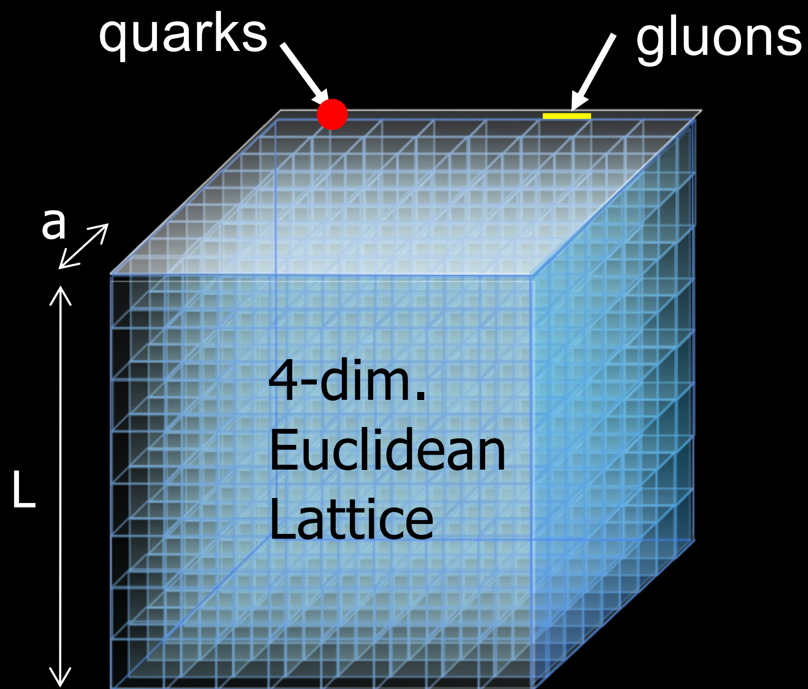
Hadron-Hadron Interactions from Lattice QCD
- Theory meets experiments -

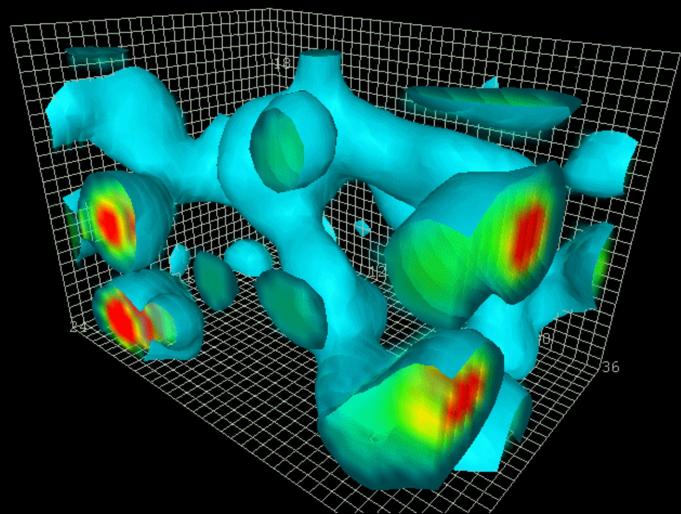
Tetsuo Hatsuda (RIKEN iTHEMS)

LQCD (since 1974) : Ab initio approach to solve QCD

K. Wilson

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





by D.Leinweber

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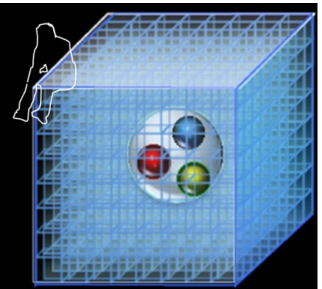

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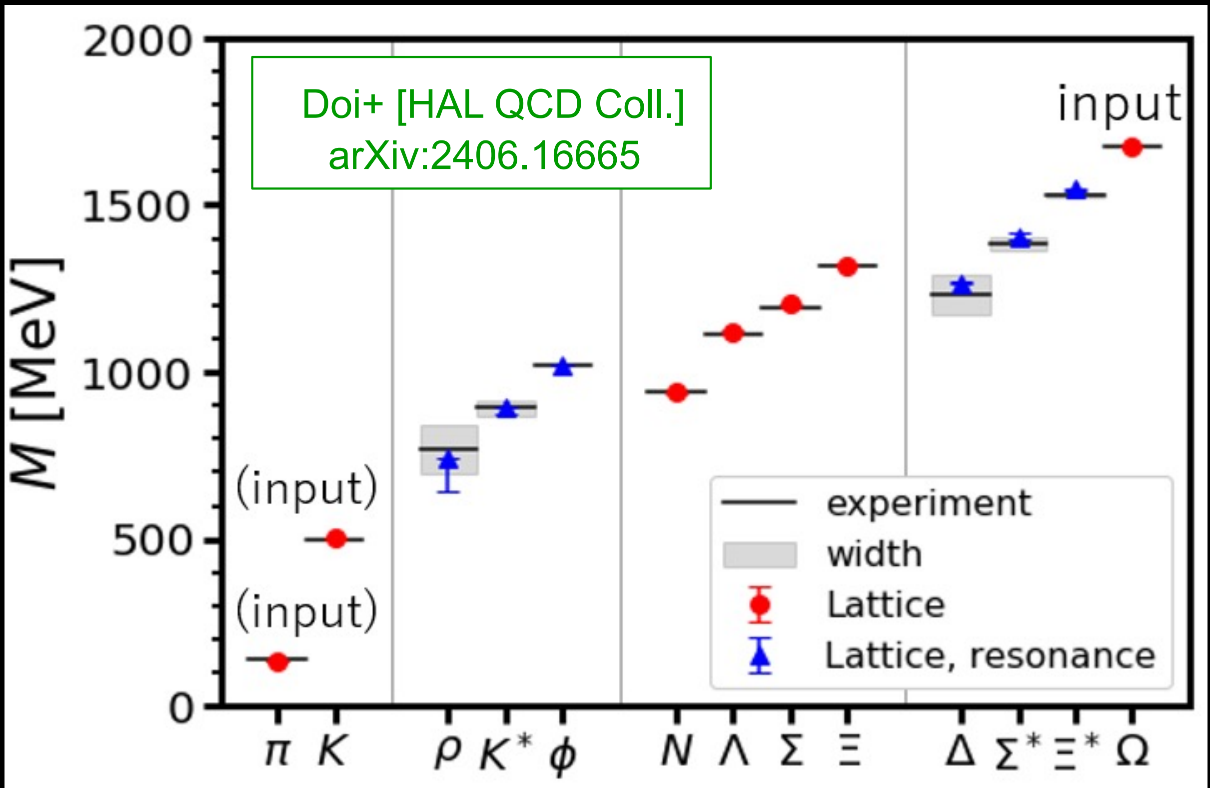


(2+1)-flavor QCD on
FUGAKU@RIKEN (440PFlops)
m_π=137.1 MeV, L=8.1 fm

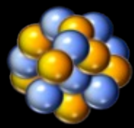
Hadron-hadron interactions : Why do we care ?

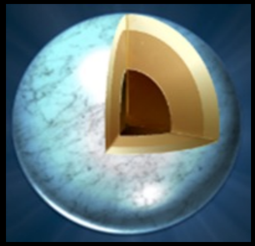
- **Nuclear forces & Hyperon forces**

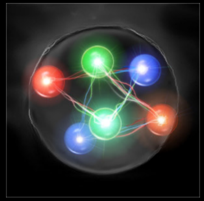
  ⇔ Atomic nuclei, hypernuclei, and EoS for neutron stars

- **Exotic hadrons & Exotic nuclei**

  ⇔ Deeper understanding of "confinement"







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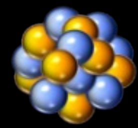

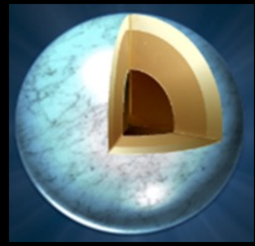

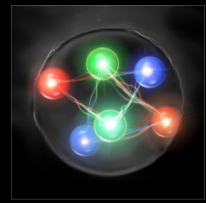

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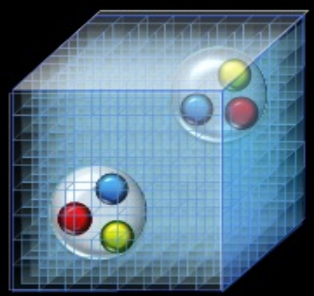
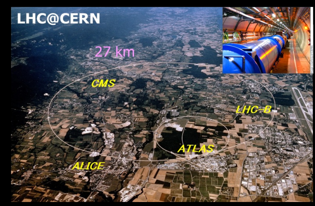


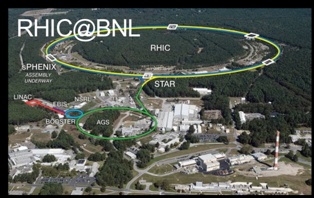
Era of "co-evolution" of LQCD and Expt.

BB: $\Lambda\Lambda$–$N\Xi$, $N\Omega$, $\Omega\Omega$

MM: T_{cc}^{+}

MB: $s\bar{s}$ -N, $c\bar{c}$ -N





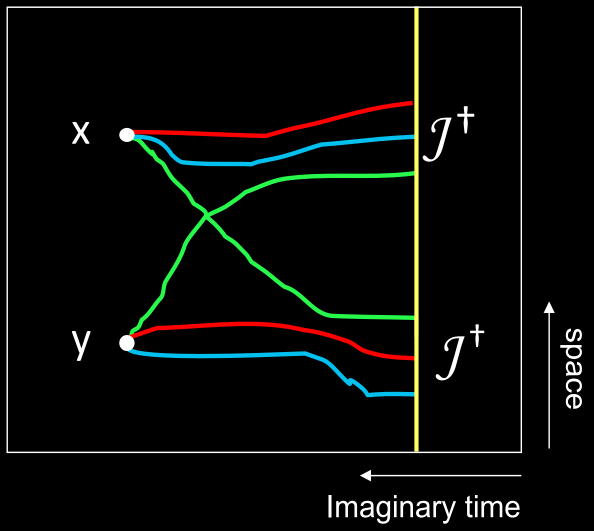
GSI, J-Lab., BESIII, Belle, BaBar …

How to extract hadron-hadron int. in LQCD ?

Spacetime correlation of composite particles -> S-matrix

- Haag-Nishijima-Zimmermann formula (1958)
- Borchers Theorem (1960)

$$R(r,\tau) = \sum_n \Psi_n(r) e^{-E_n \tau}$$



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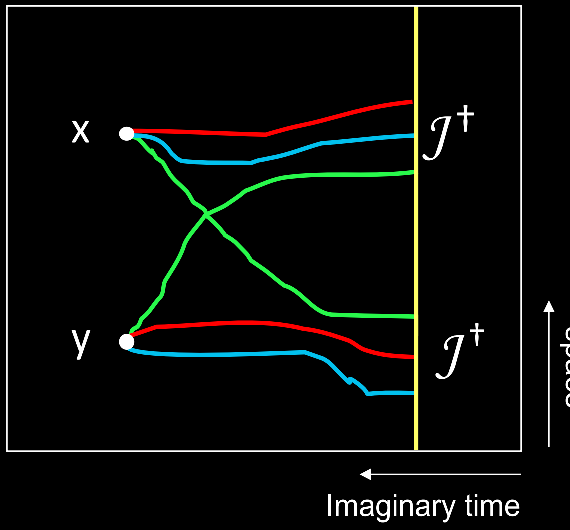


Luscher' s Method

E_n → relative momentum k_n → phase shift, binding energy

Luscher, Nucl. Phys. B354 (1991) 531

HAL QCD Method

$R(r,\tau)$ → LS equation ($T = U + GUT$) → phase shift, binding energy

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

Relation between the two: Iritani+ [HAL QCD Coll.], JHEP 03 (2019) 007.
Lyu+ [HAL QCD Coll.], PRD 105 (2022) 074512.

How to extract hadron-hadron int. in LQCD ?

HAL QCD Method

$R(\mathrm{r},\tau)$ → LS equation ($T = U + GUT$) → phase shift, binding energy

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

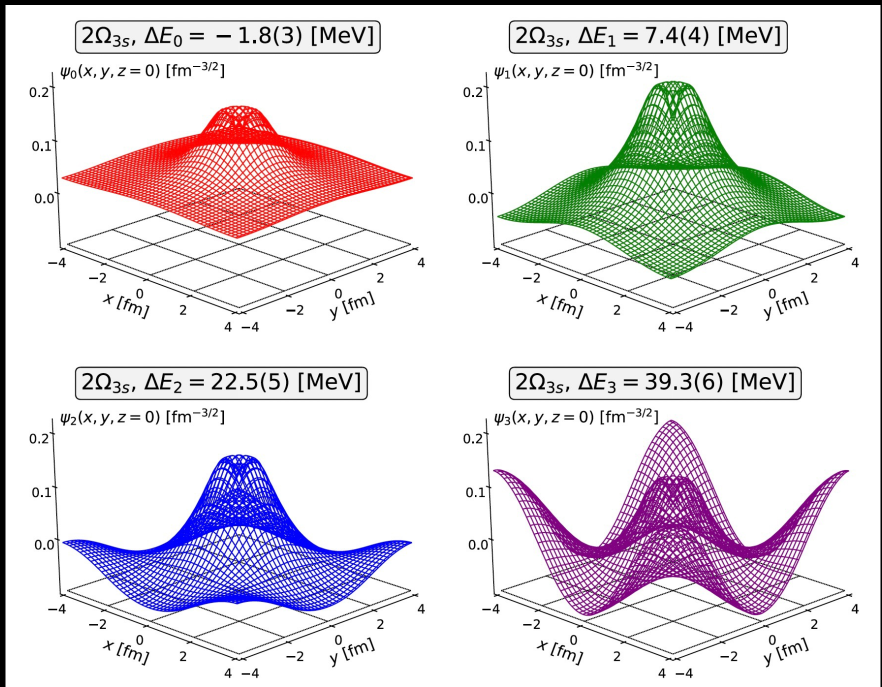
How to extract hadron-hadron int. in LQCD ?

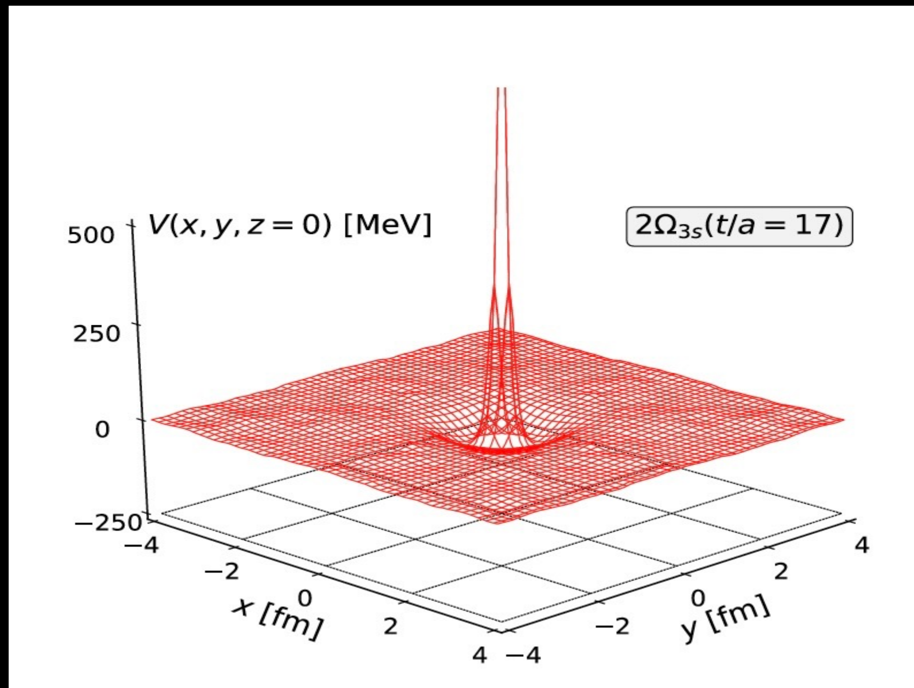
HAL QCD Method

$R(\mathrm{r},\tau)$ → LS equation ($T = U + GUT$) → phase shift, binding energy

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

$R(\mathrm{r},\tau)$ $\quad\quad$ $U(\mathrm{r}, \mathrm{r}')$





Lyu+ [HAL QCD Coll.] , PRD 105 (2022) 074512.

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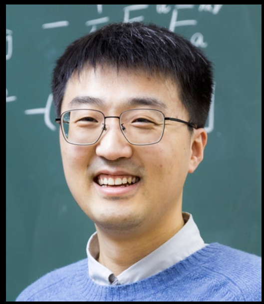
$R(r,\tau)$ → LS equation ($T = U + GUT$) → phase shift, binding energy

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

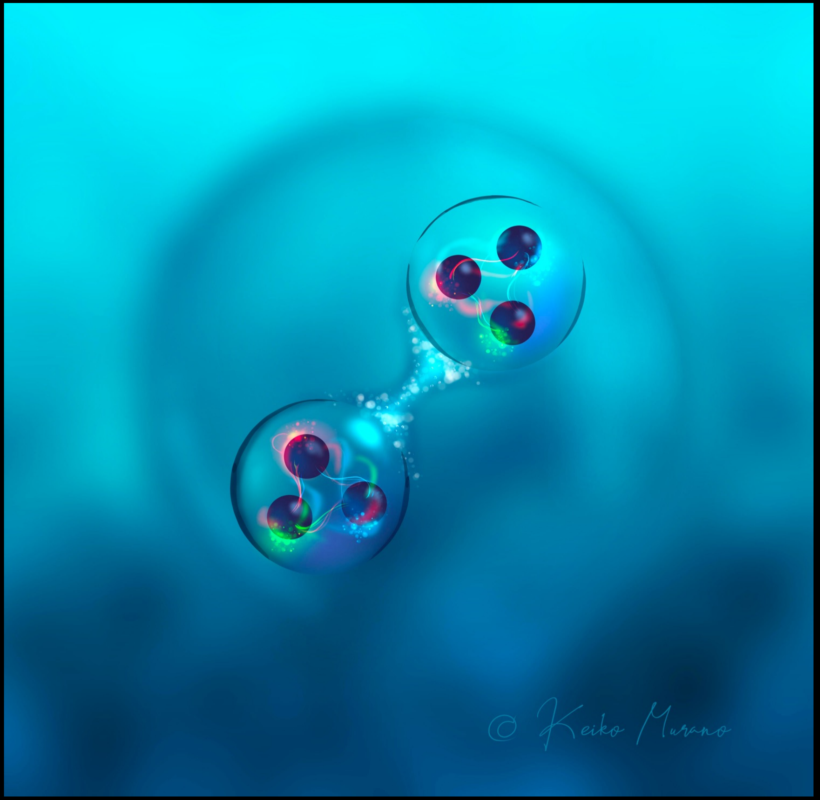
$R(r,\tau)$ → $U(r, r')$ (Inverse Problem)

- Derivative expansion: Aoki, Hatsuda, Ishii (2010)
- Separable expansion: L. Meng & Epelbaum (2023)
- Machine leaning: L. Wang+ (2024)

Lingxiao Wang
Parallel talk at
H: Statistical
Methods
(18:00-, Aug. 21)

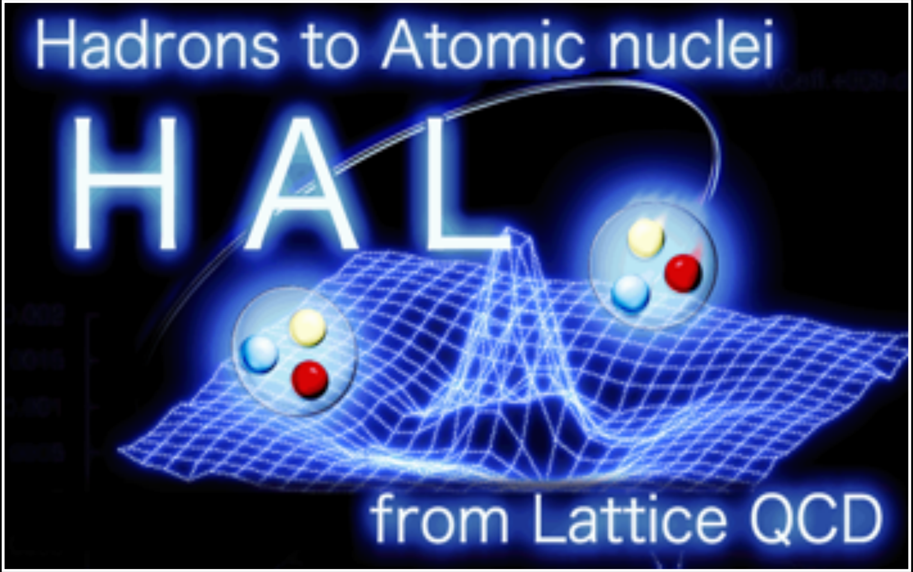


Baryon-Baryon Interactions
- roles of strangeness and charm -



$\Lambda\Lambda - N\Xi$ (S=-2)
$N\Omega$ (S=-3)
$\Omega\Omega$ (S=-6)

Large Scale LQCD Simulations of Hadron-Hadron Int.
(HAL QCD Collaboration since 2010)



(KEK) T. Aoyama
(RIKEN) T. Doi, T. Hatsuda, Y. Liu, L. Zhang, R. Yamada, Lingxiao Wang
(Nihon) T. Inoue
(Rissho) T. Sugiura
(TIT) K. Murakami
(TMU) K. Murase
(YITP) S. Aoki, E. Itou
(Kyoto) T. M. Doi
(RCNP) N. Ishii, P. Junnarkar, H. Nemura
(Osaka) Y. Ikeda, K.Sasaki
(Birjand) F. Etminani
(Bonn) H. Tong

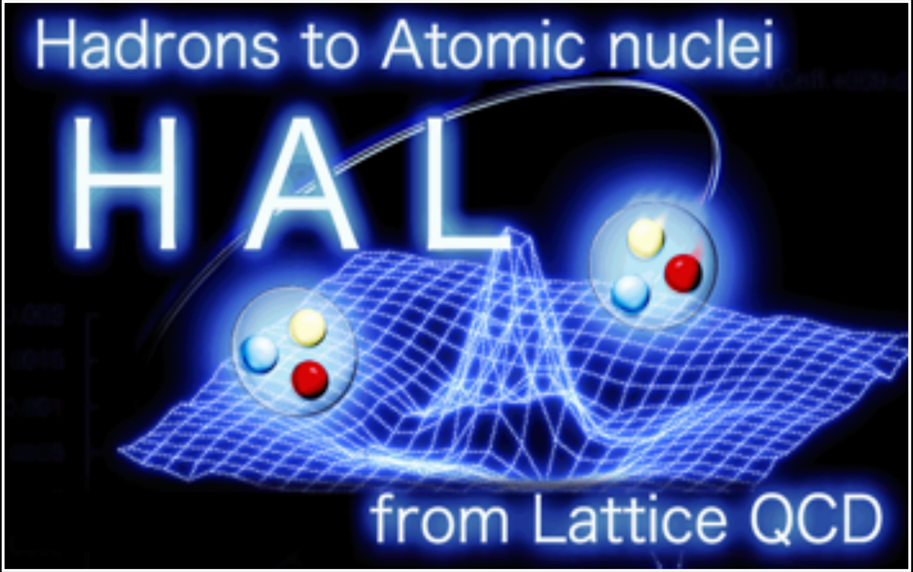
$V=(8.1\ \text{fm})^3,\ m_\pi=146$ MeV

K @RIKEN: 11PFlops (2011–2019)

$V=(8.1\ \text{fm})^3,\ m_\pi=137$ MeV

FUGAKU @RIKEN: 440 PFlops (2020–)

Large Scale LQCD Simulations of Hadron-Hadron Int.
(HAL QCD Collaboration since 2010)



