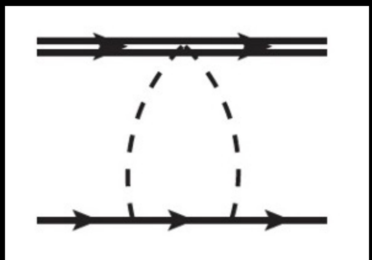

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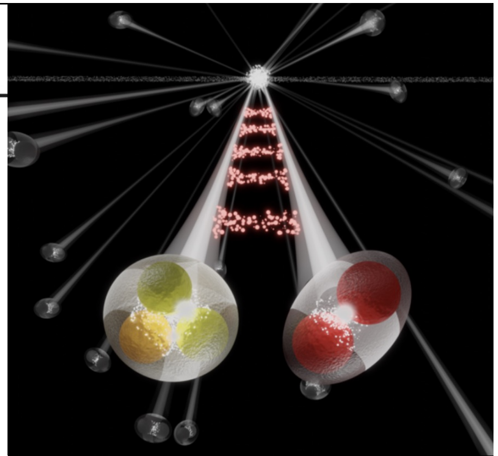
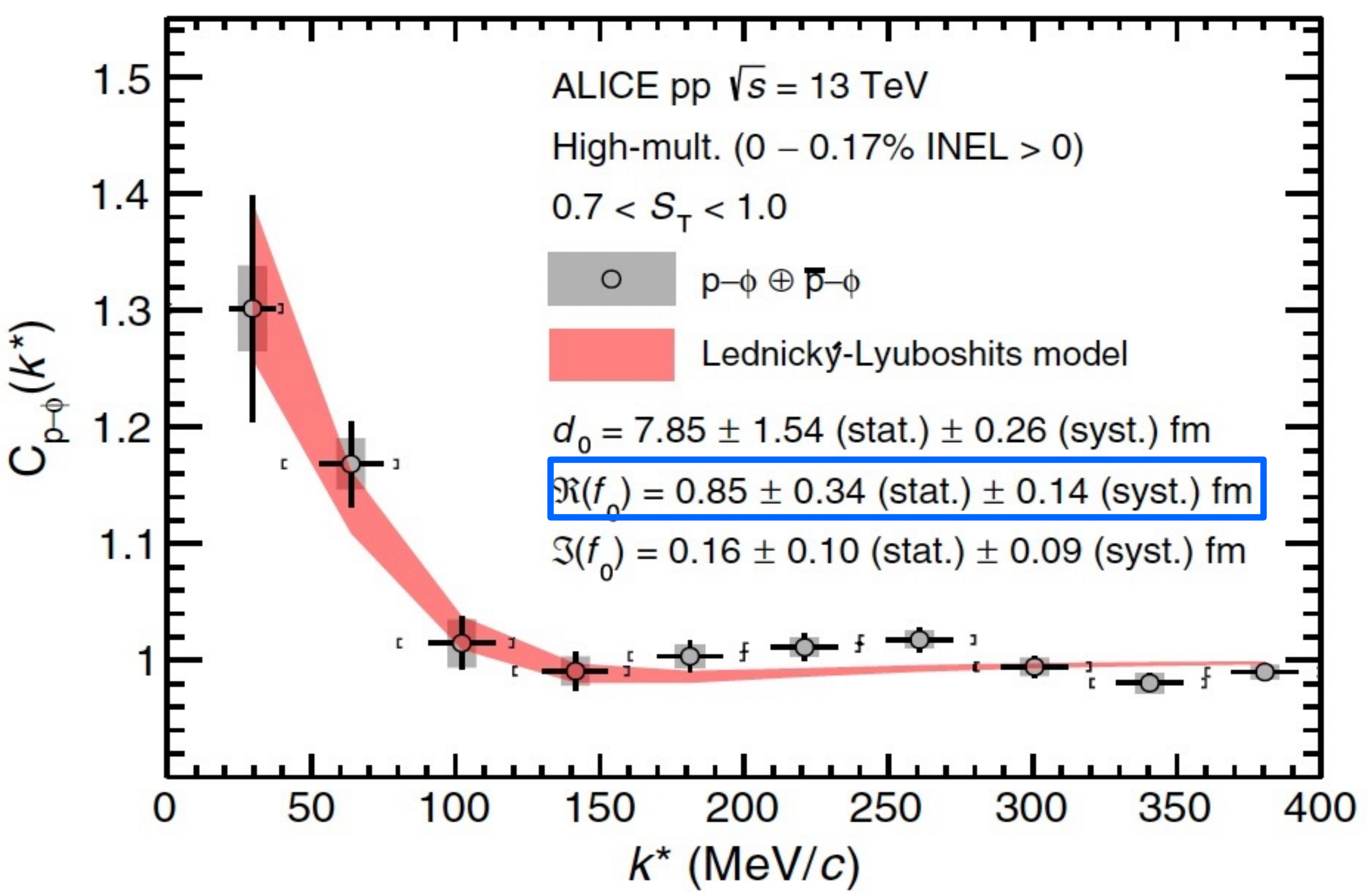
Krein and Casttela , Phys. Rev. D98 (2018) 0140289.

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

Summary and future

1. "LQCD → realistic hadron-hadron interactions" became possible.
2. Comparison of LQCD data with femtoscopy and hypernuclei has been started.
3. H(uuddss) dibaryon is not likely to exist below $\Lambda\Lambda$.
4. $\Omega\Omega$(ssssss) dibaryon may exist and should be searched experimentally.
5. Hyperon–nucleon interaction & 3-baryon force. <--> neutron star structure.
6. Heavy tetraquarks (e.g. T_{cc}, T_{bb}) are highly interesting in both Exp. and LQCD.

More LQCD results at
the physical pion mass will come soon.

Thank you!