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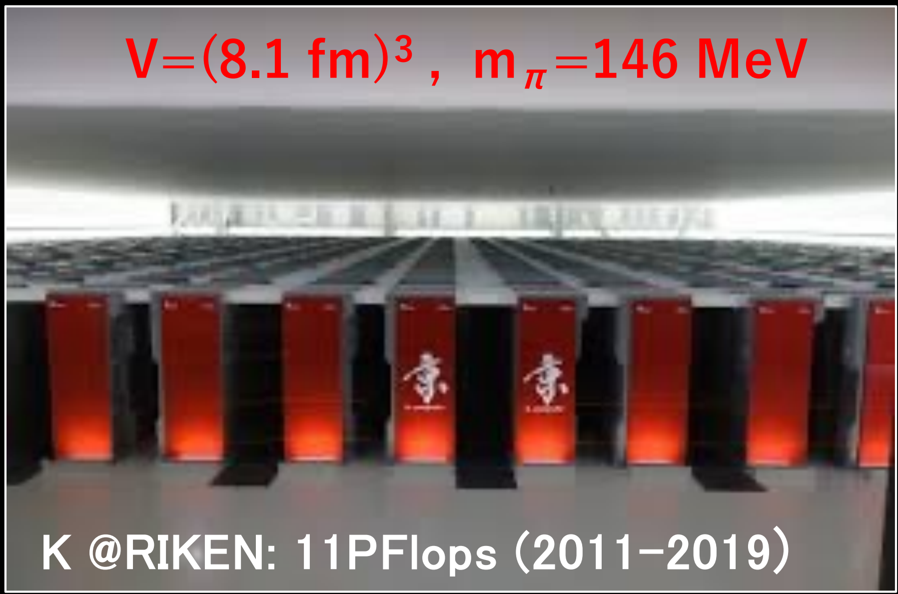
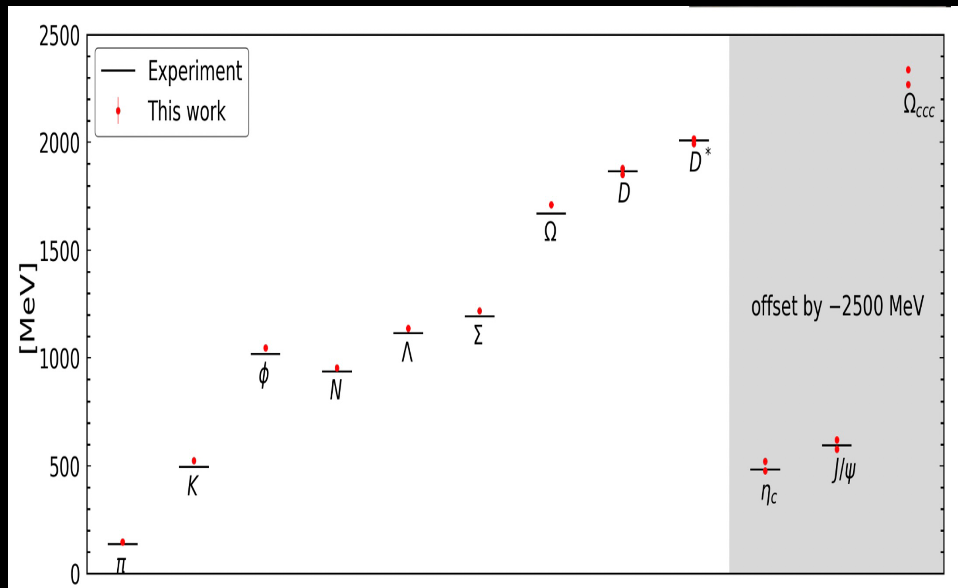


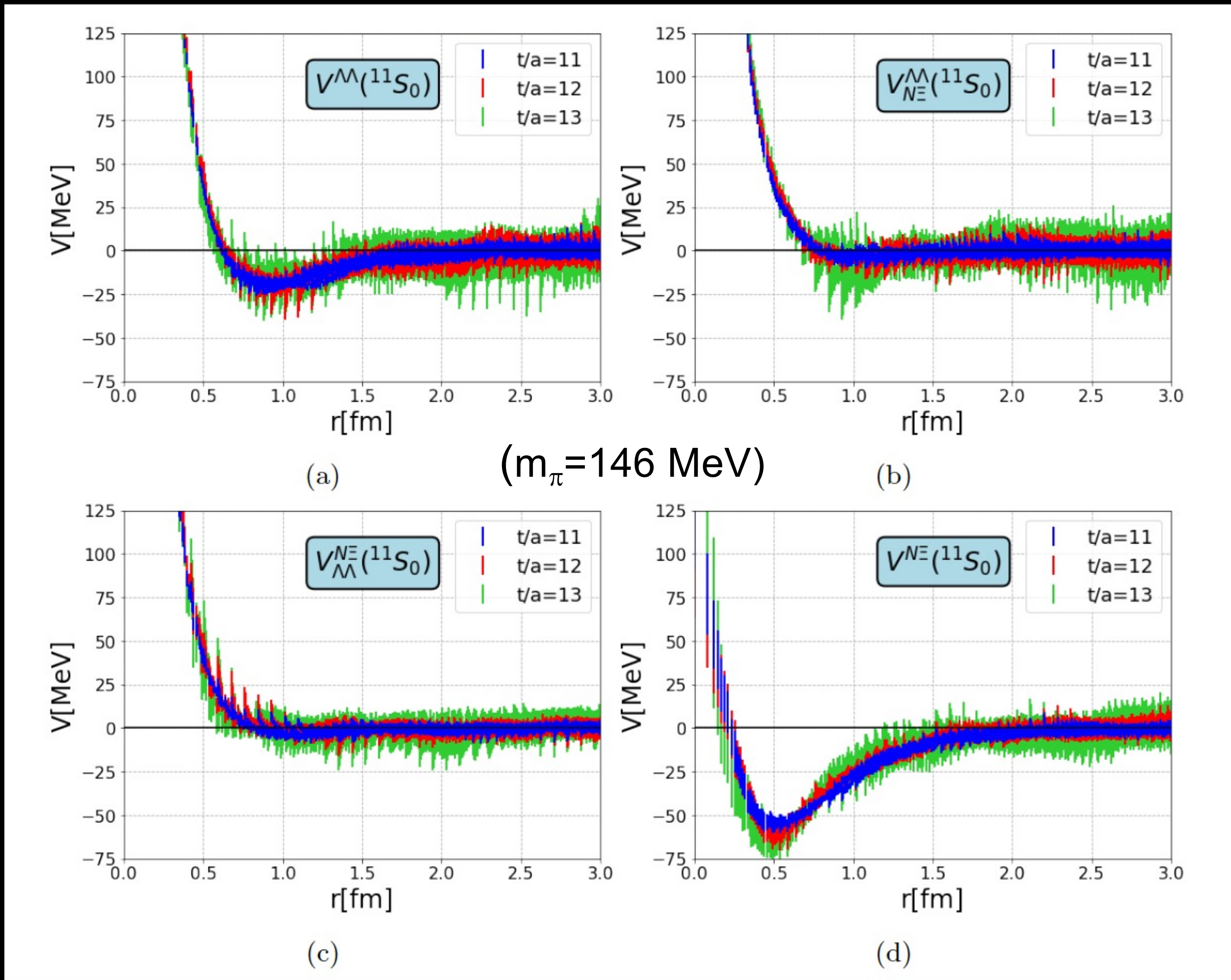


ΛΛ−NΞ system (LQCD)

Sasaki+ [HAL QCD Coll.]
NPA (2020)

Small ΛΛ attraction

Short-range NΞ-ΛΛ coupling



Short-range NΞ-ΛΛ coupling

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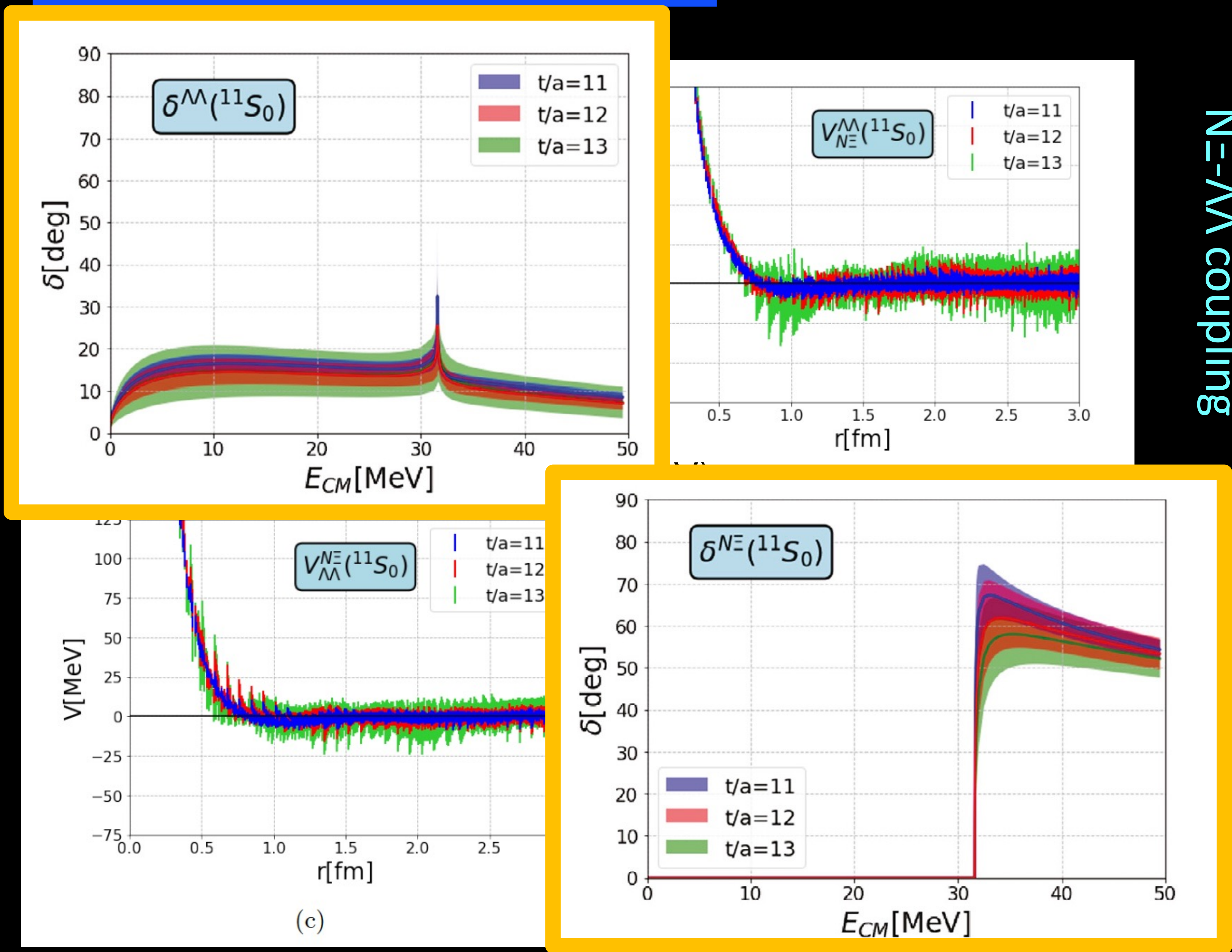
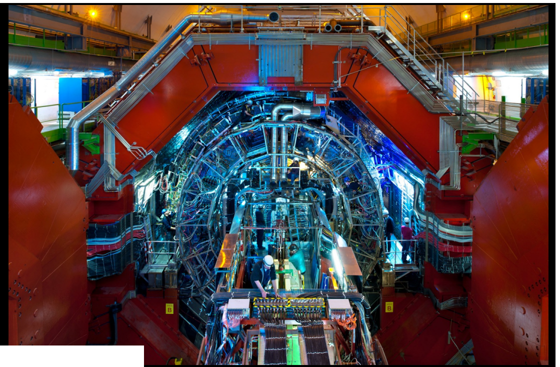


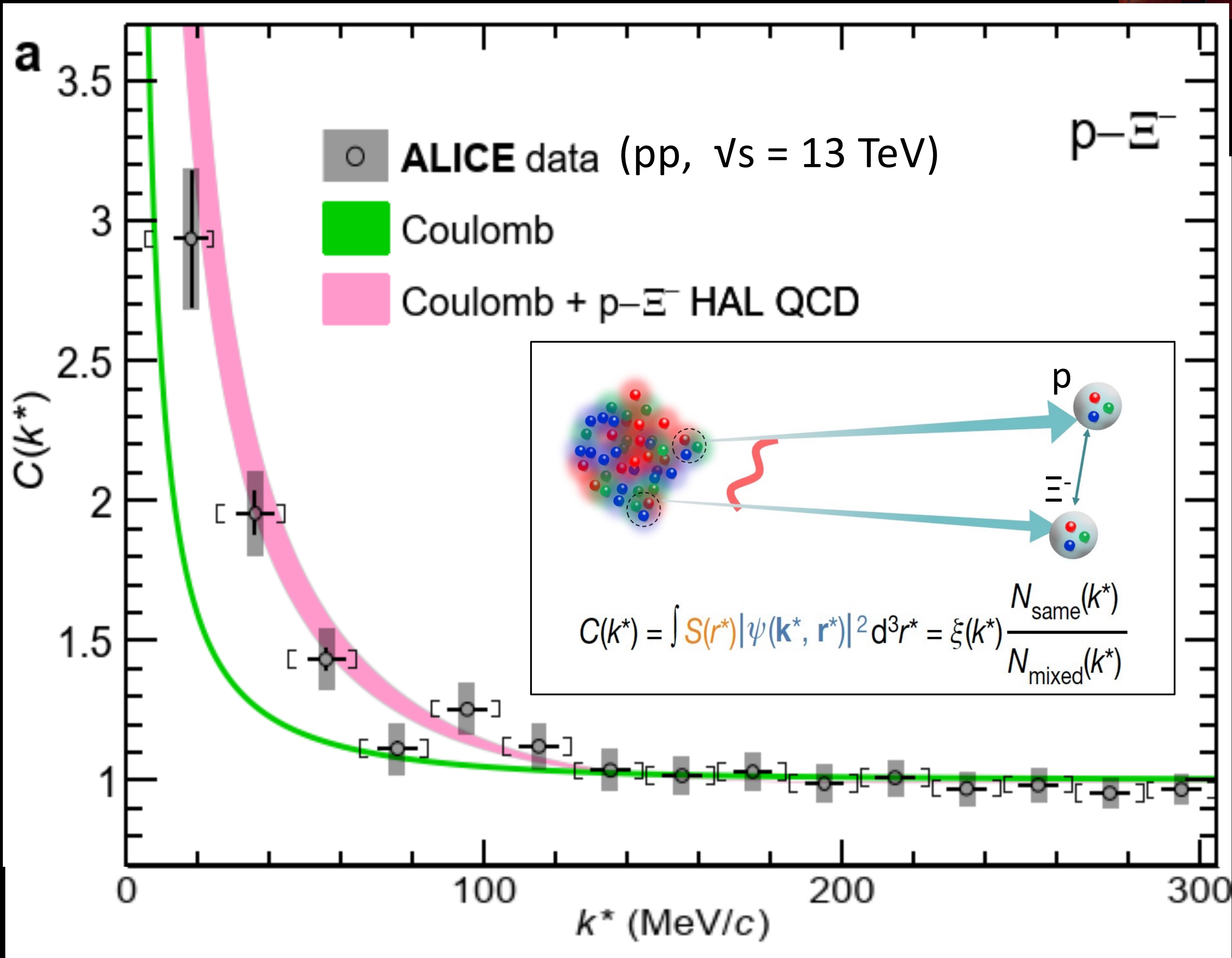
Short-range NΞ-ΛΛ coupling

Large NΞ attraction

NΞ femtoscopy (expt.)

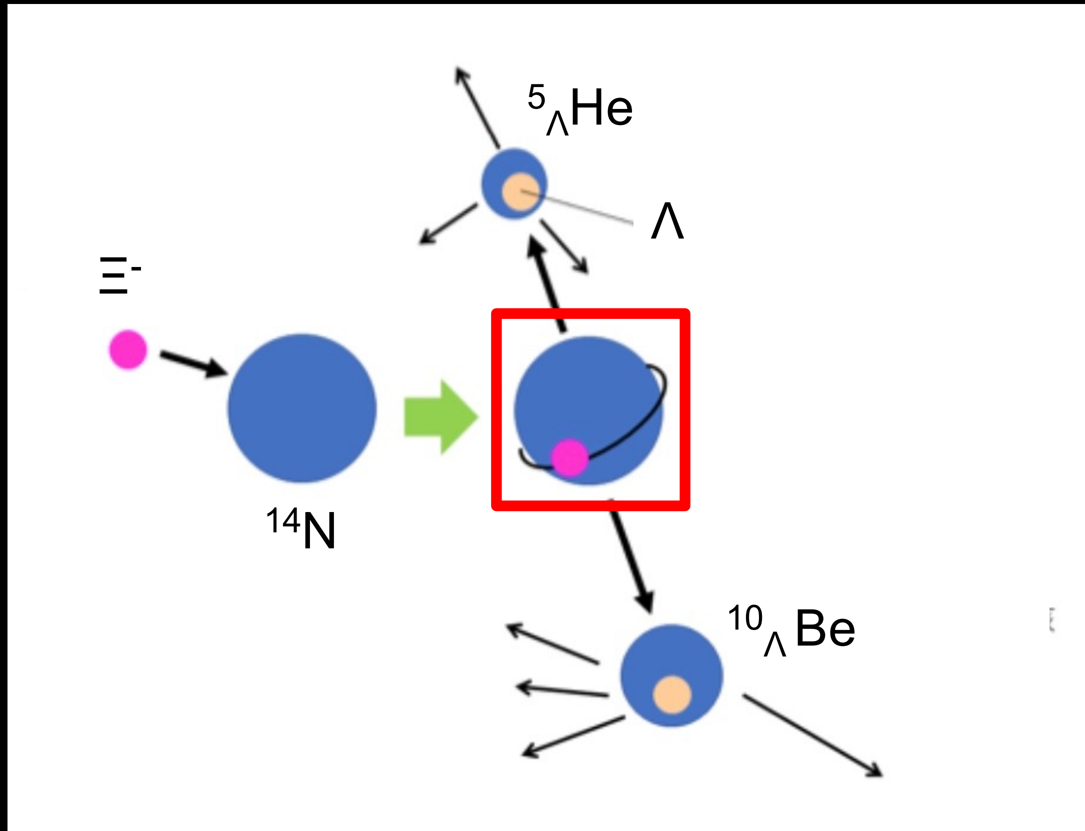
ALICE Coll. (LHC), Nature 588 (2020) 232





Ξ hypernuclei at J-PARC (expt.)

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



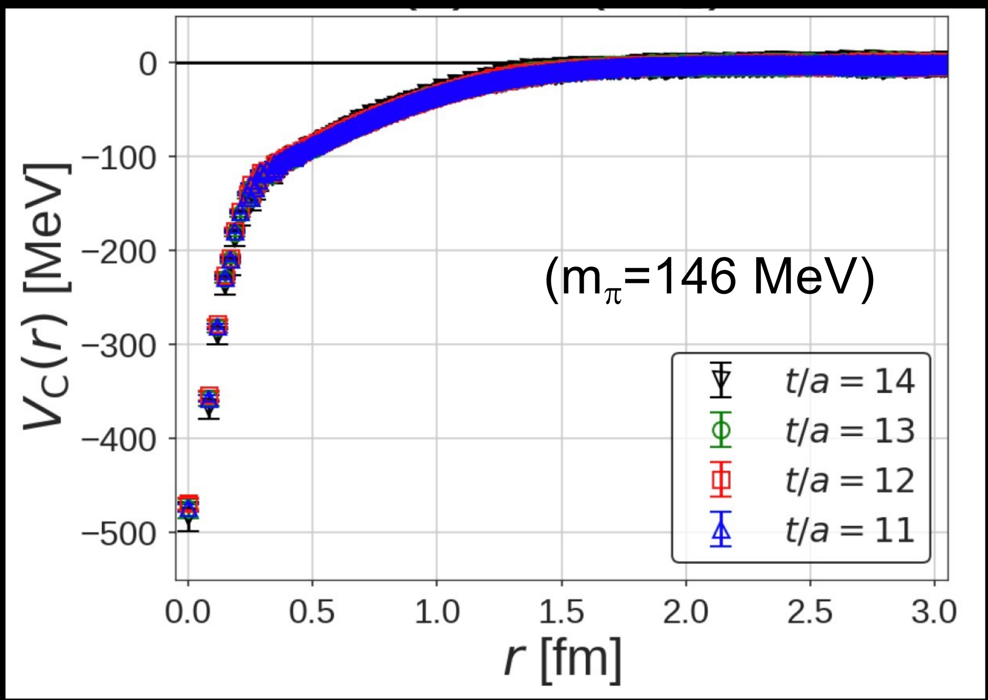
LQCD prediction of

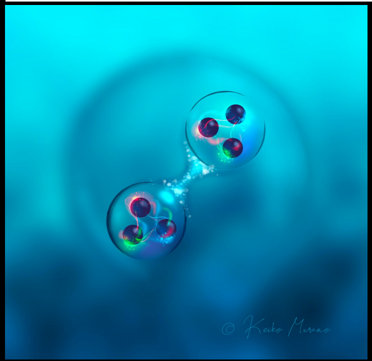
- attraction in NΞ in $^{11}S_0$
- weak NΞ -ΛΛ coupling

cosisitent with the expt. data

Isaka+, Phys.Rev. C109 (2024) 044317

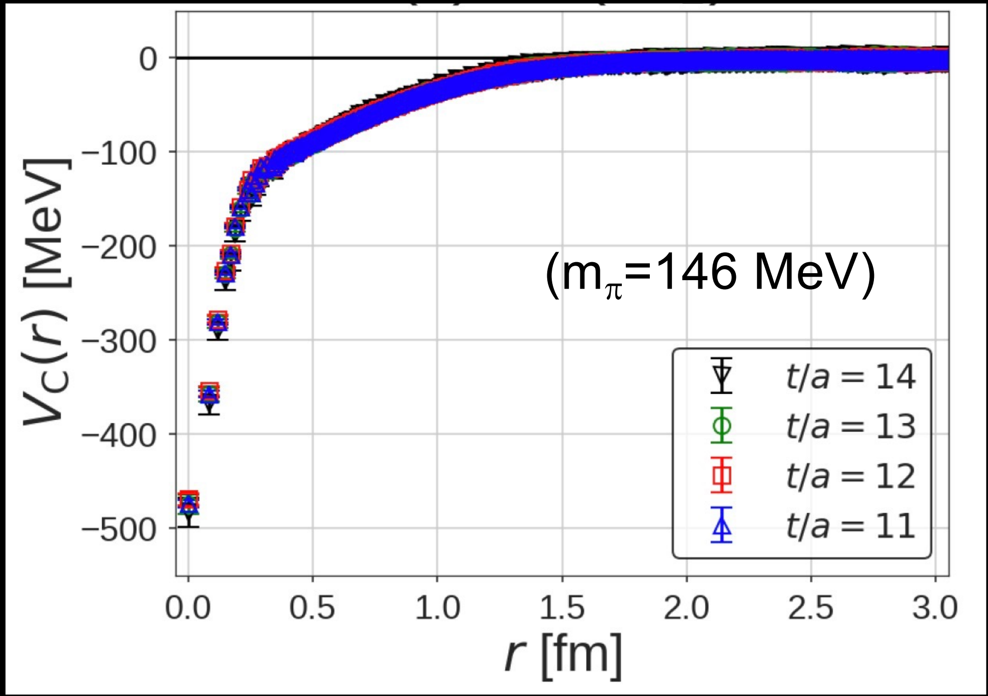
NΩ system (LQCD)

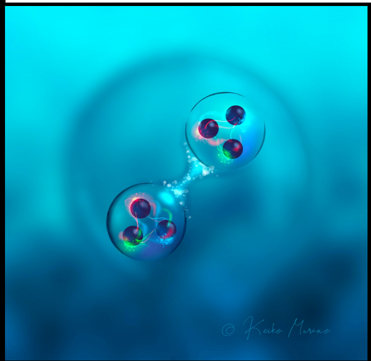




Iritani+ [HAL QCD Coll.],
PLB (2019)

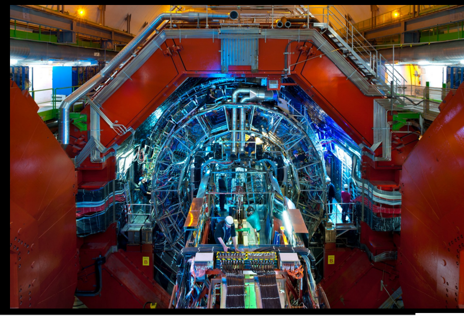
NΩ system (LQCD)

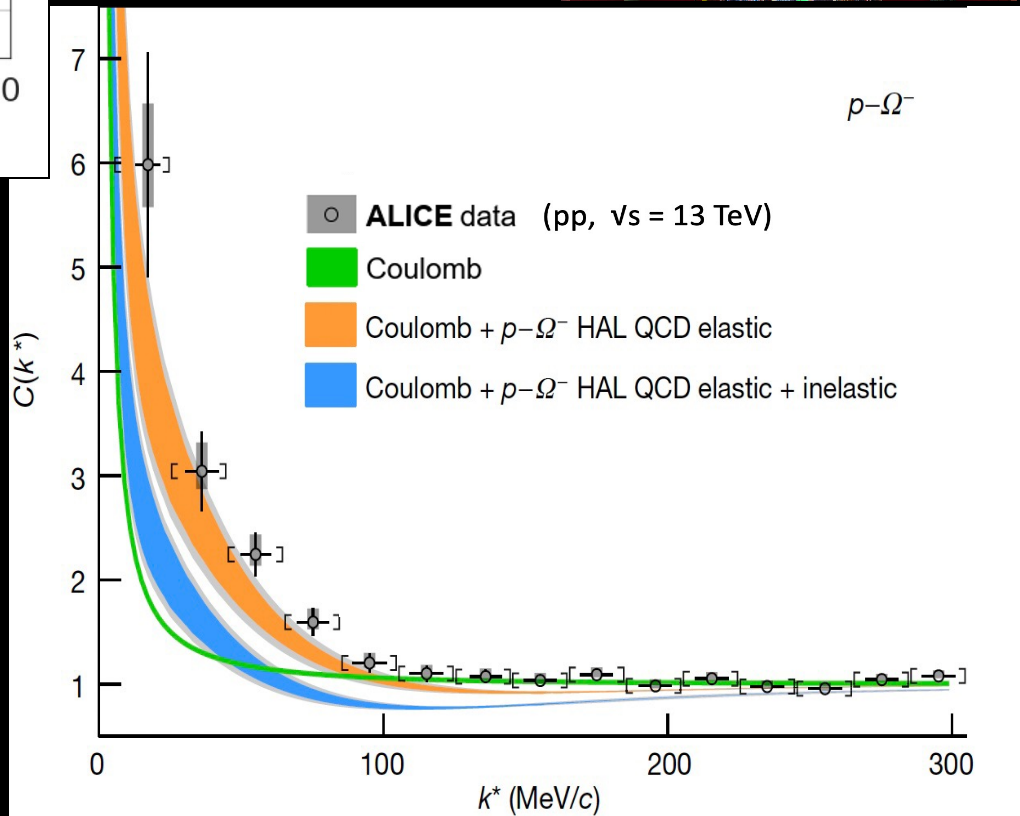




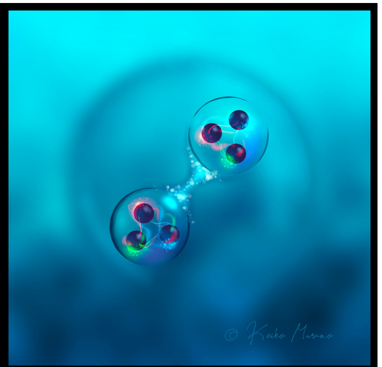
Iritani+ [HAL QCD Coll.], PLB (2019)

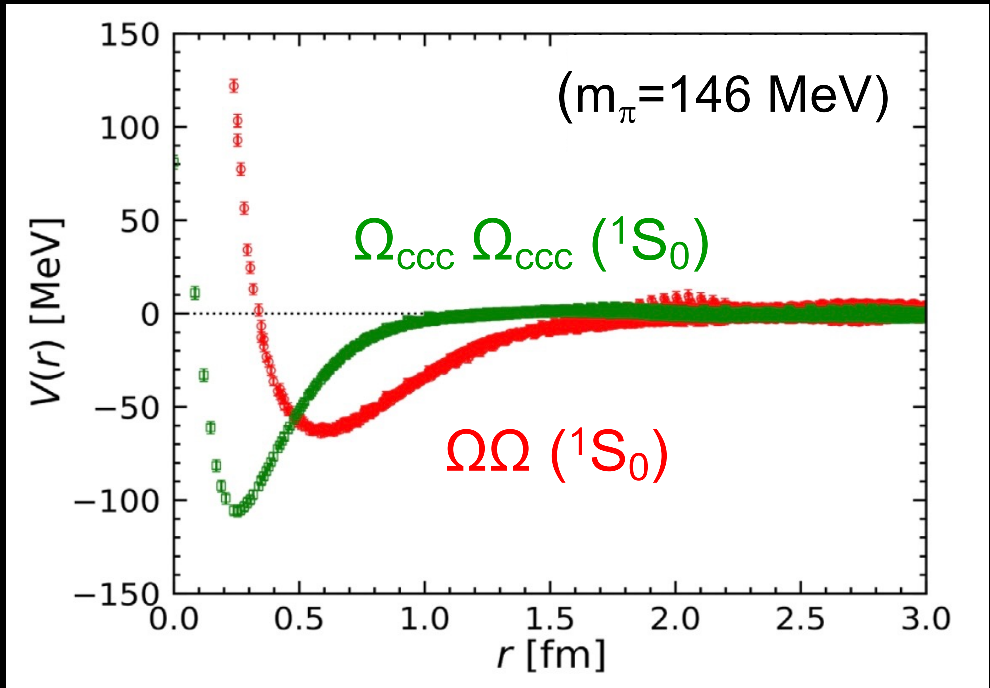
ALICE Coll. (LHC), Nature (2020)





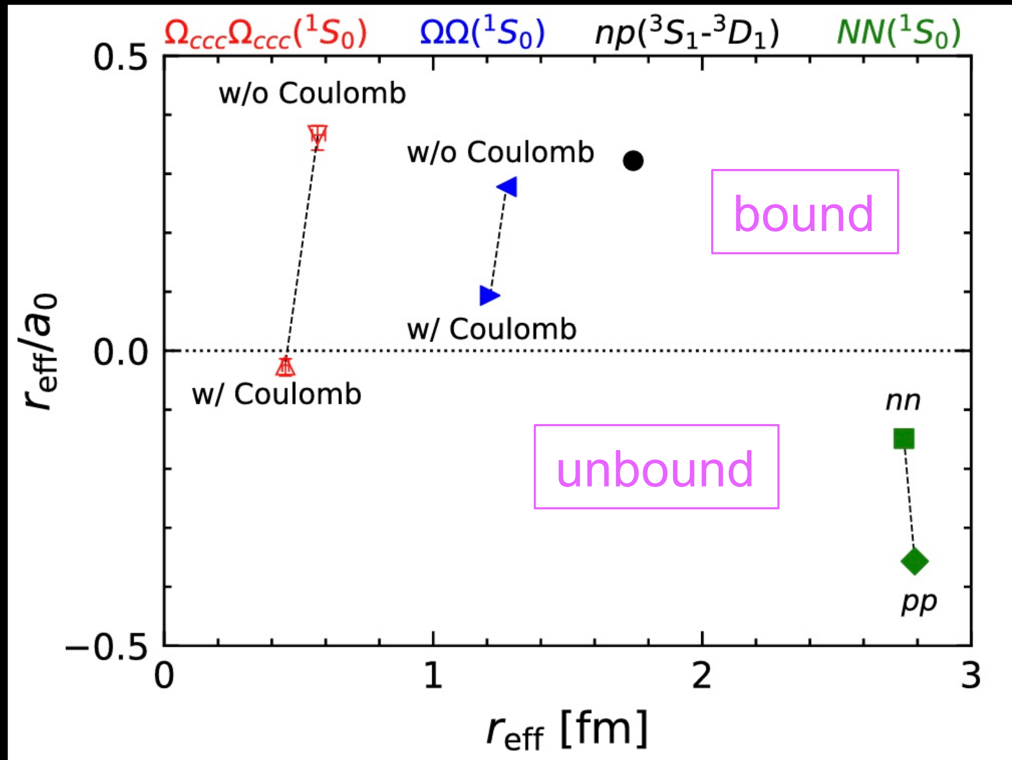
ΩΩ systems (LQCD)





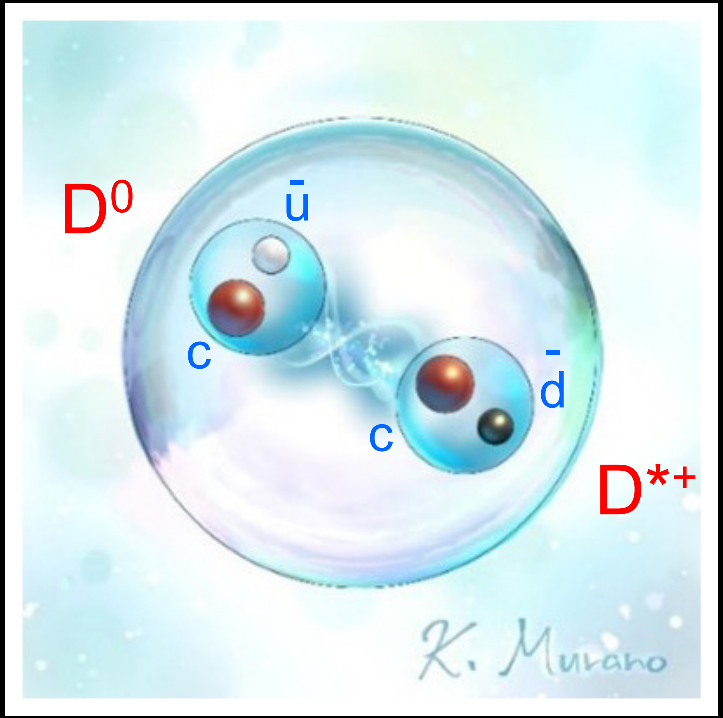
Gongyo+ [HAL QCD Coll.], PRL (2018)

Tong+ [HAL QCD Coll.], PRL (2021)



Meson-Meson Interactions

- genuine tetraquark ?-



$T_{cc}^{+}(3875)$

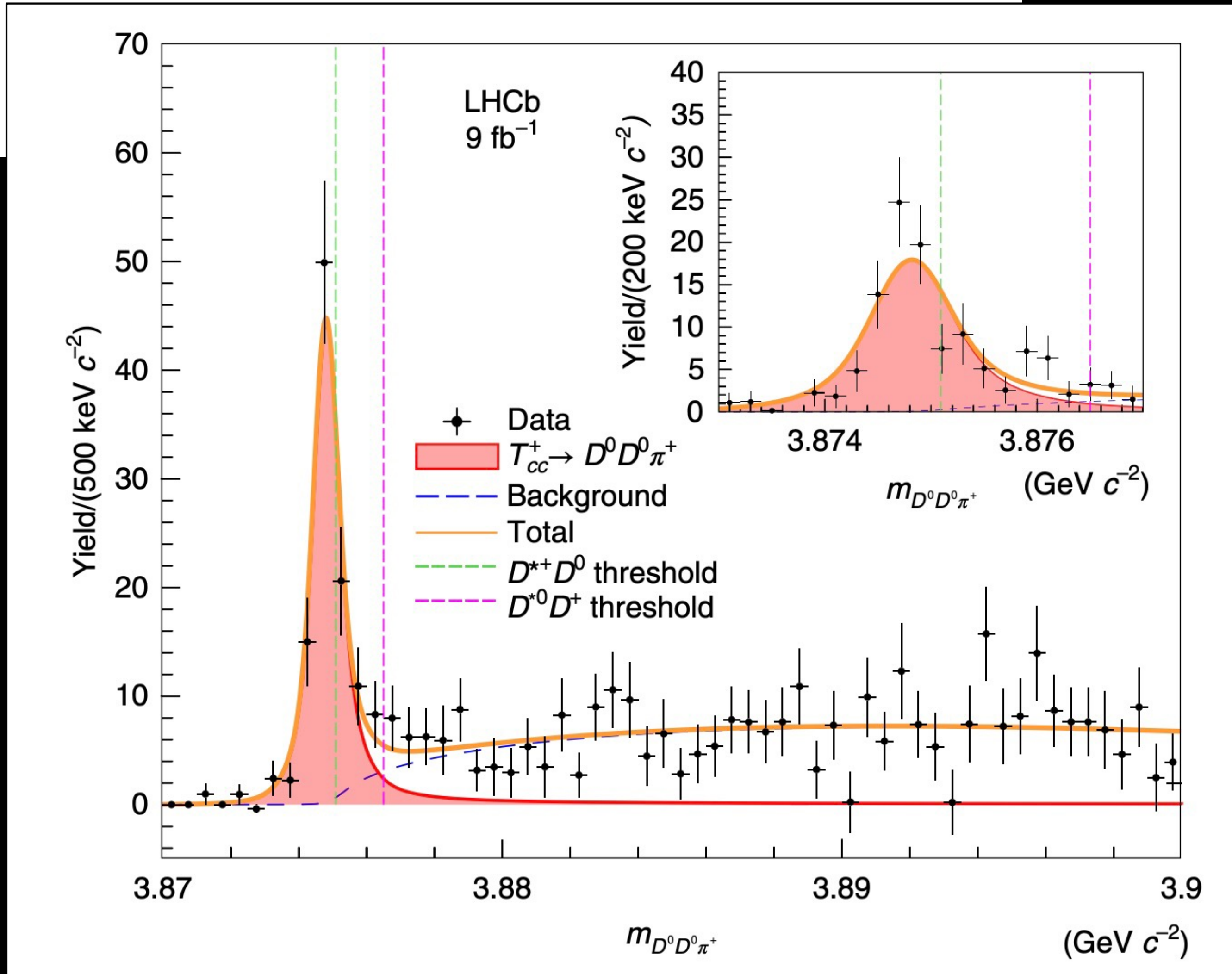
nature physics
LETTERS
https://doi.org/10.1038/s41567-022-01614-y
NATURE PHYSICS | VOL 18 | JULY 2022 | 751–754 |
Check for updates

OPEN

Observation of an exotic narrow doubly charmed tetraquark

LHCb Collaboration*

$T_{cc}^{+}(3875)$



nature COMMUNICATIONS

Study of the doubly charmed tetraquark T_{cc}^{+}

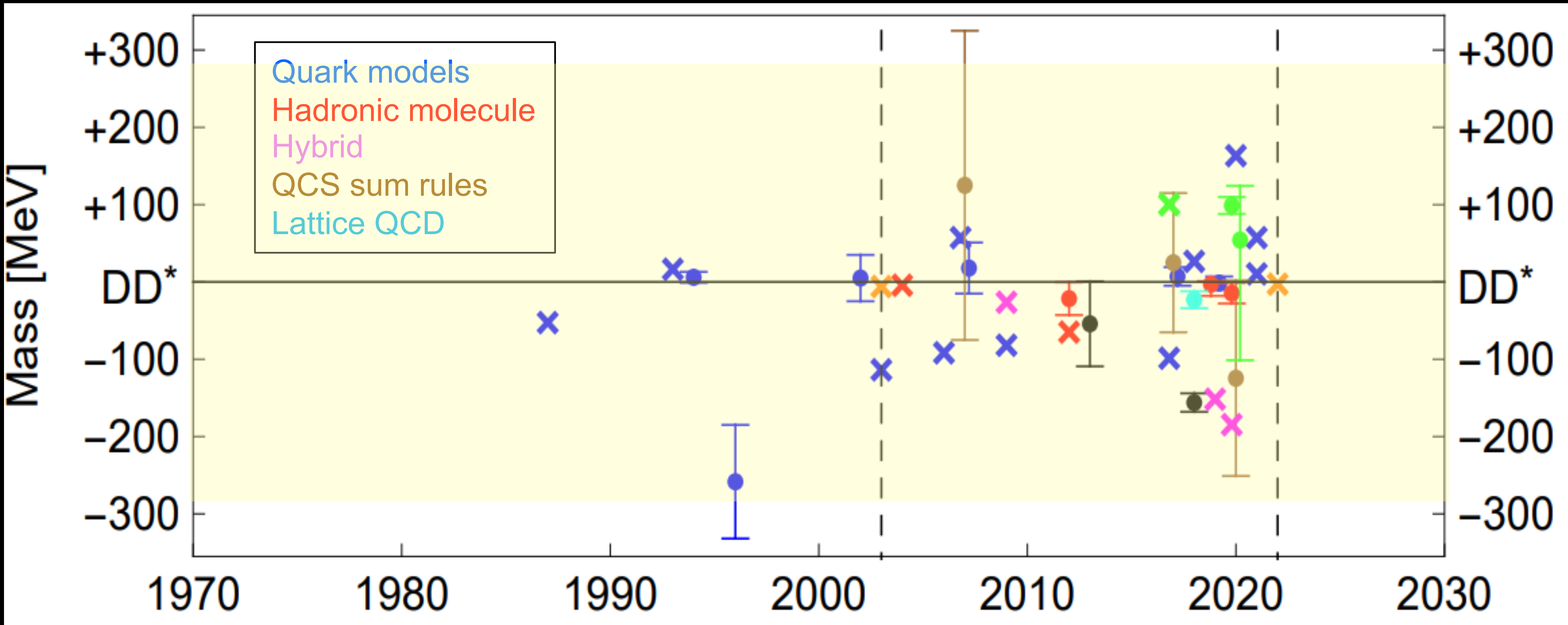
LHCb collaboration

Nature Communications **13**, Article number: 3351 (2022) | Cite this article

$I(J^P)$	δm_{pole}	Γ_{pole}
$0(1^+)$	-360±40 keV	48±2 keV

$\text{Re}(a_0)$	$\text{Im}(a_0)$
7.16 ± 0.51 fm	-1.85 ± 0.28 fm

Theory history (< 2022) of T_{cc}^+ $(cc\bar{u}\bar{d})$ $(IJ^P = 01^+)$



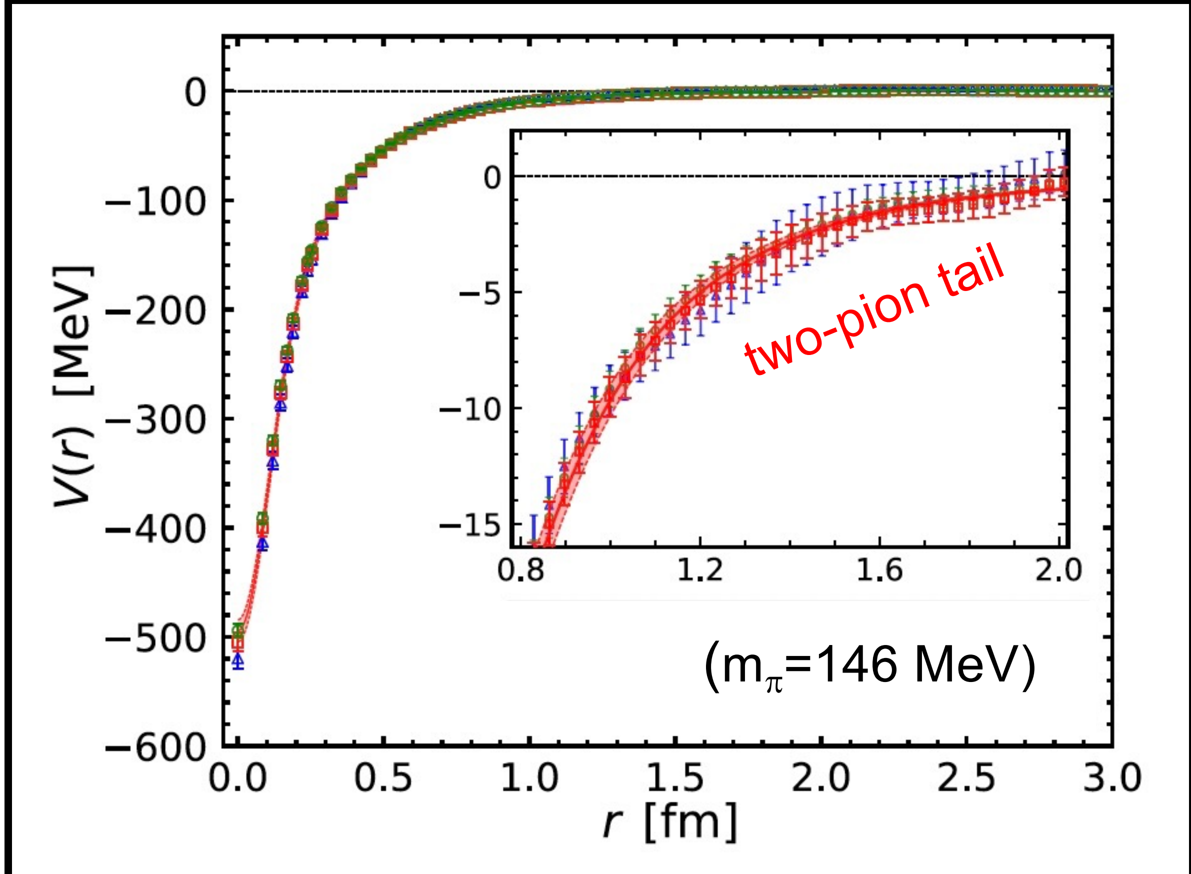
H.-X. Chen *et al.*, Rept. Prog. Phys. 86, 026201 (2023)

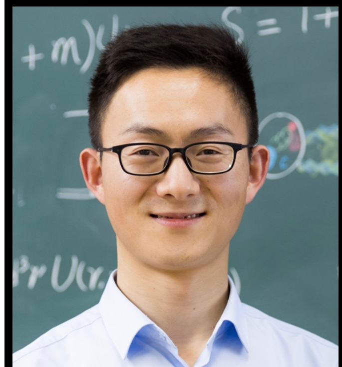
$\pm$300 MeV uncertainty with respect to DD* threshold

Doubly Charmed Tetraquark T_{cc}^{+} from Lattice QCD near Physical Point

Yan Lyu,[1,2,*] Sinya Aoki,[3,2,†] Takumi Doi,[2,‡] Tetsuo Hatsuda,[2,§] Yoichi Ikeda,[4,‖] and Jie Meng[1,5,¶]

PHYSICAL REVIEW LETTERS **131,** 161901 (2023)





Yan Lyu
Parallel talk at
C: Heavy qiarks
(11:20-, Aug. 22)

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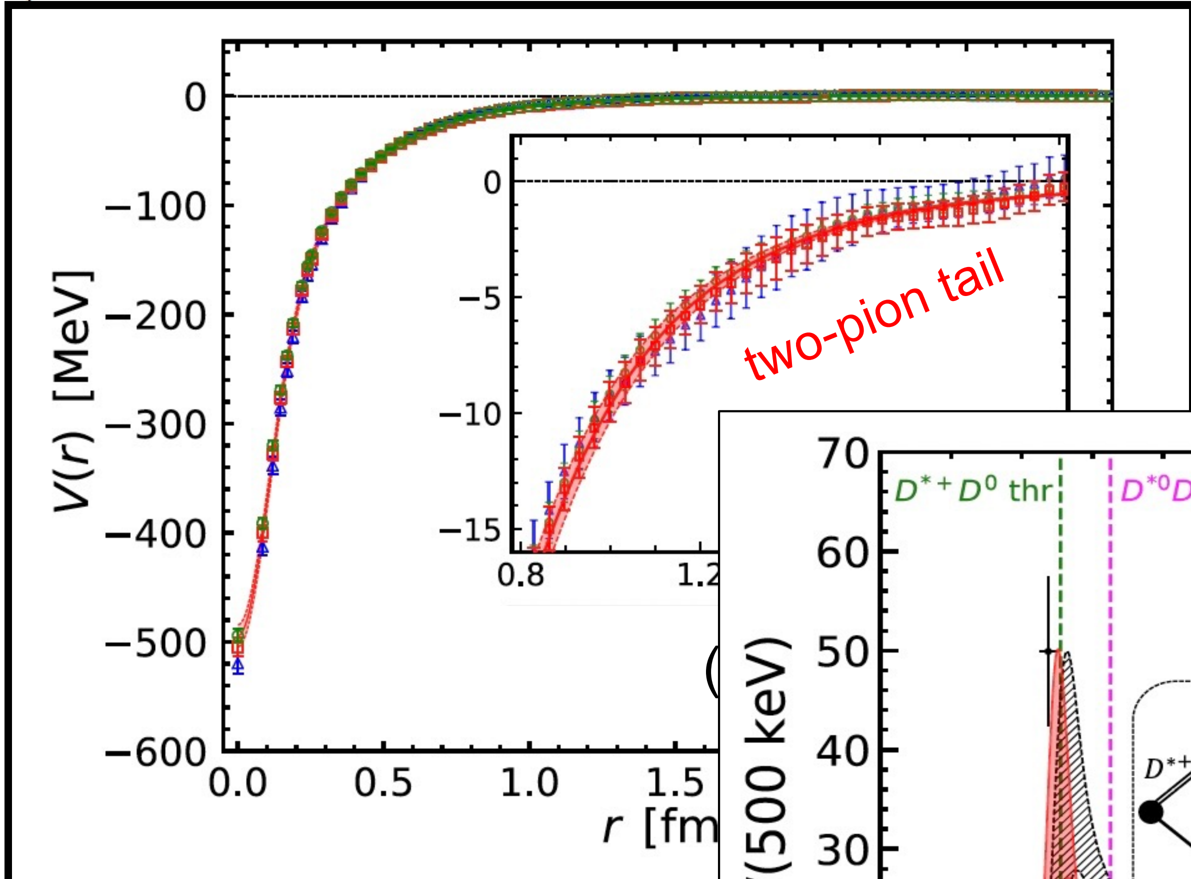
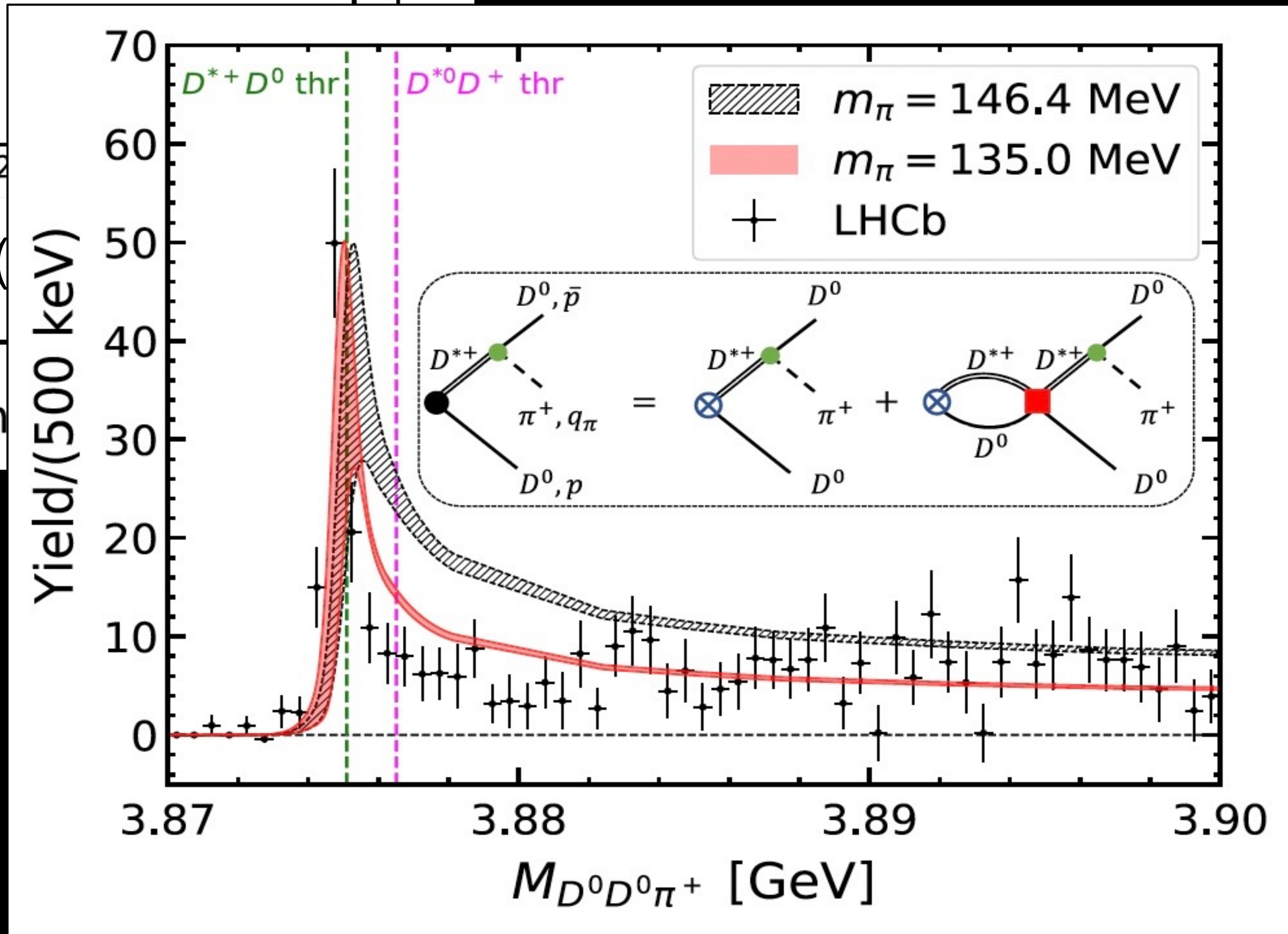
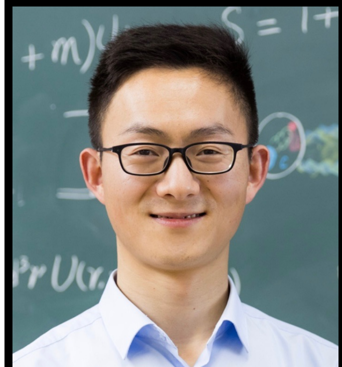
PHYSICAL REVIEW LETTERS **131,** 161901 (2023)

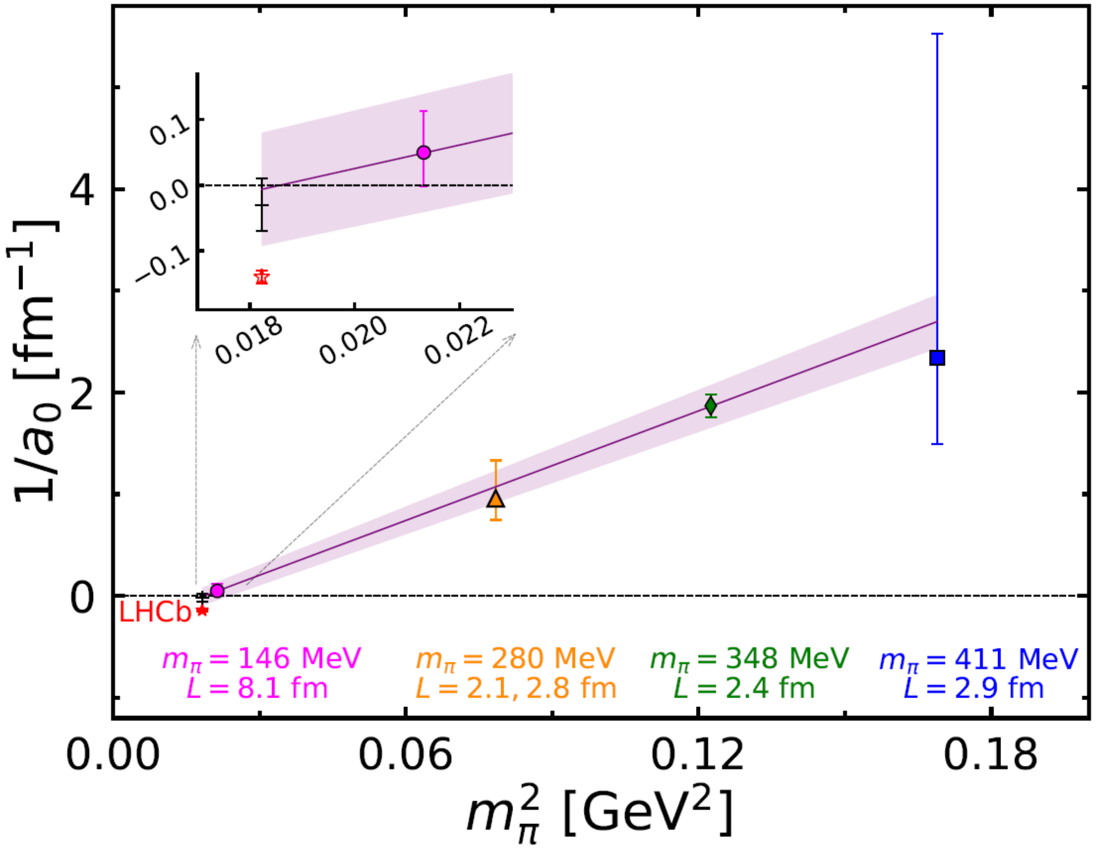






Yan Lyu
Parallel talk at
C: Heavy qiarks
(11:20-, Aug. 22)

DD* scattering length as a function of the pion mass



HAL QCD: Ikeda+, Phys. Lett. B 729, 85 (2014) HAL QCD

Luscher: Chen et al., Phys. Lett. B 833, 137391 (2022)

Luscher: Padmanath and Prelovsek, Phys. Rev. Lett. 129, 032002 (2022)

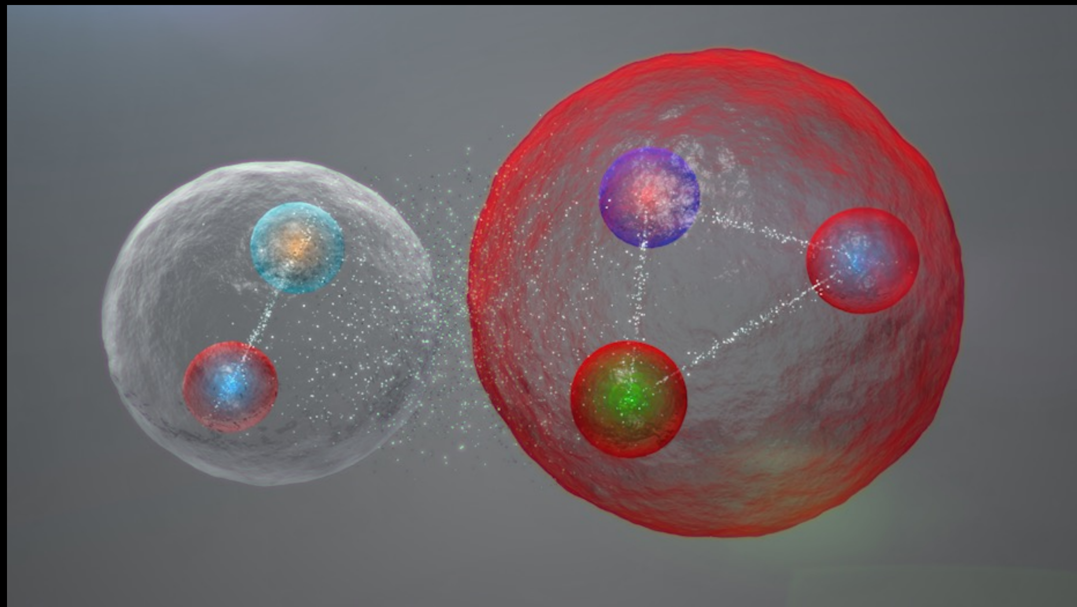
HAL QCD: Yan+, Phys.Rev.Lett. 131, 161901 (2023)

Not the end of the story:

(i) Isospin breaking (QED and QCD), (ii) coupled channel effect,

(iii) one-pion exchange and the "left hand cut", S. Collins et al., PRD 109 (2024) 094509

Meson-Baryon Interactions
- color-dipole and nucleon -

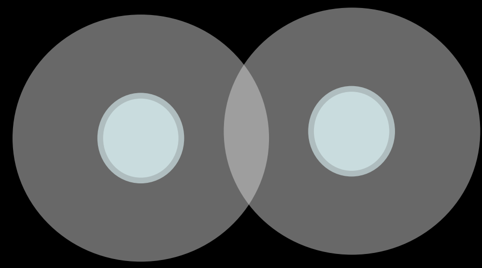


$s\bar{s}$ -N

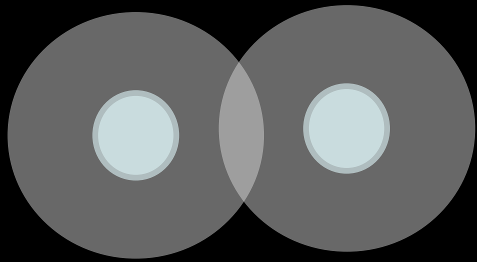
$c\bar{c}$ -N

Question:

What is the force between
“neutral particles” at long range ?



Question:



What is the force between
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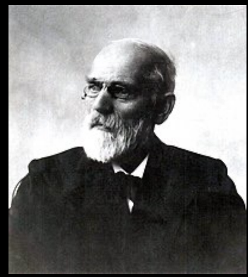
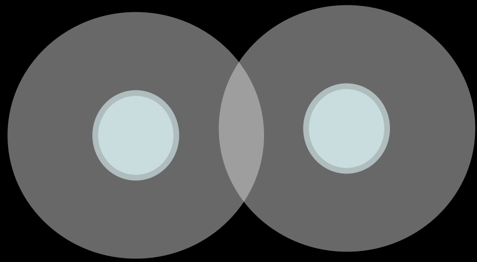
Answer:



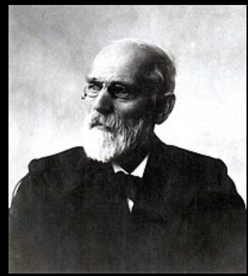
QED
 2-photon exchange force
 = van der Waals (Casimir-Polder) force → $-1/r^7$

Question:

What is the force between
“neutral particles” at long range ?



Answer:



QED

2-photon exchange force

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

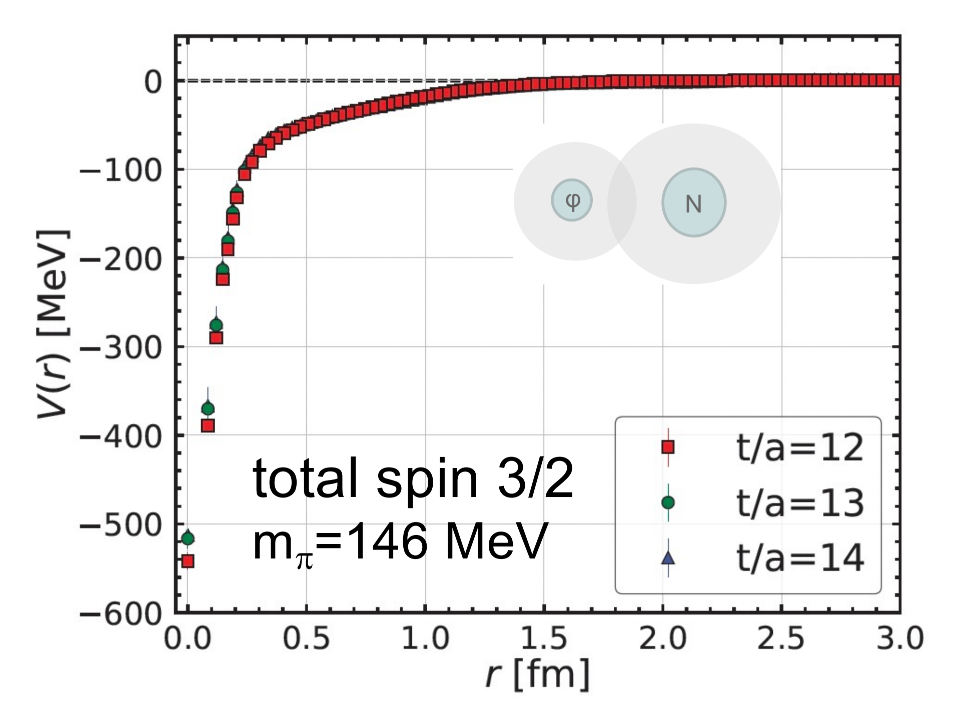
QCD

2-pion exchange force

Bhanot and Peskin, Nucl. Phys. B156 (1979) 391
Fujii and Kharzeev, Phys. Rev. D60 (1999) 114039
Brambilla, Klein, Tarrus Castella and Vairo Phys. Rev. D93 (2016) 054002

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

Yan Lyu, Takumi Doi, Tetsuo Hatsuda, Yoichi Ikeda, Jie Meng, Kenji Sasaki, and Takuya Sugiura
Phys. Rev. D **106**, 074507 – Published 21 October 2022



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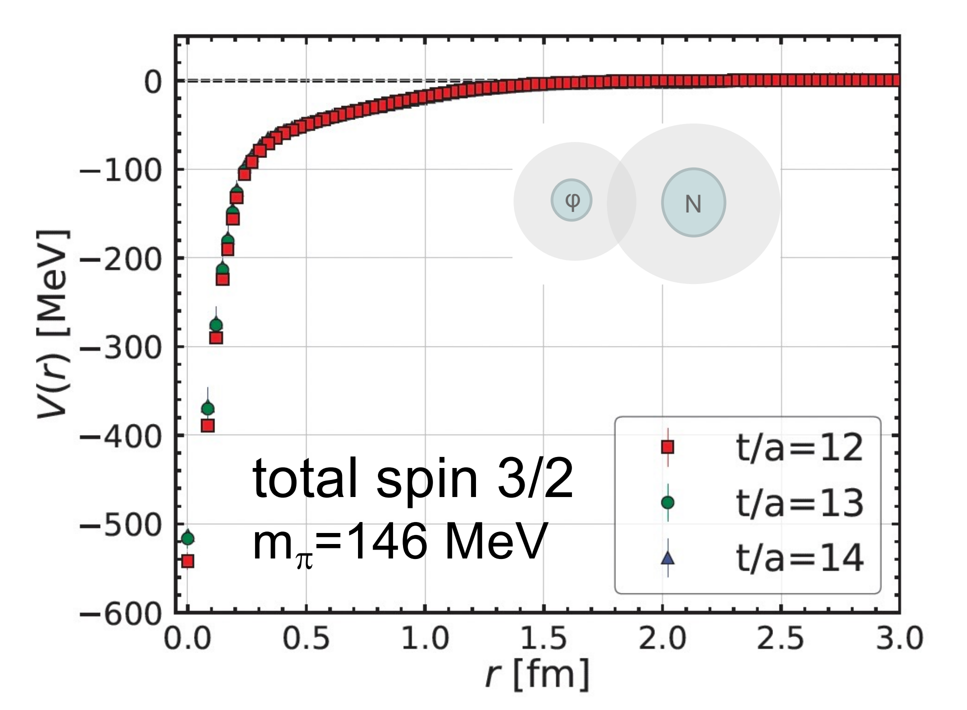
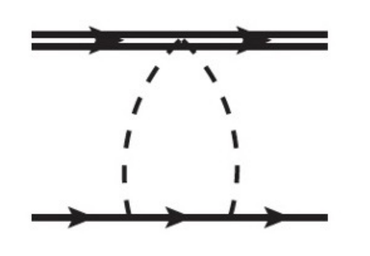
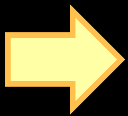


Two-pion Tail at $r > (2m_\pi)^{-1}$





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

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

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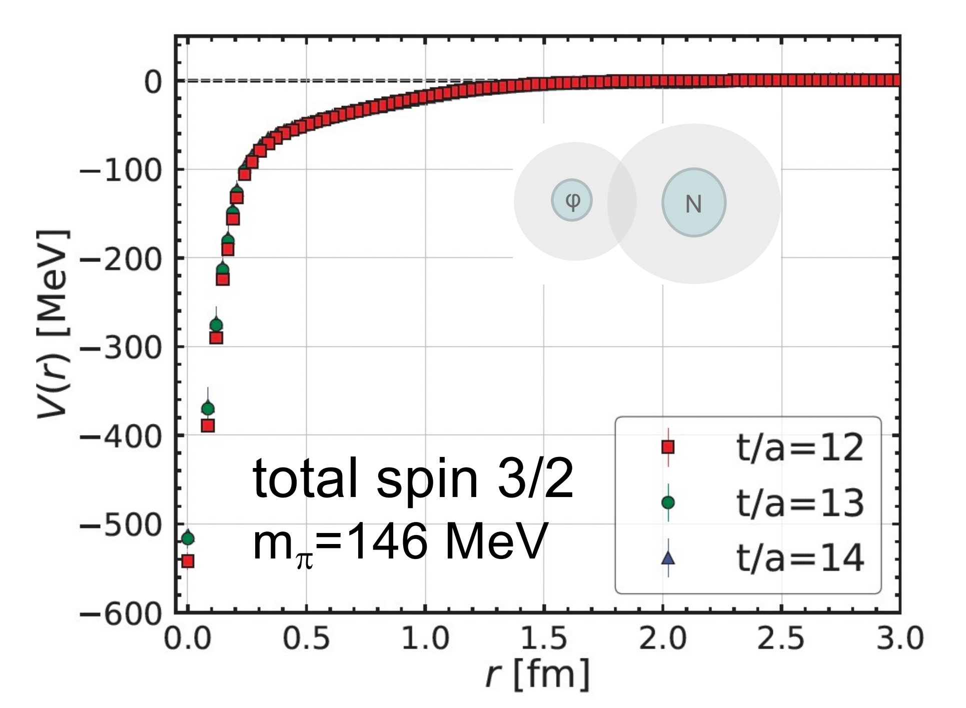

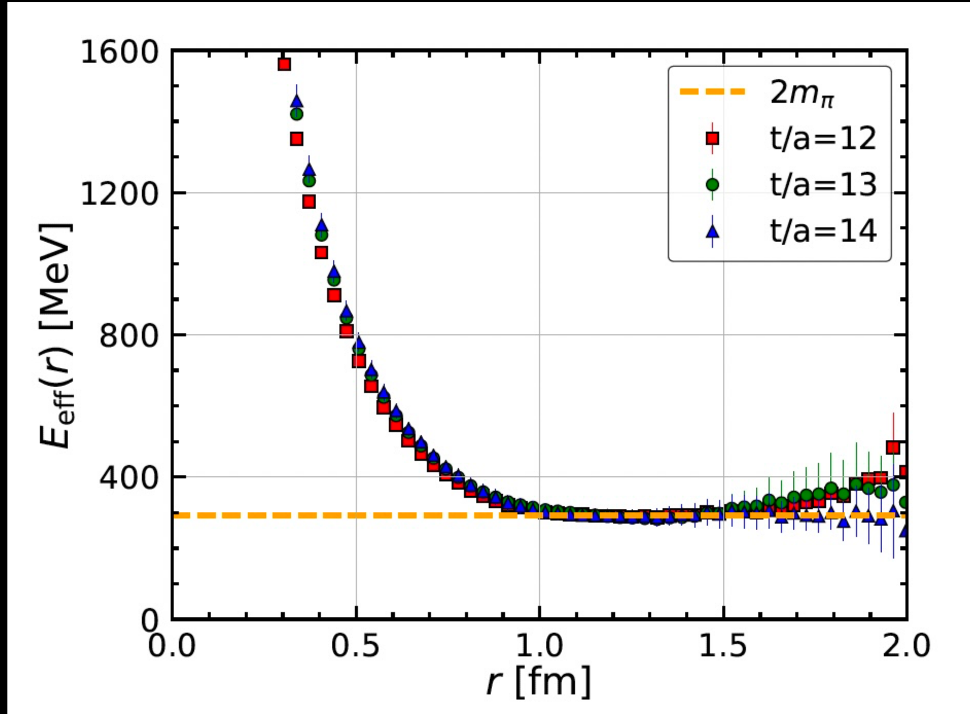

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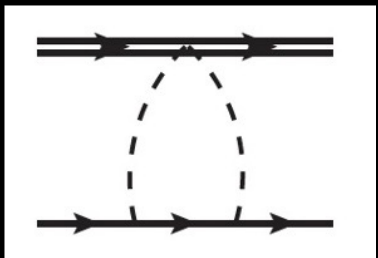

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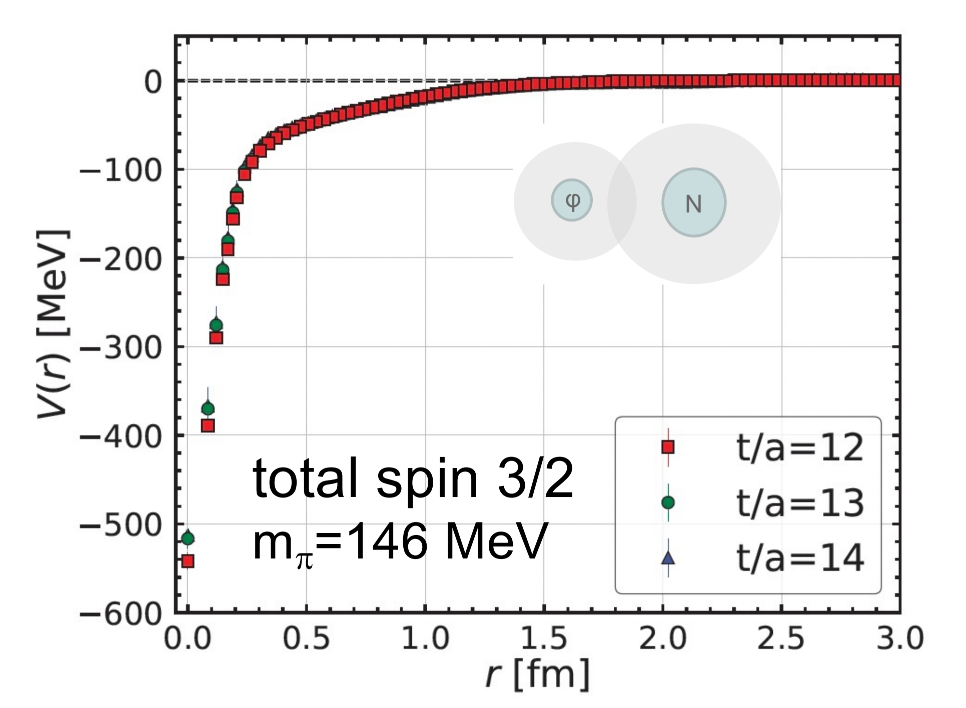

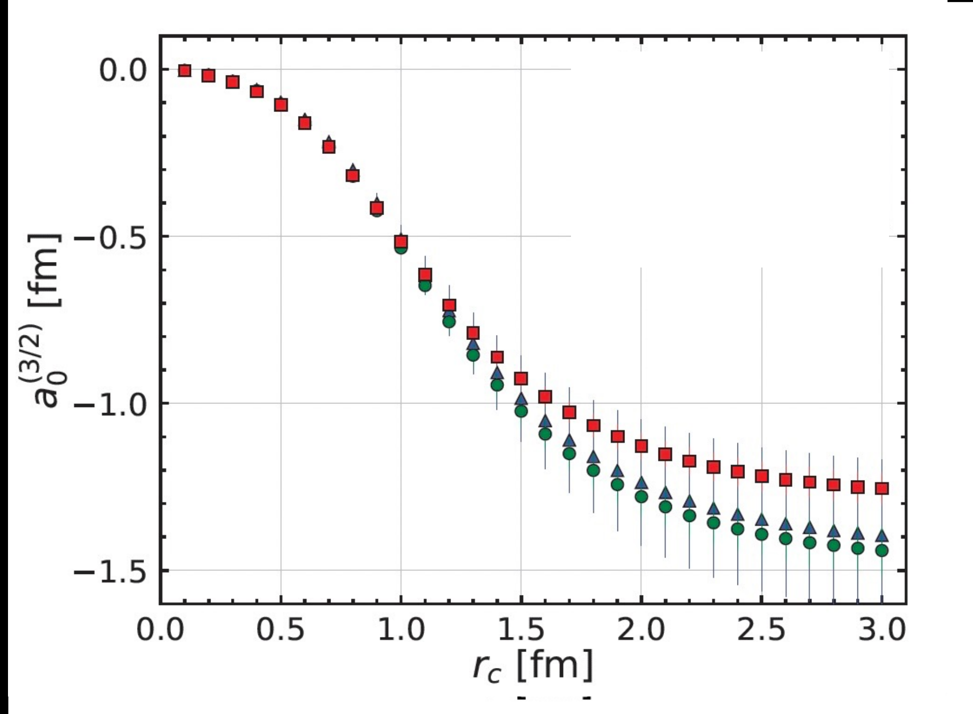

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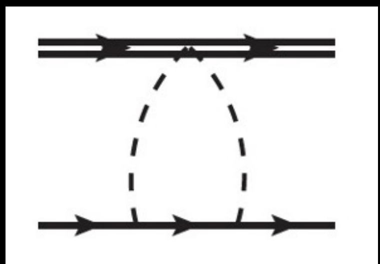

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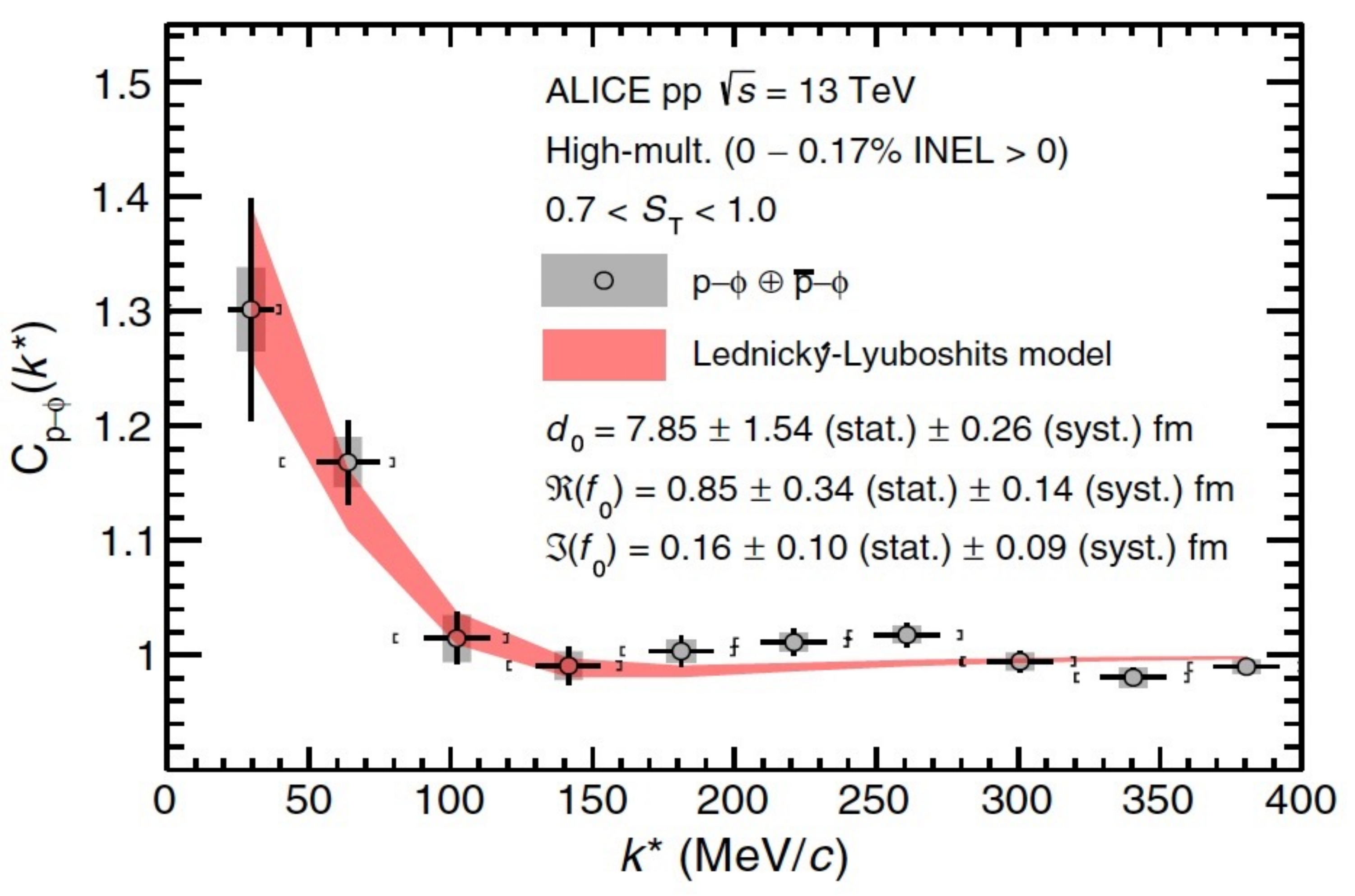
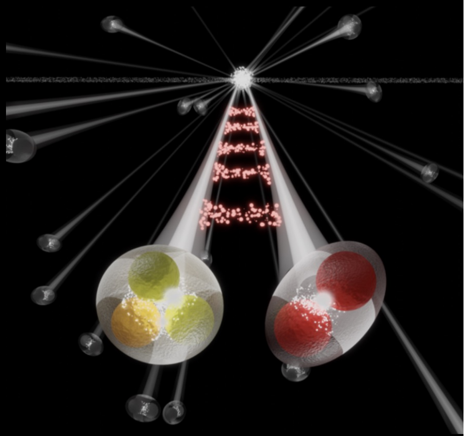
Krein and Casttela , Phys. Rev. D98 (2018) 0140289.

Experimental Evidence for an Attractive p-ϕ Interaction

S. Acharya *et al.* (ALICE Collaboration)
Phys. Rev. Lett. **127**, 172301 – Published 20 October 2021





→ possible spin ½ bound ϕN system; Chizzali+, Phys. Lett. B848 (2024) 138358

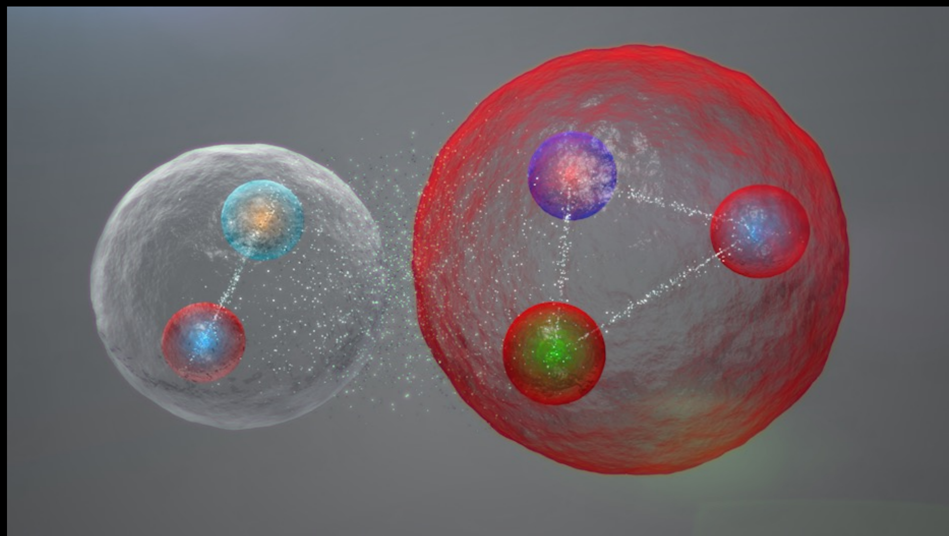
What about $c\bar{c}$ -N interaction ?

The nucleon-charmonium interactions from lattice QCD

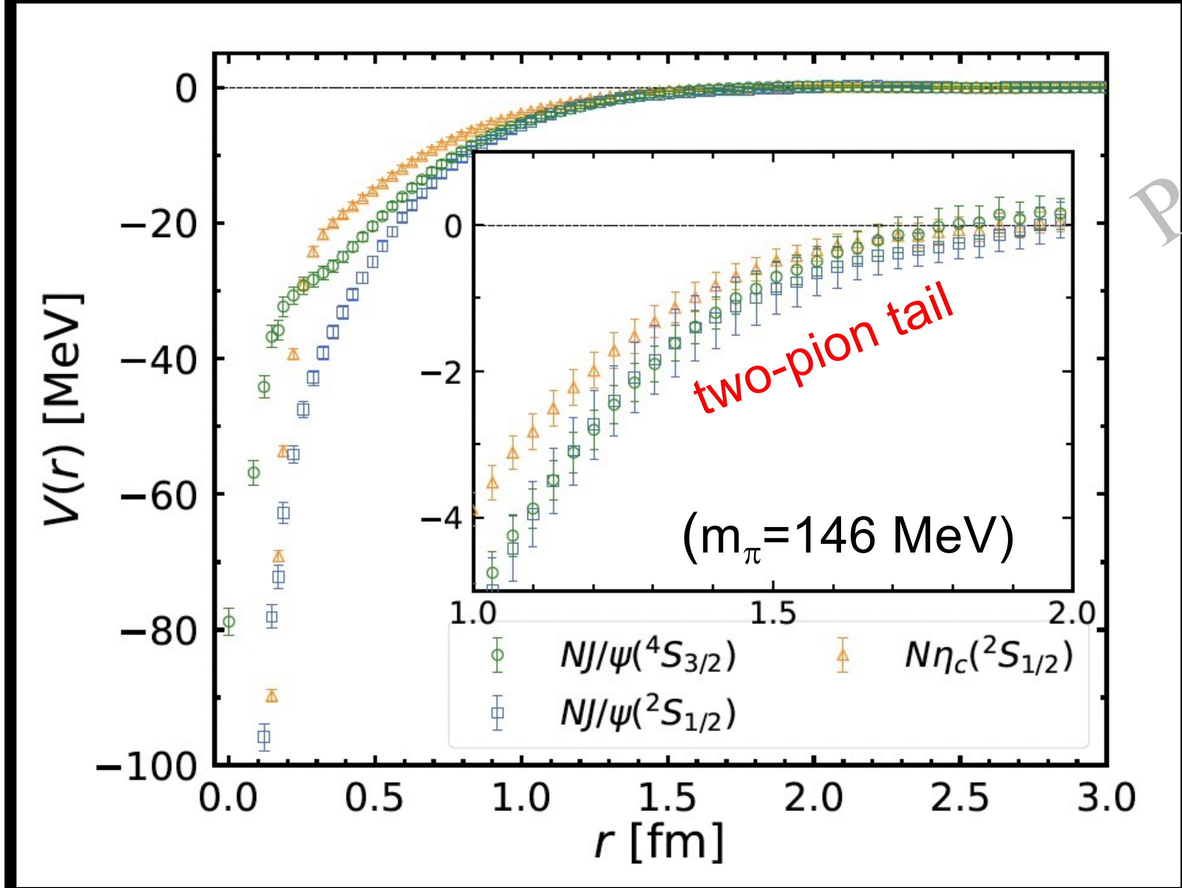
Preliminary

Yan Lyu[a], Takumi Doi[a], Tetsuo Hatsuda[a], Takuya Sugiura[b,a]

[a] *Interdisciplinary Theoretical and Mathematical Sciences Program (iTHEMS), RIKEN, Wako, 351-0198, Japan*
[b] *Faculty of Date Science, Rissho University, Kumagaya, 360-0194, Japan*

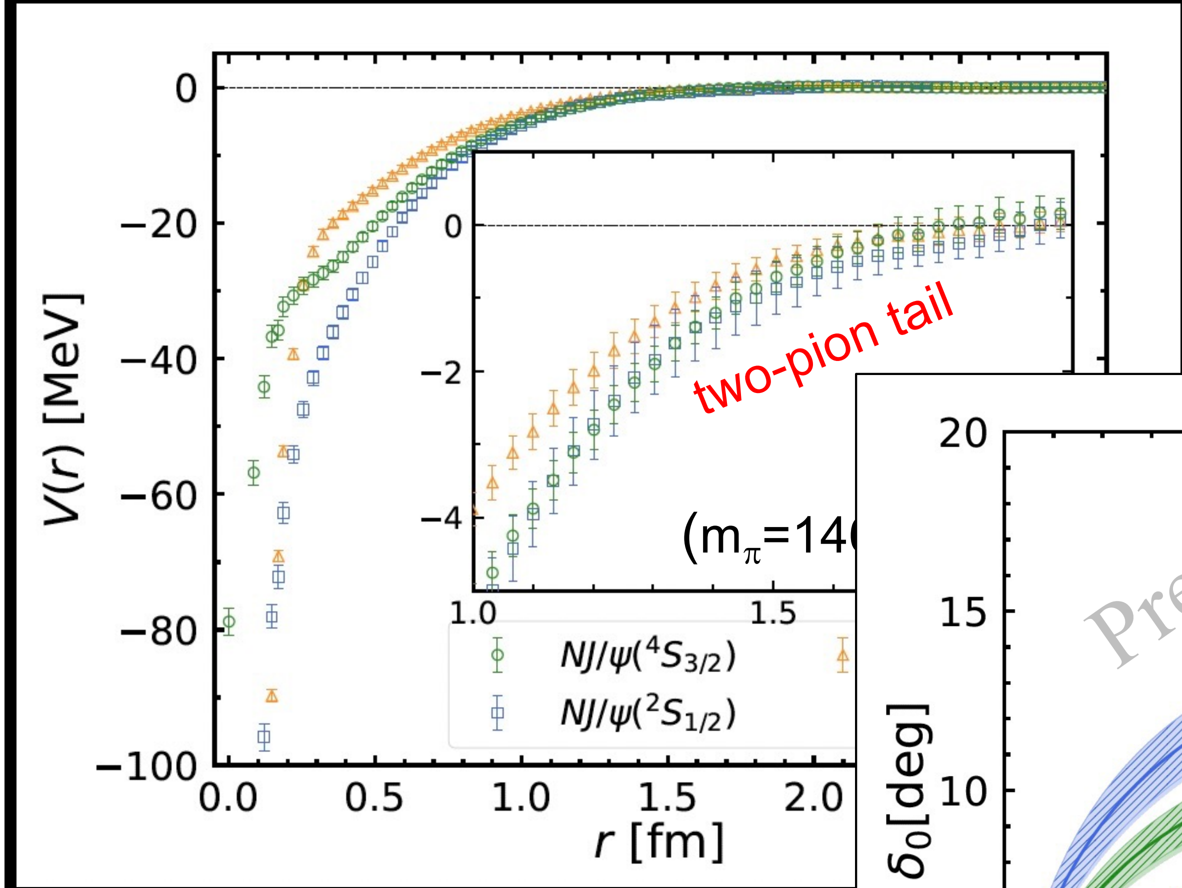


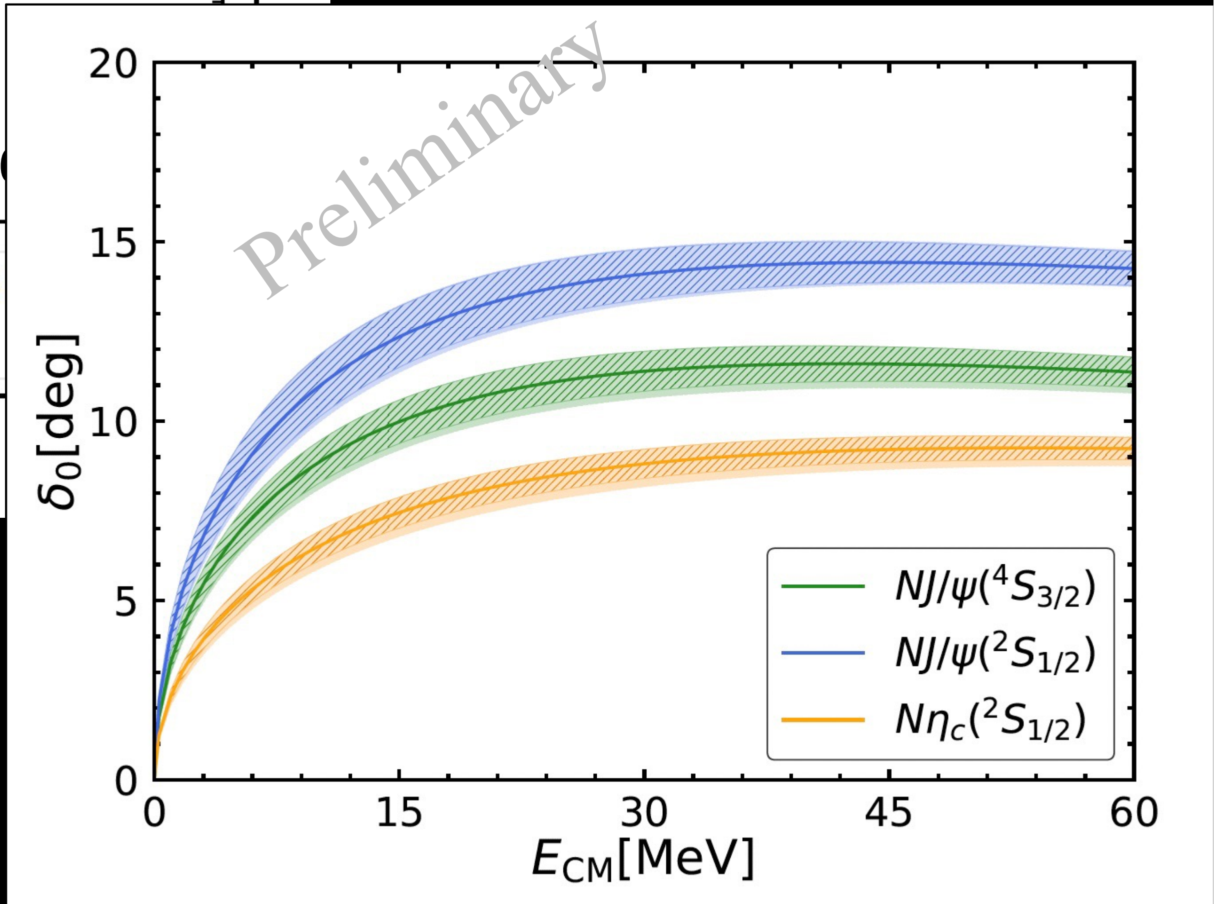
$c\bar{c}$ -N Potentials and phase shifts



Preliminary

$c\bar{c}$ -N Potentials and phase shifts





Scattering length and effective range

Preliminary

channel	a_0 [fm]	r_{eff} [fm]
$NJ/\psi(^4S_{3/2})$	$0.30(2)\binom{+0}{-2}$	$3.25(12)\binom{+6}{-9}$
$NJ/\psi(^2S_{1/2})$	$0.38(4)\binom{+0}{-3}$	$2.66(21)\binom{+0}{-10}$
$N\eta_c(^2S_{1/2})$	$0.21(2)\binom{+0}{-1}$	$3.65(20)\binom{+0}{-6}$

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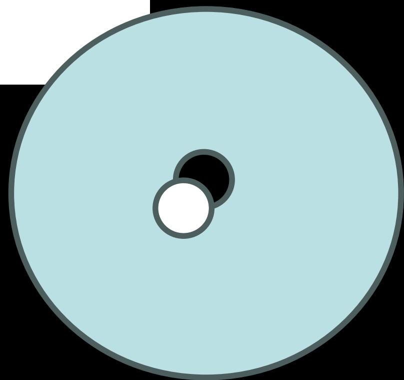
J/ψ optical potential in nuclear matter

$$\delta m_{J/\psi} \simeq \frac{2\pi(m_N + m_{J/\psi})}{m_N m_{J/\psi}} a_{J/\psi}^{\text{spin-av}} \rho_{\text{nm}} = 19(3)\ \text{MeV},$$



⇔ Krein, Tsushima, Thomas,
Nuclear-bound quankonia and heavy-flavor hadros
Prog. in Part. Nucl. Phys. 100 (2018) 161

Summary

Hadron-hadron int. from LQCD at m_π=146 MeV opens the door
to the "co-evolution" of LQCD and expt.

- examples -

BB: $\Lambda\Lambda-N\Xi$, $N\Omega$, $\Omega\Omega$, MM: T_{cc}^+ , MB: $s\bar{s}$ -N, $c\bar{c}$ -N

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Take-home messages

1. $\Omega\Omega$ could be bound: first stable B=2 system other than the deuteron?
2. Two-pion exchange : universal for long-range part of hadron interactions
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1. $\Omega\Omega$ could be bound: first stable B=2 system other than the deuteron?
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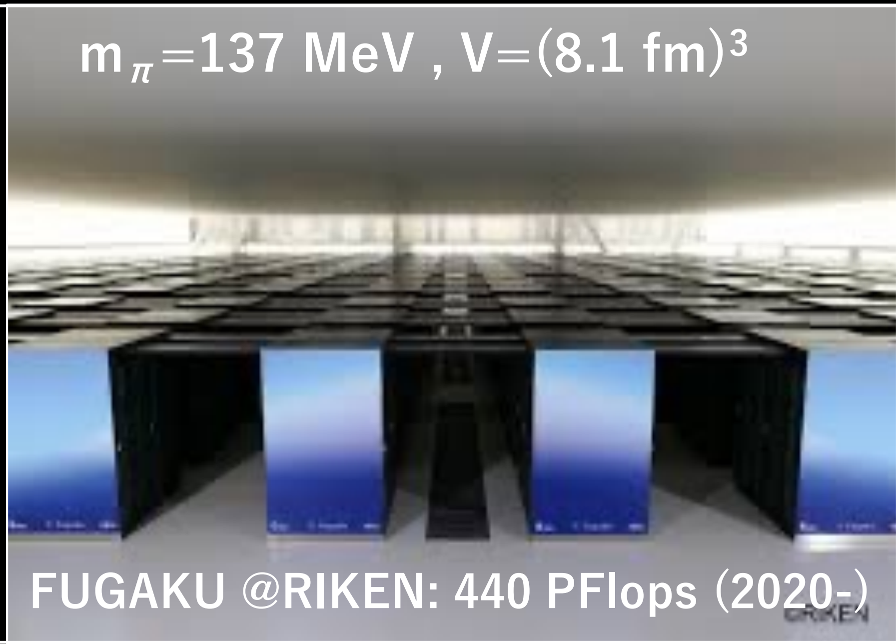
3. Heavy quarks: useful probes for the two-pion exchange.

- New results at m_π=137 MeV will come soon.
- Open issues:
  - coupled channel effects
  - isospin breaking (QED & QCD) near threshold.

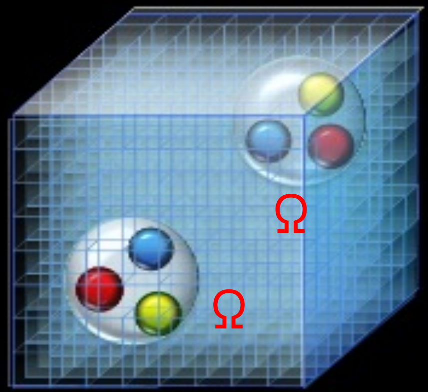
Stay tuned !



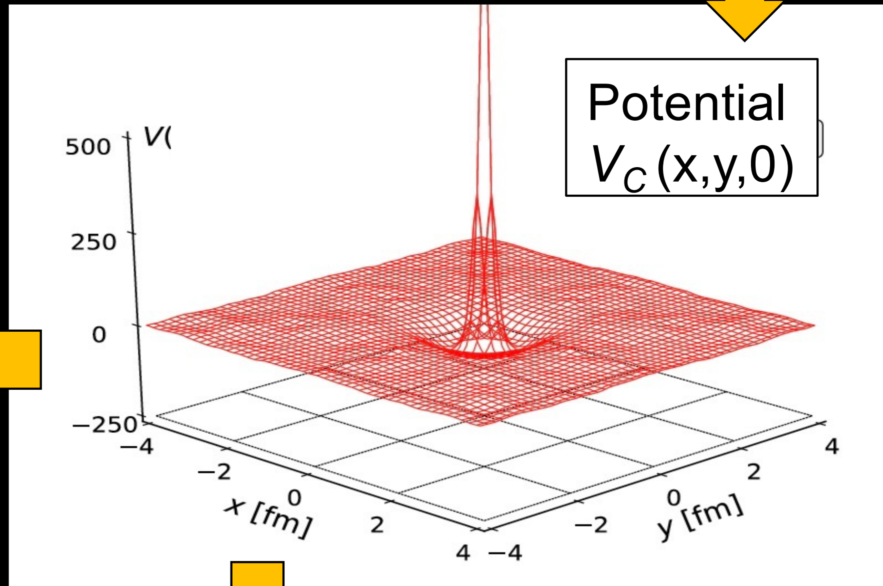
Backup slides

HAL QCD Procedure: an example
(ΩΩ at m_π=146MeV)

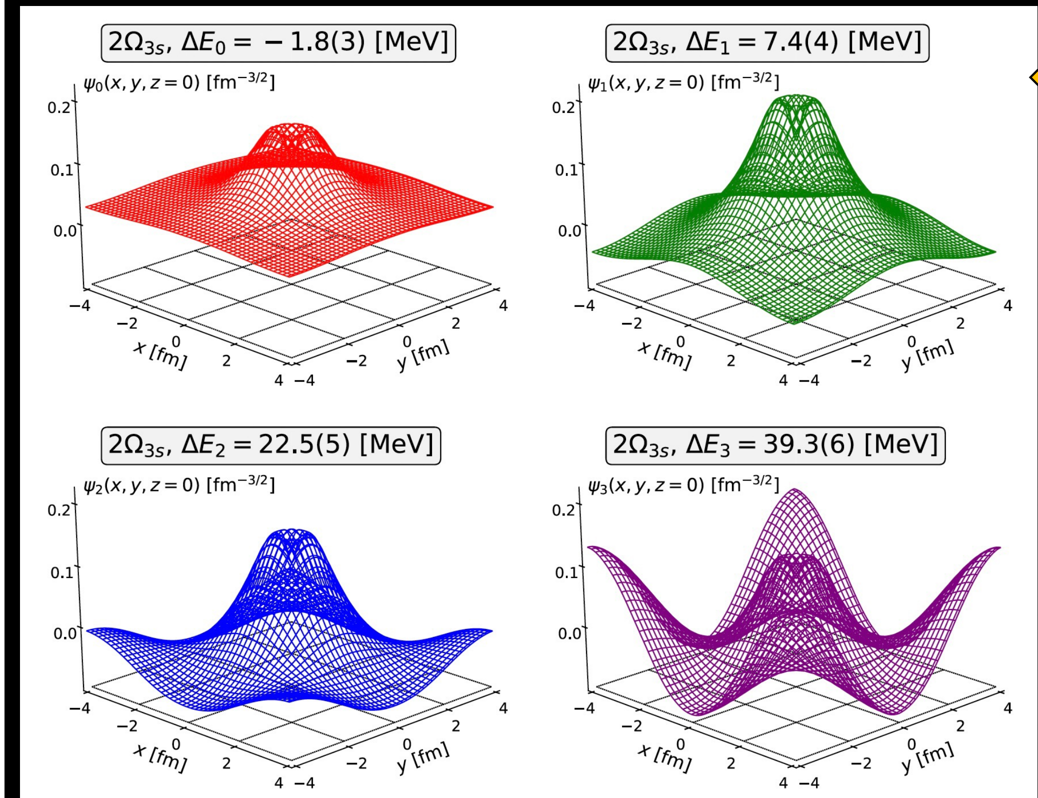
Gongyo+ [HAL QCD], PRL 120 (2018) 212001
Lyu+ [HAL QCD], PRD 105 (2022) 074512

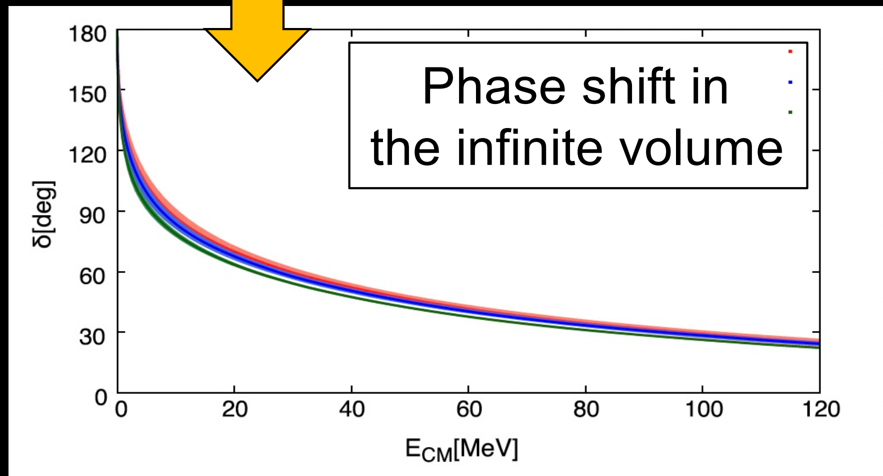


$$F^J(\mathbf{r},t) = \sum_n a_n^J \psi_n(\mathbf{r}) e^{-E_n t} \rightarrow V_C(r)$$

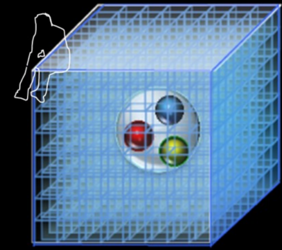


Ψ_n (r) and E_n in a finite volume

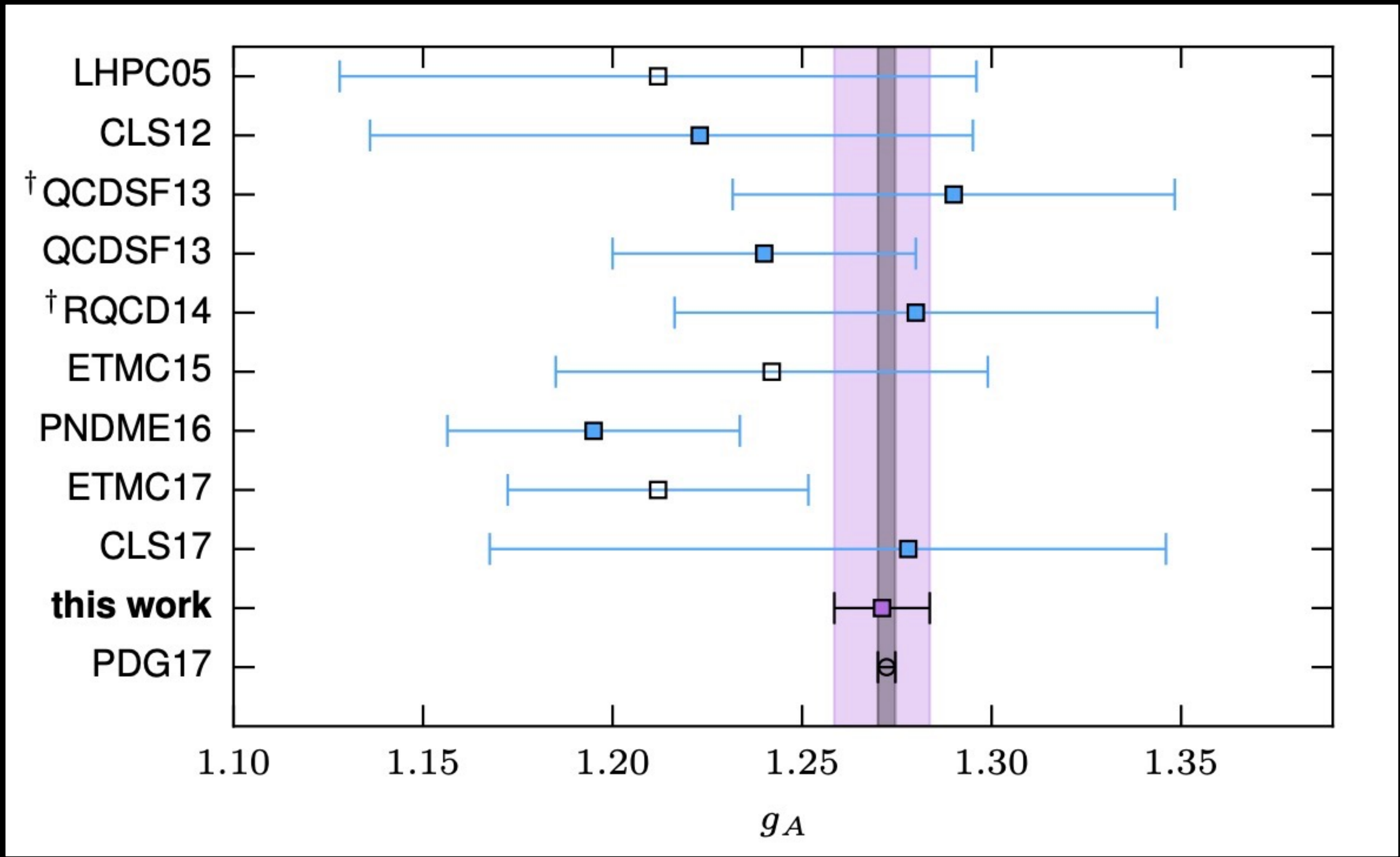




Percent-level determination of g_A from LQCD



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



$(g_A)_{LQCD} = 1.271(13)$

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

⇔

$(g_A)_{expt} = 1.272(2)$

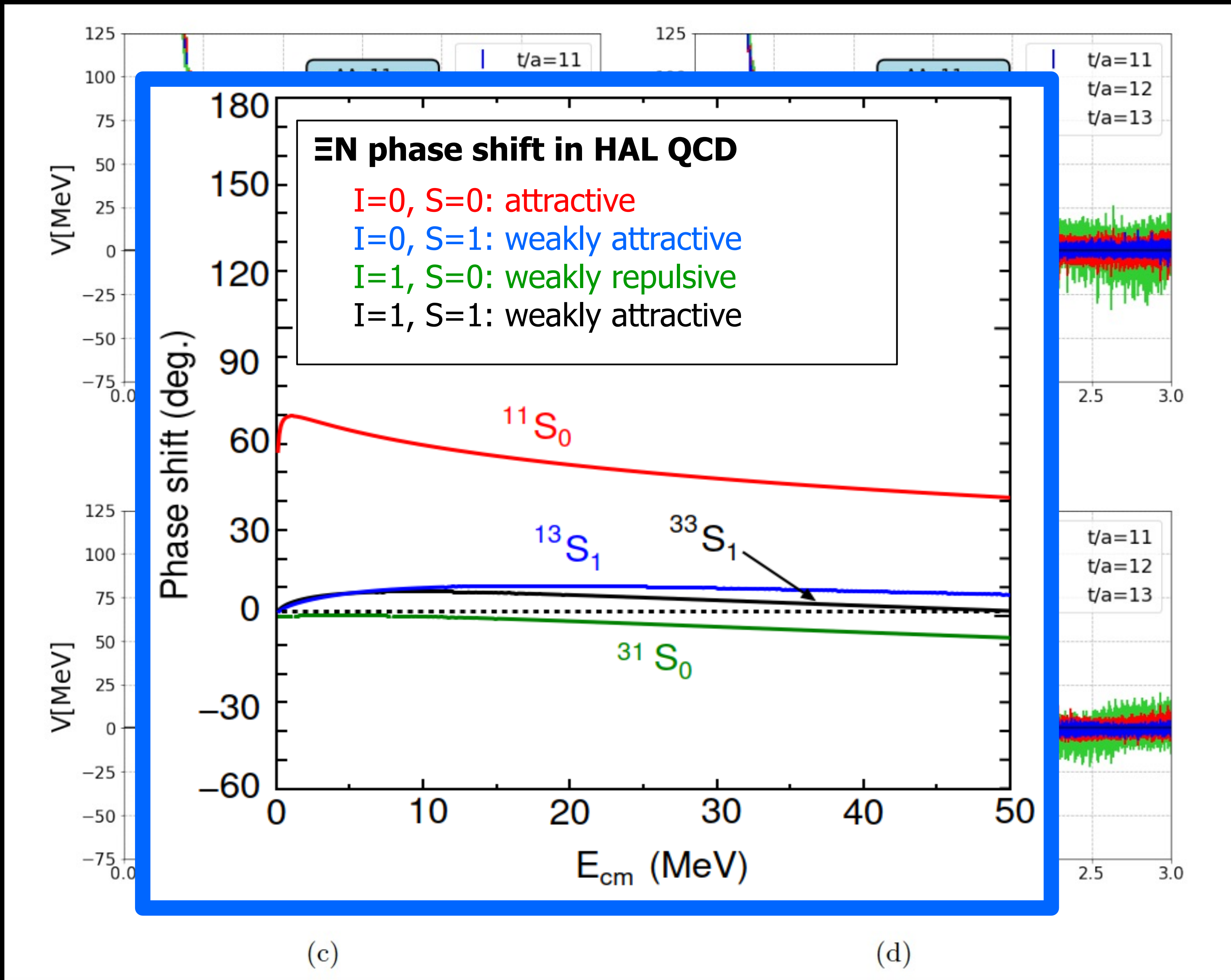
$(\tau_n)_{PDG} = 880.2(1.0)$ s

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

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

Small ΛΛ attraction

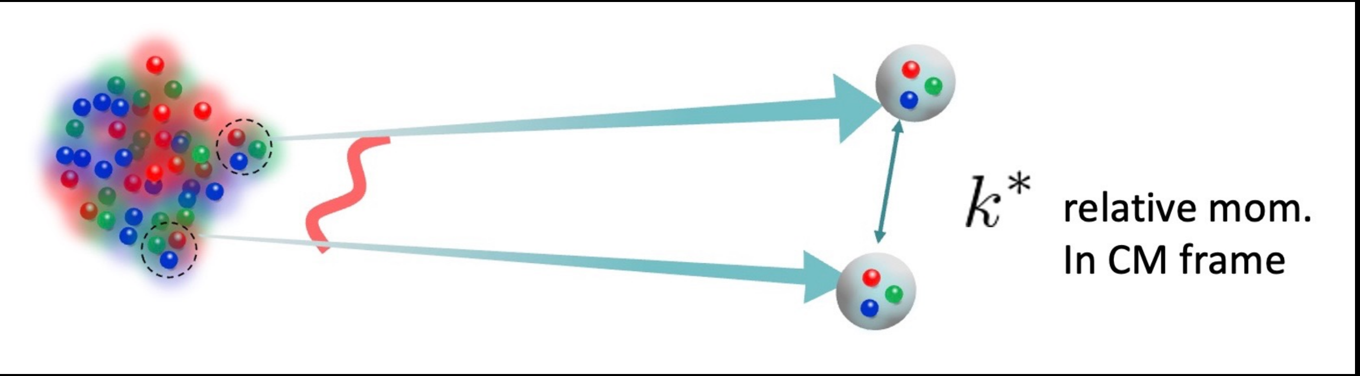
Short-range NΞ-ΛΛ coupling



Short-range NΞ-ΛΛ coupling

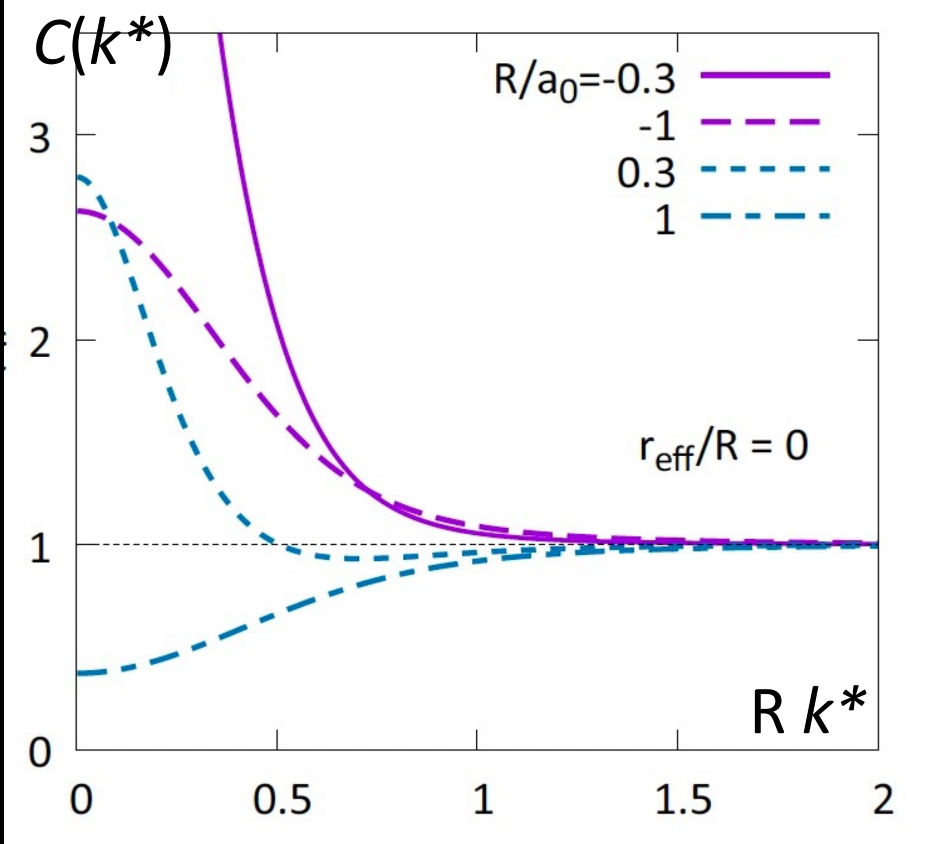
Large NΞ attraction

Femtoscopy : particle correlations in pp, pA and AA



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

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

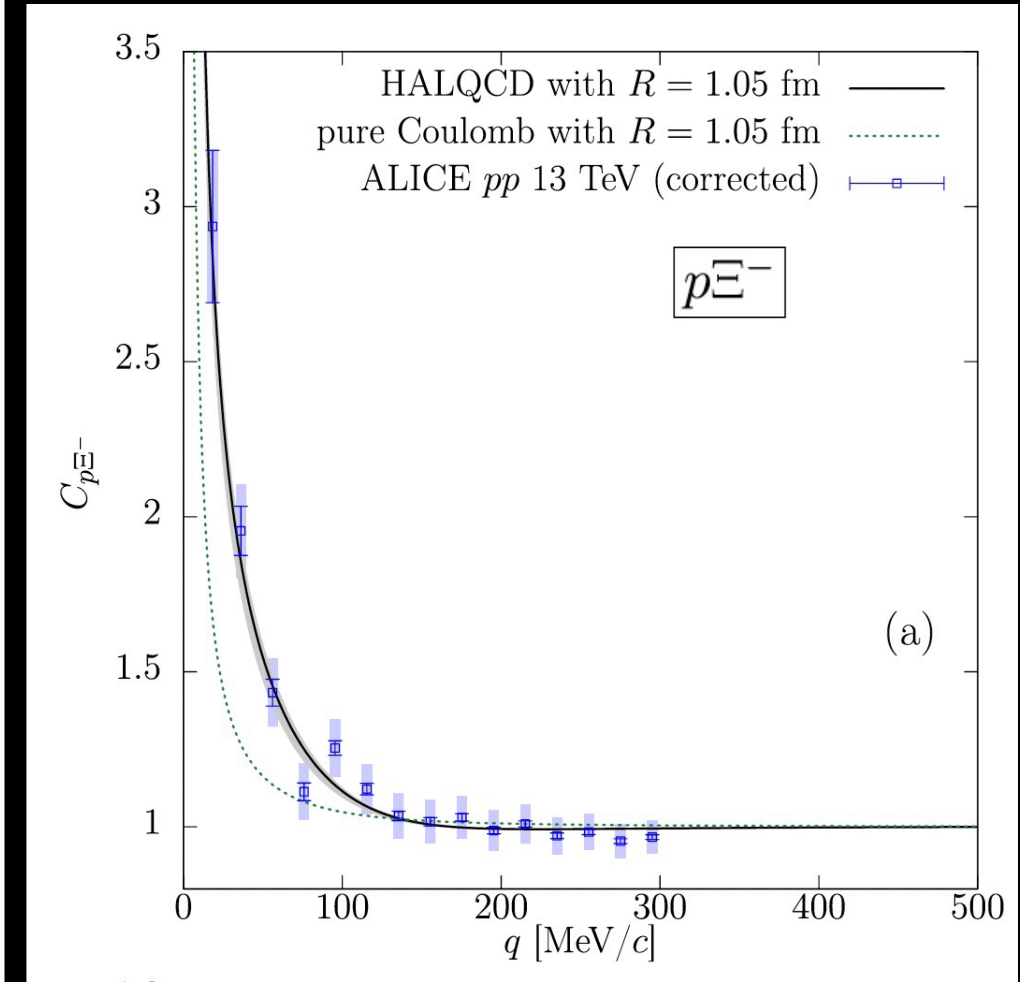


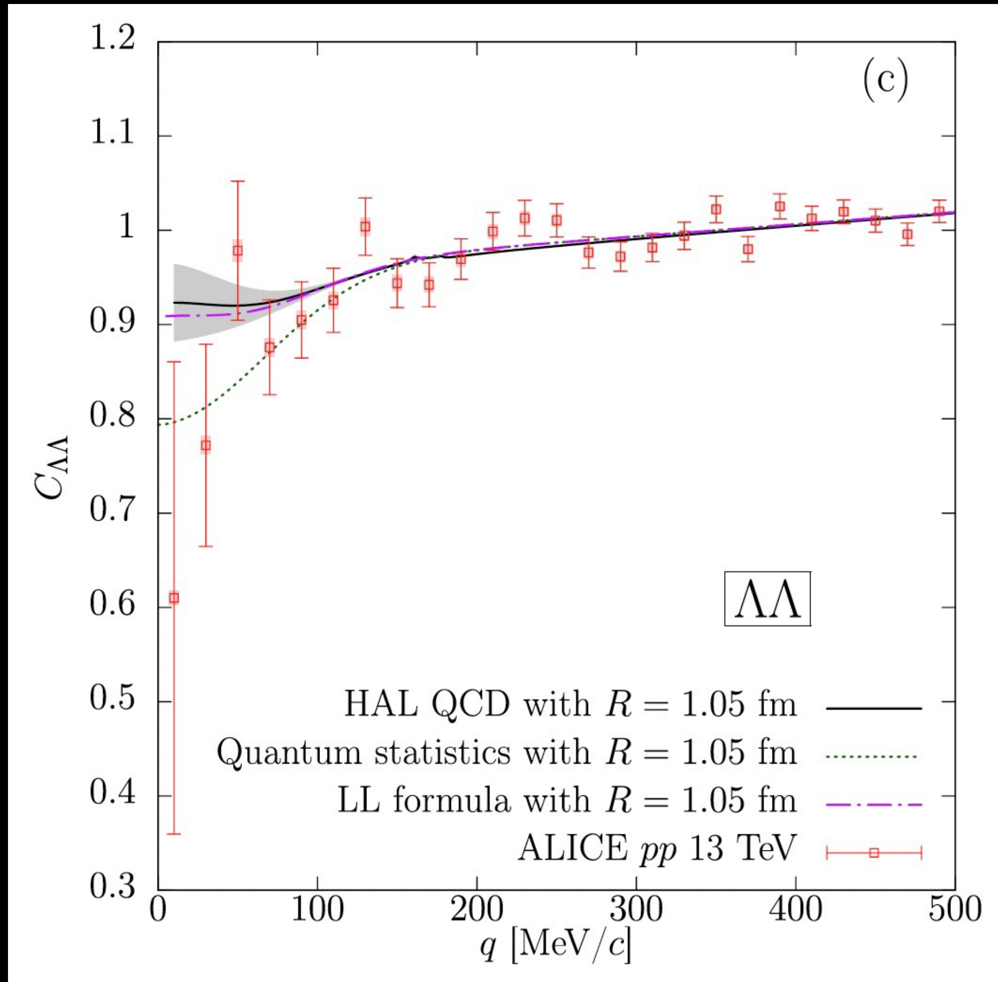
Morita et al., Phys. Rev. C101 (2020) 015201

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).

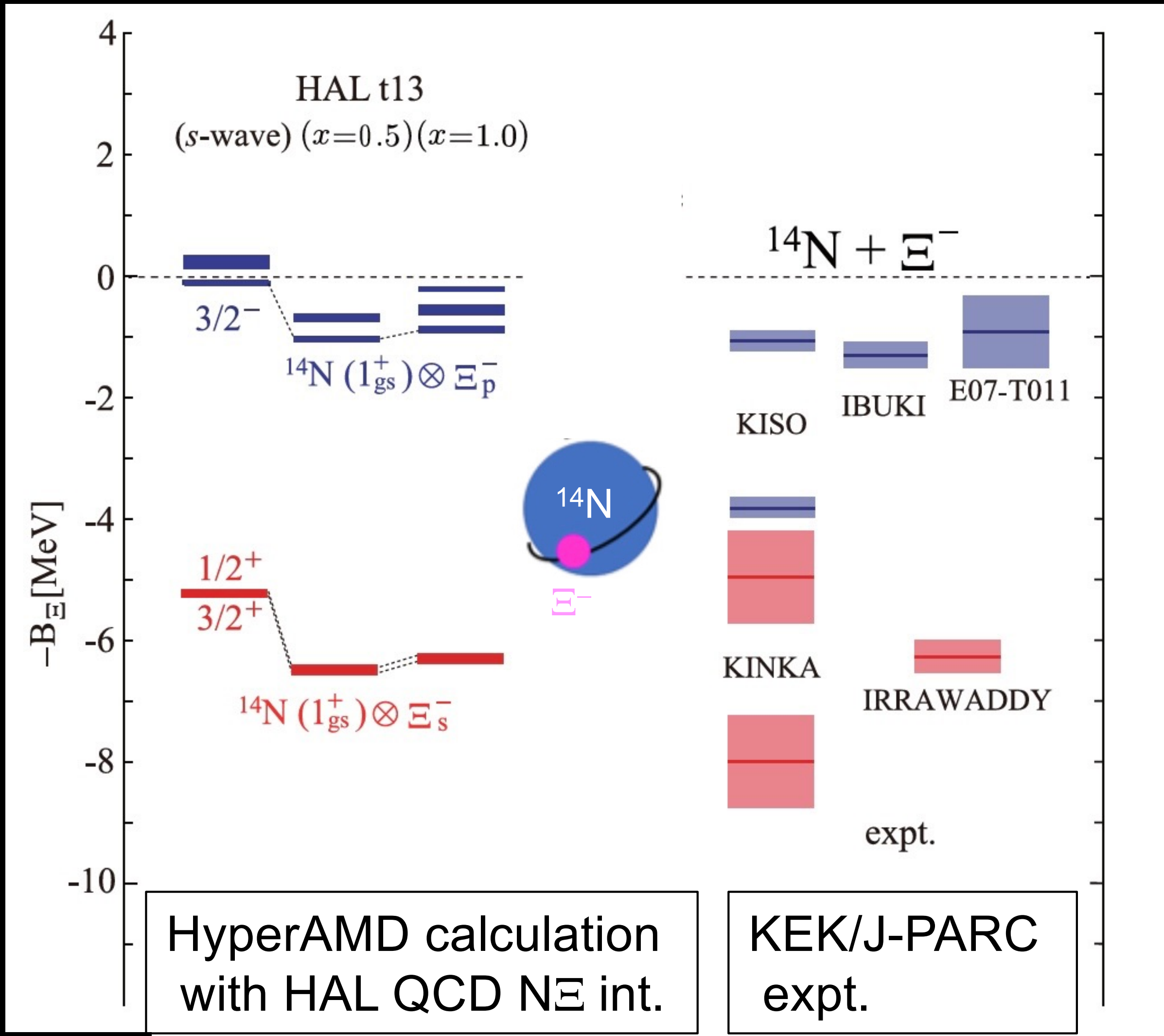
Fully coupled channel analysis

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

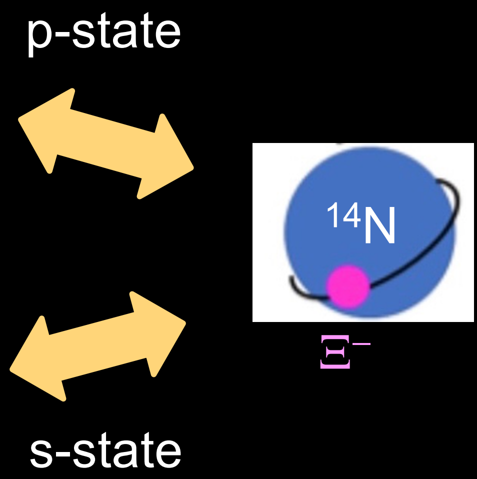




Excitation spectra of $^{15}_{\Xi}\mathrm{C}$ and $^{12}_{\Xi}\mathrm{Be}$ calculated with a ΞN interaction from lattice QCD



Isaka+,
Phys.Rev. C109 (2024) 044317

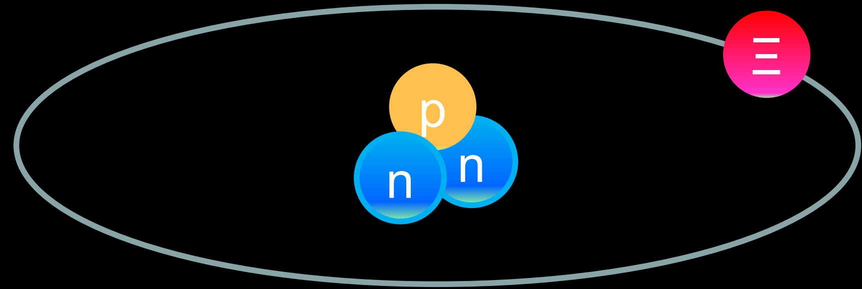


LQCD prediction of
- attraction in NΞ in $^{11}S_0$
- weak NΞ -ΛΛ coupling
cosisistent with the expt. data

Attempts towards lighter Ξ-nuclei such as ^{3}He-Ξ and ααNΞ:
Hiyama+, PRL 124 (2020); PRC 106 (2022)

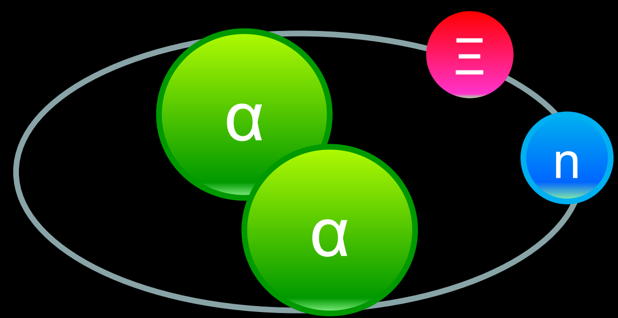
What is the lightest Ξ hypernuclei?

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



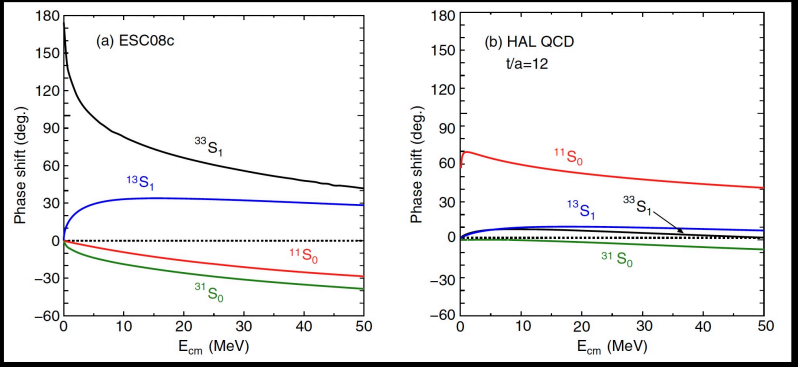
Can we test the spin-isospin dependence of ΞN int.?

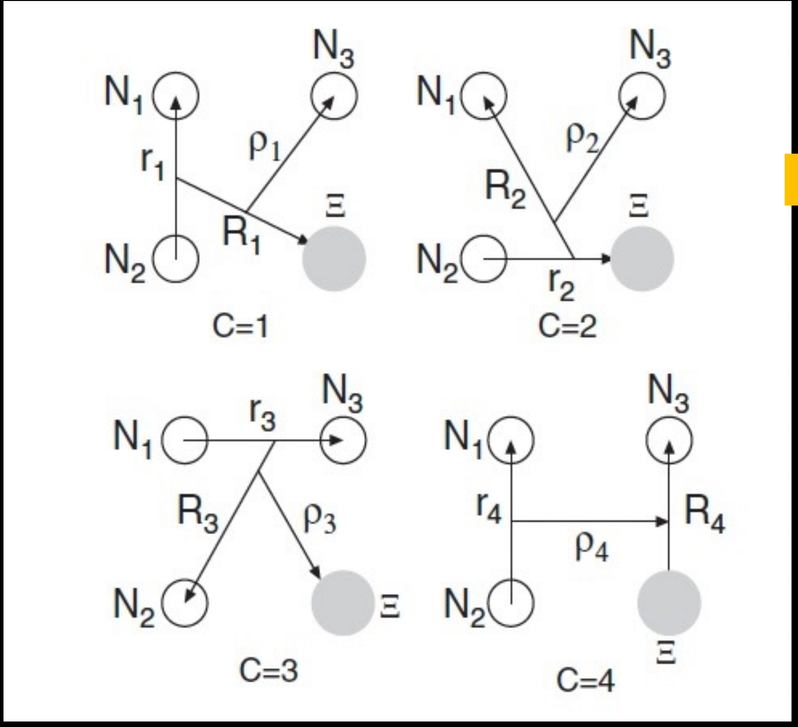
Hiyama, Isaka, Doi, Hatsuda,
Phys. Rev. C 106 (2022) 064318



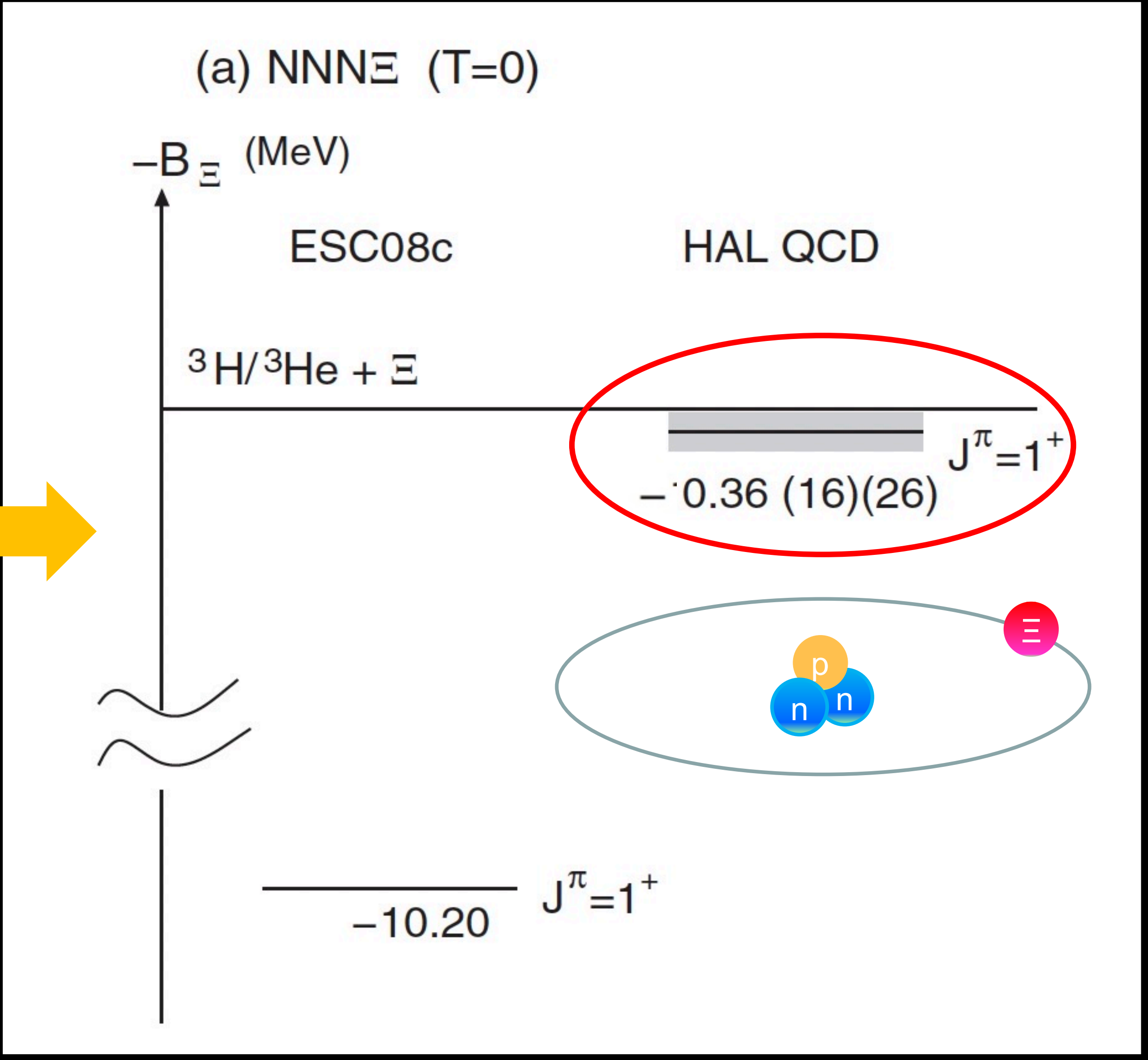
Q1. What is the lightest Ξ hypernuclei?

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





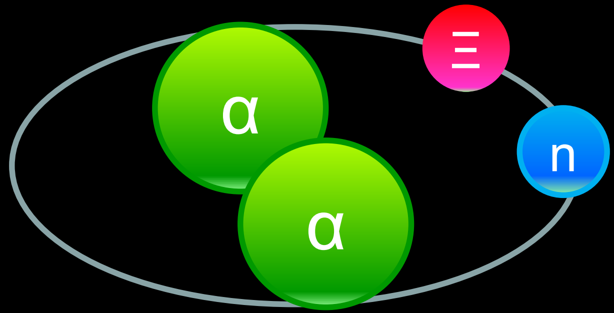
Gaussian expansion method
(Hiyama et al., 2003)

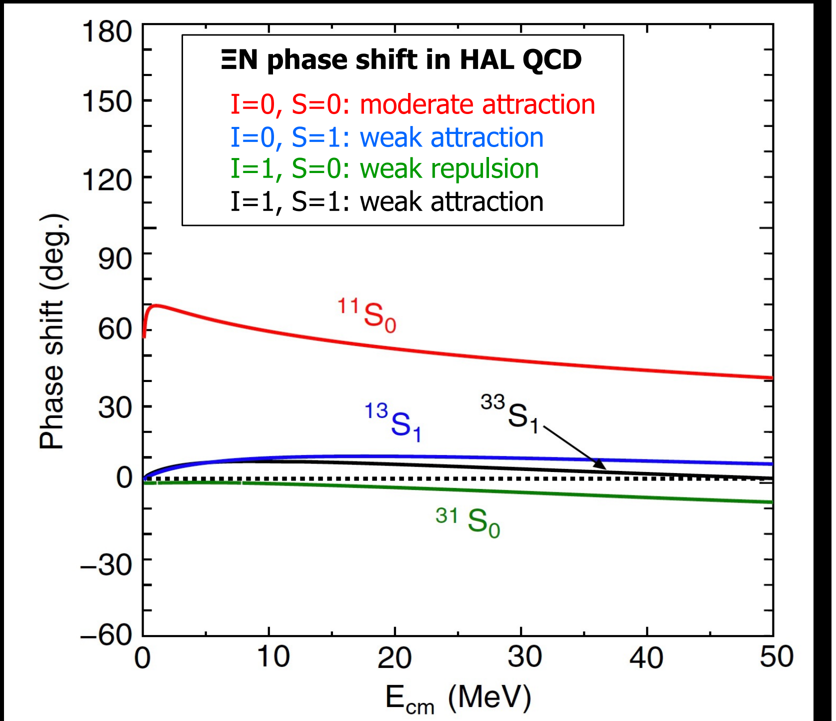


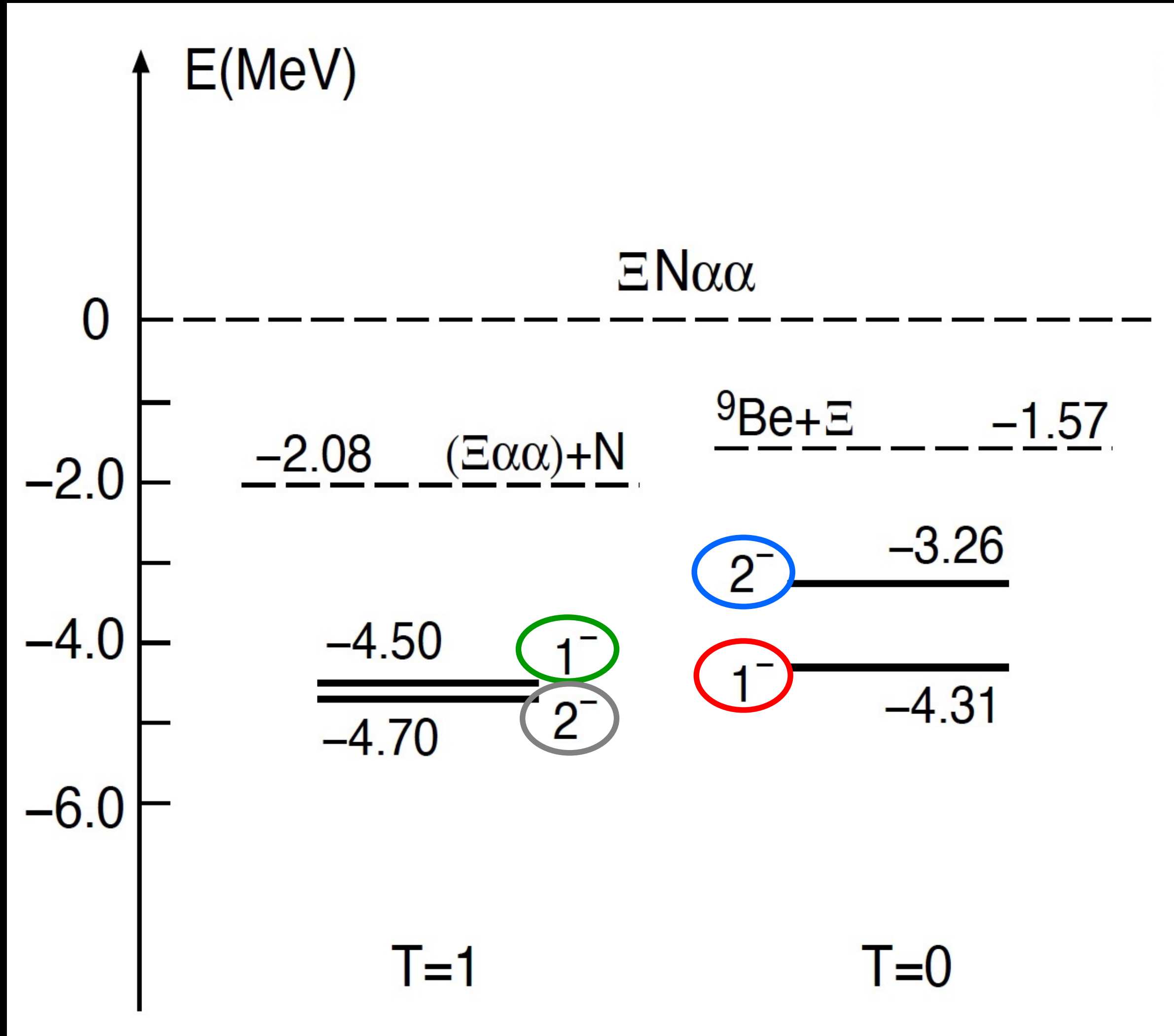
Γ ~ 60 keV

Inversion of spin-doublets in ΞNαα system

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



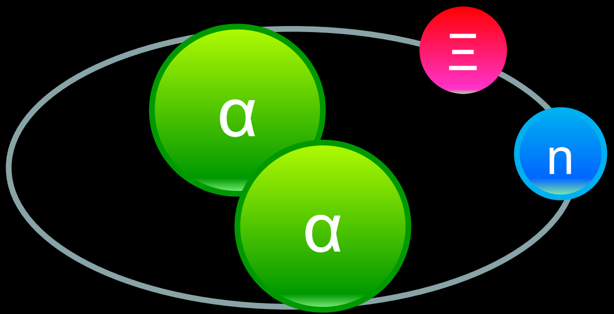


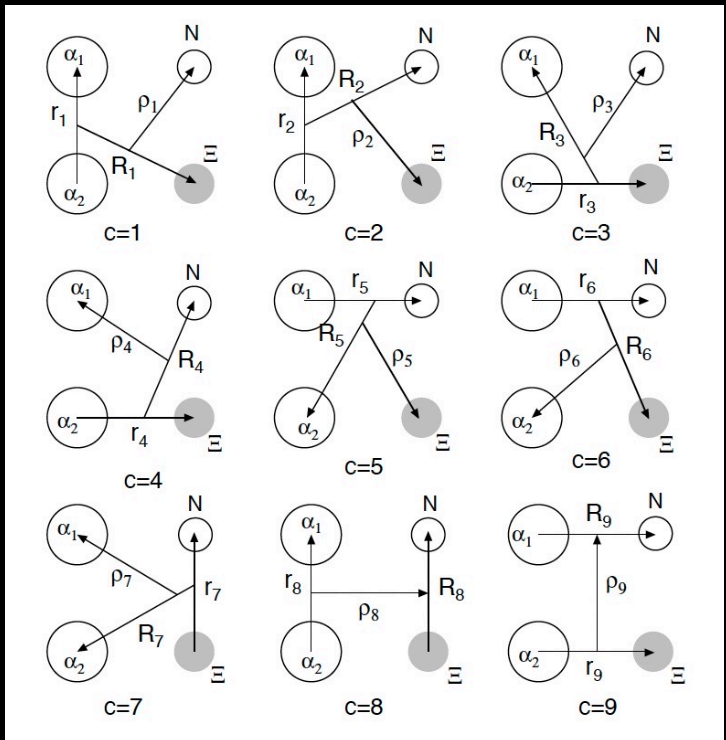


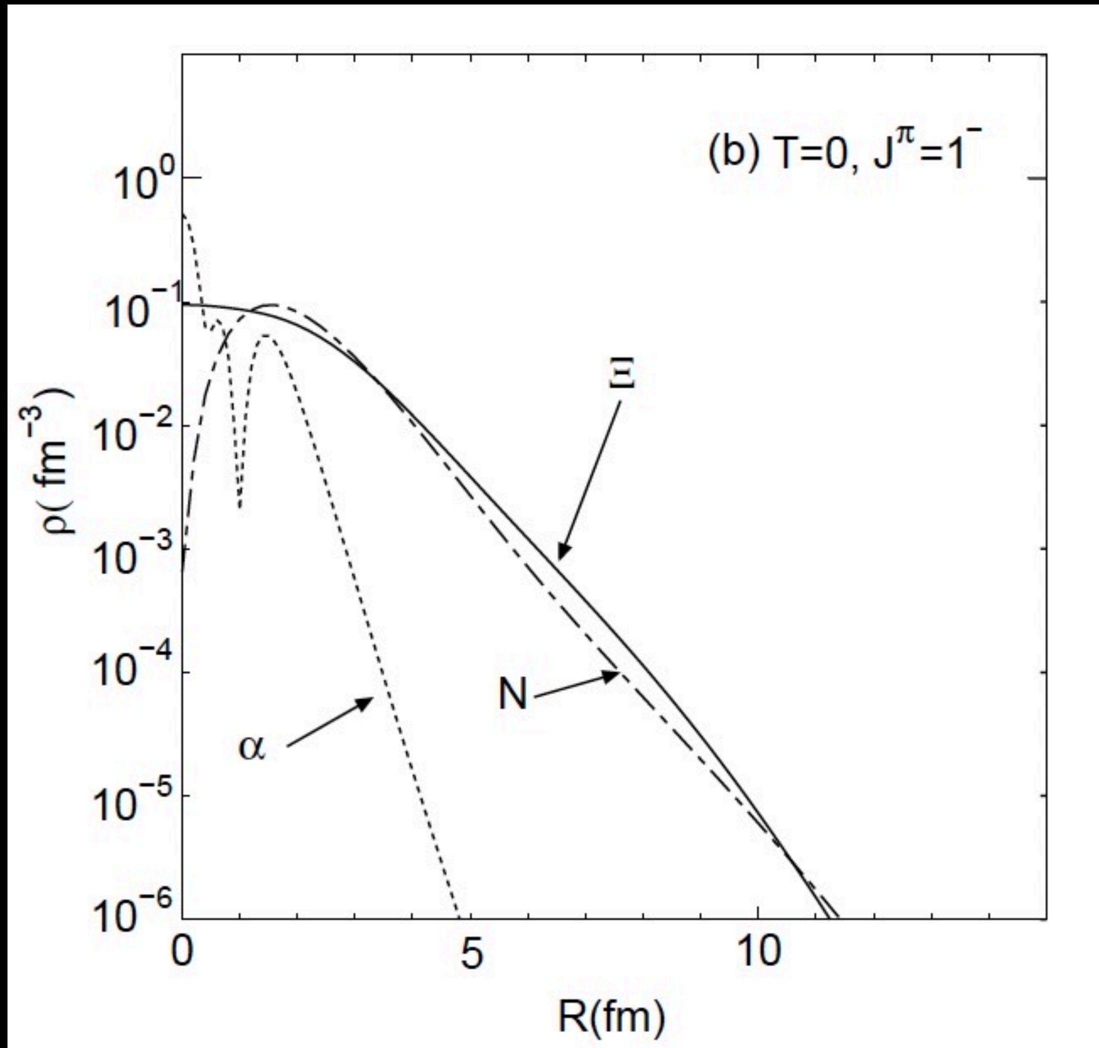
Γ=20-40 keV

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

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



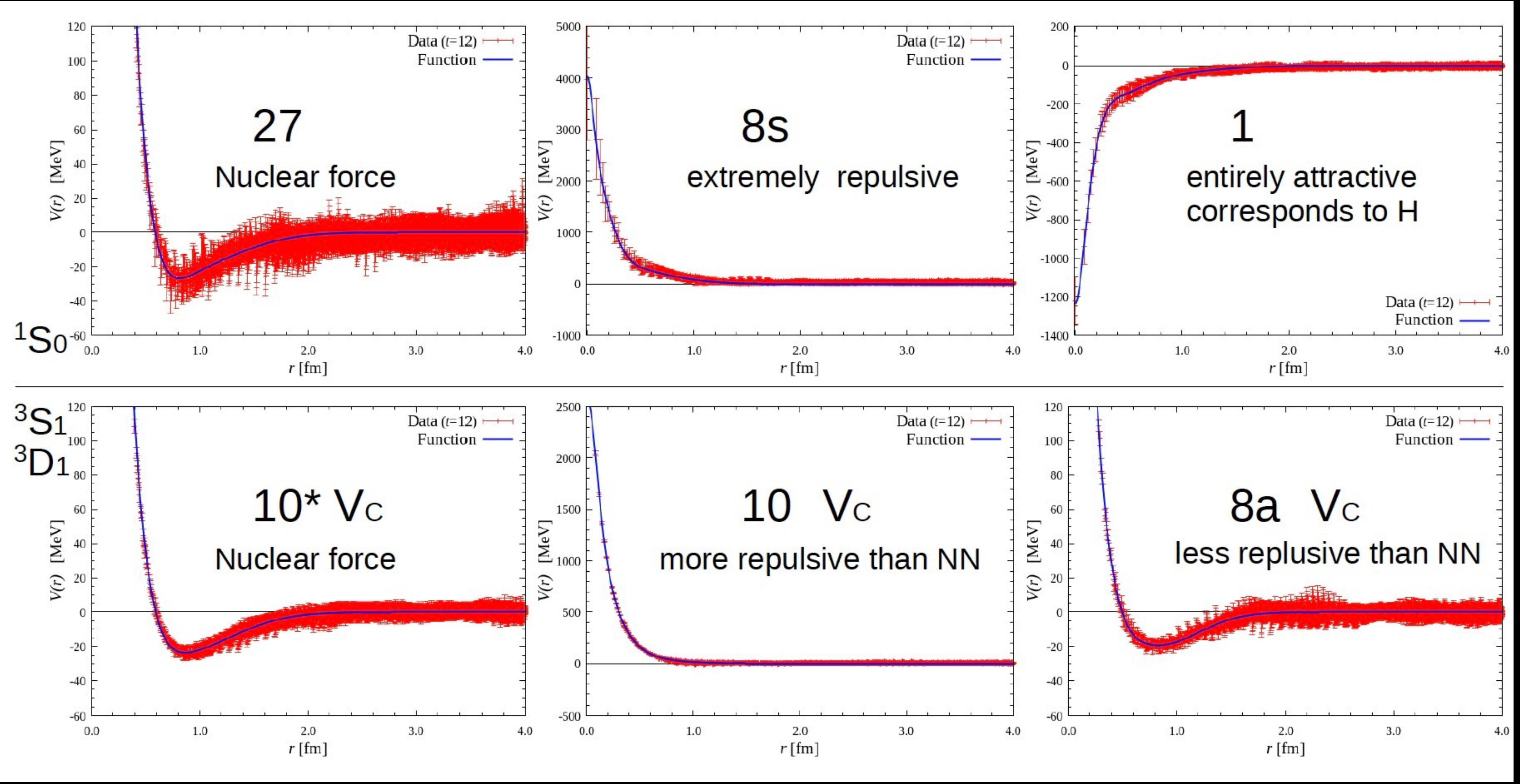




Gaussian expansion method (Hiyama et al., 2003)

Central BB interactions in the flavor basis

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



T. Inoue [HAL QCD Coll.], Few-body Syst. 62 (2021) 106

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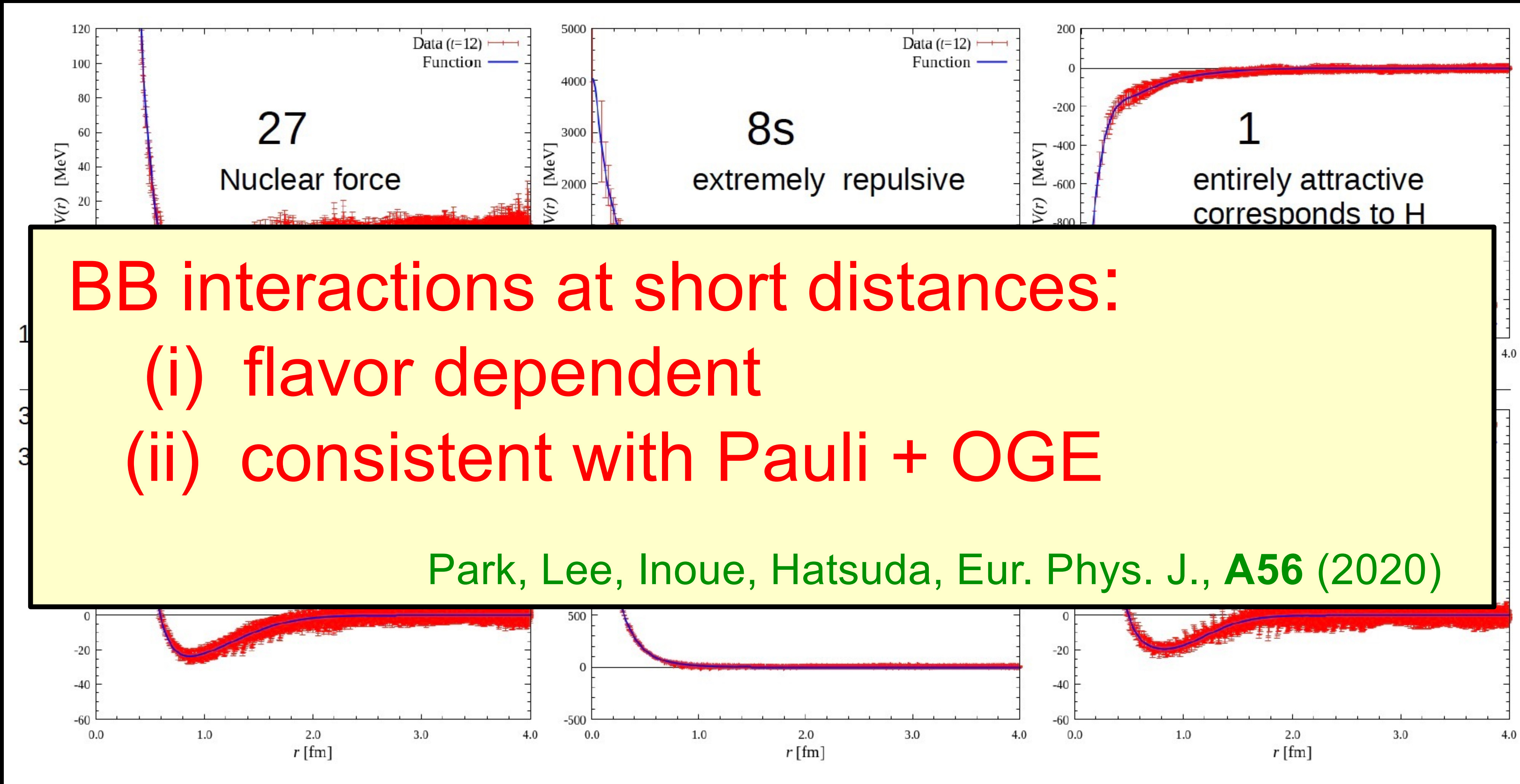


BB interactions at short distances:

(i) flavor dependent

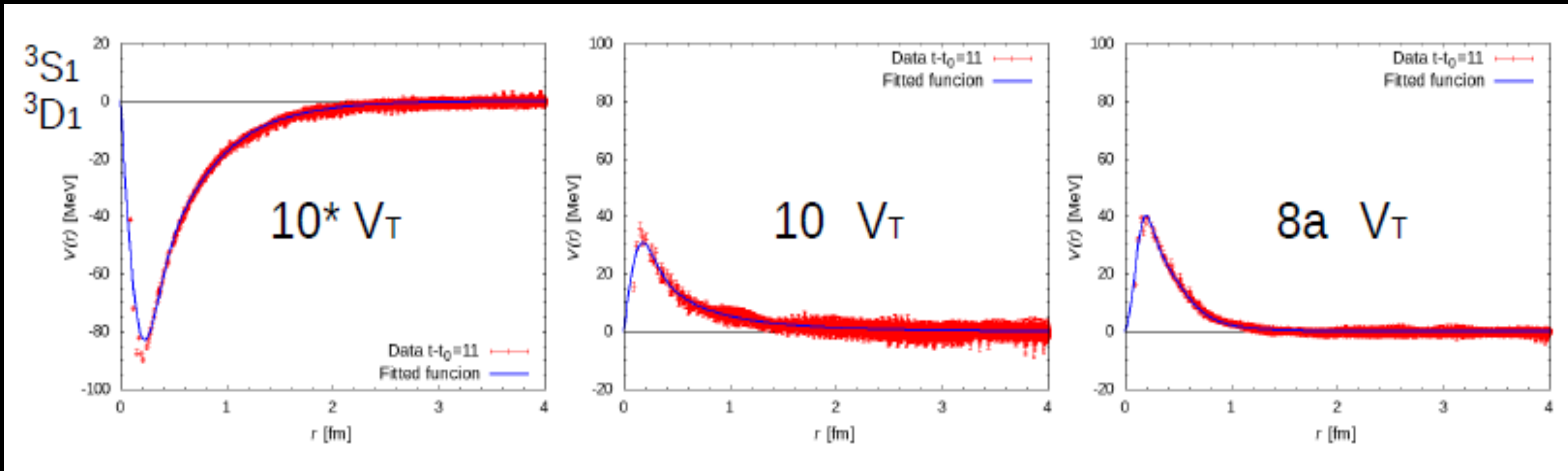
(ii) consistent with Pauli + OGE

Park, Lee, Inoue, Hatsuda, Eur. Phys. J., **A56** (2020)

T. Inoue [HAL QCD Coll.], Few-body Syst. 62 (2021) 106

Tensor BB interactions in the flavor basis

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

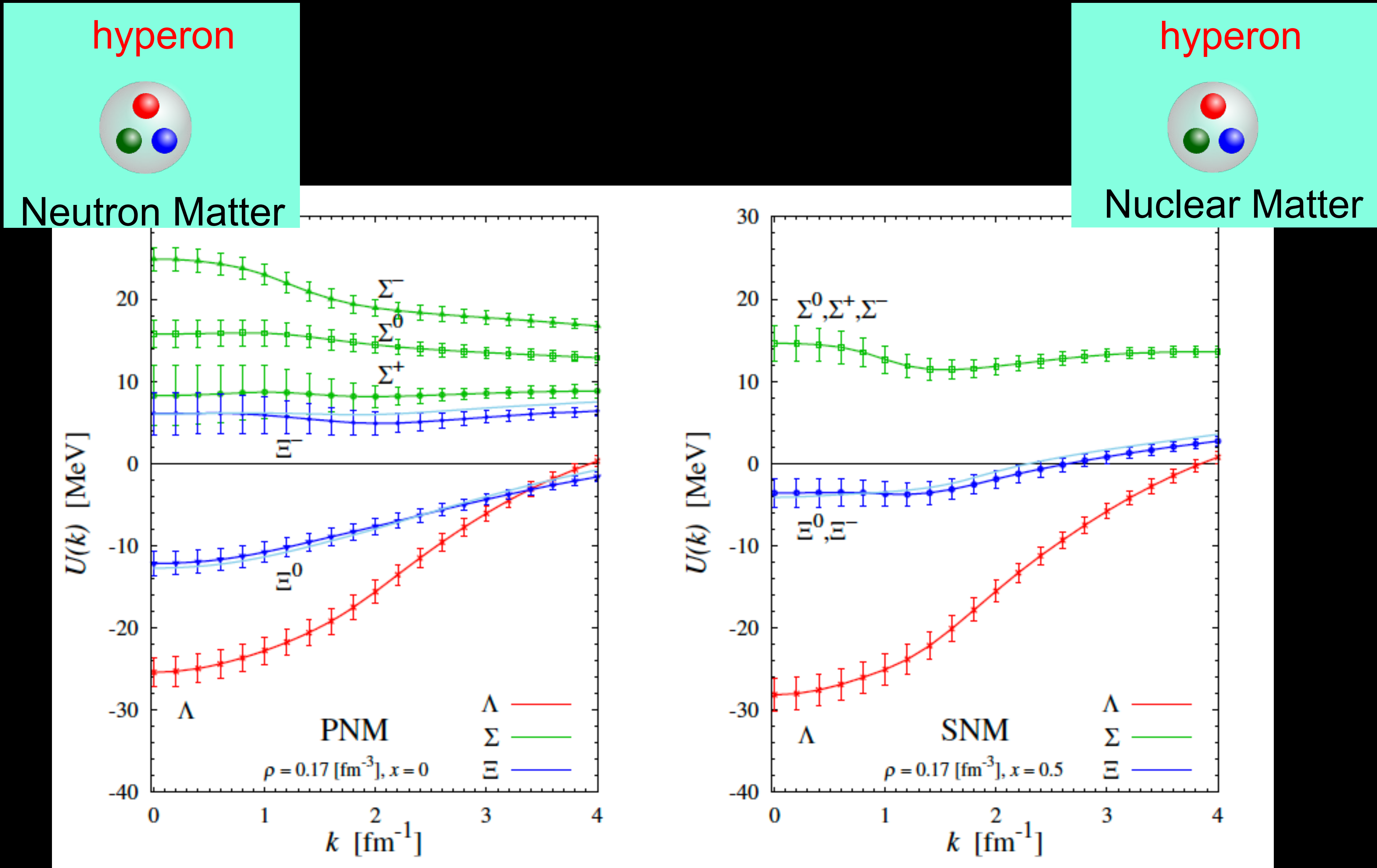


$$U(\mathbf{r},\mathbf{r}') = V(\mathbf{r},\mathbf{v})\delta(\mathbf{r}-\mathbf{r}'),$$

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

T. Inoue [HAL QCD Coll.], Few-body Syst. 62 (2021) 106

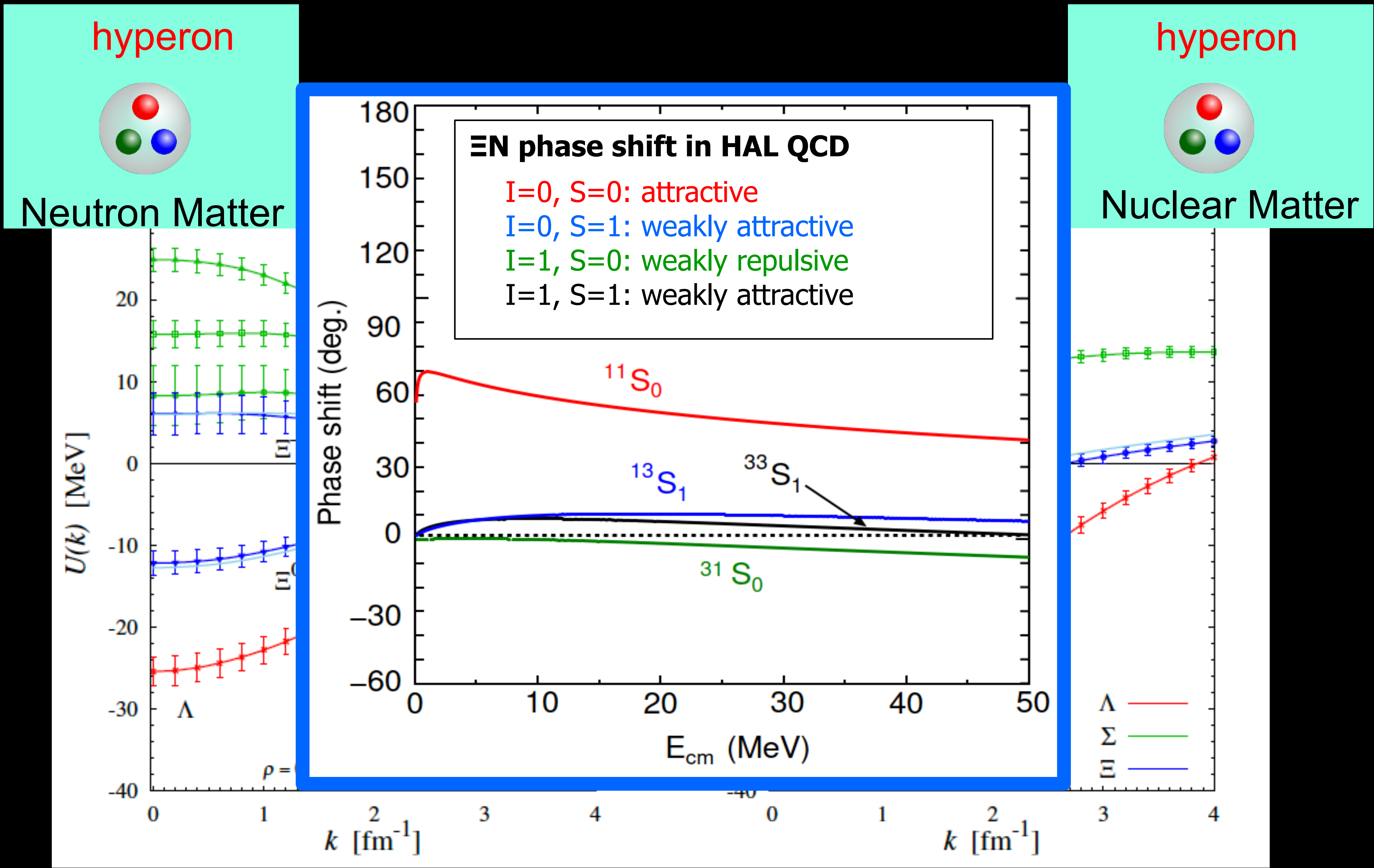
Hyperon embedded in cold nuclear matter (HAL QCD + BHF)



Inoue [HAL QCD Coll.], Few-body Syst. 62 (2021) 106

Hiyama, Sasaki, Miyamoto, Doi, Hatsuda, Yamamoto, and Rijken, PRL 124 (2020) 092501

Hyperon embedded in cold nuclear matter (HAL QCD + BHF)

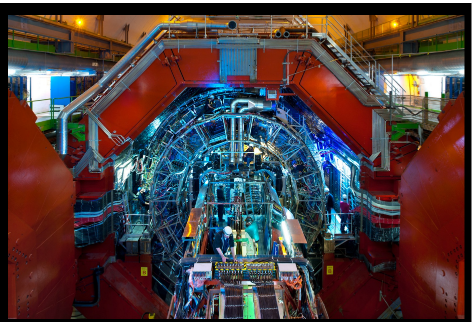


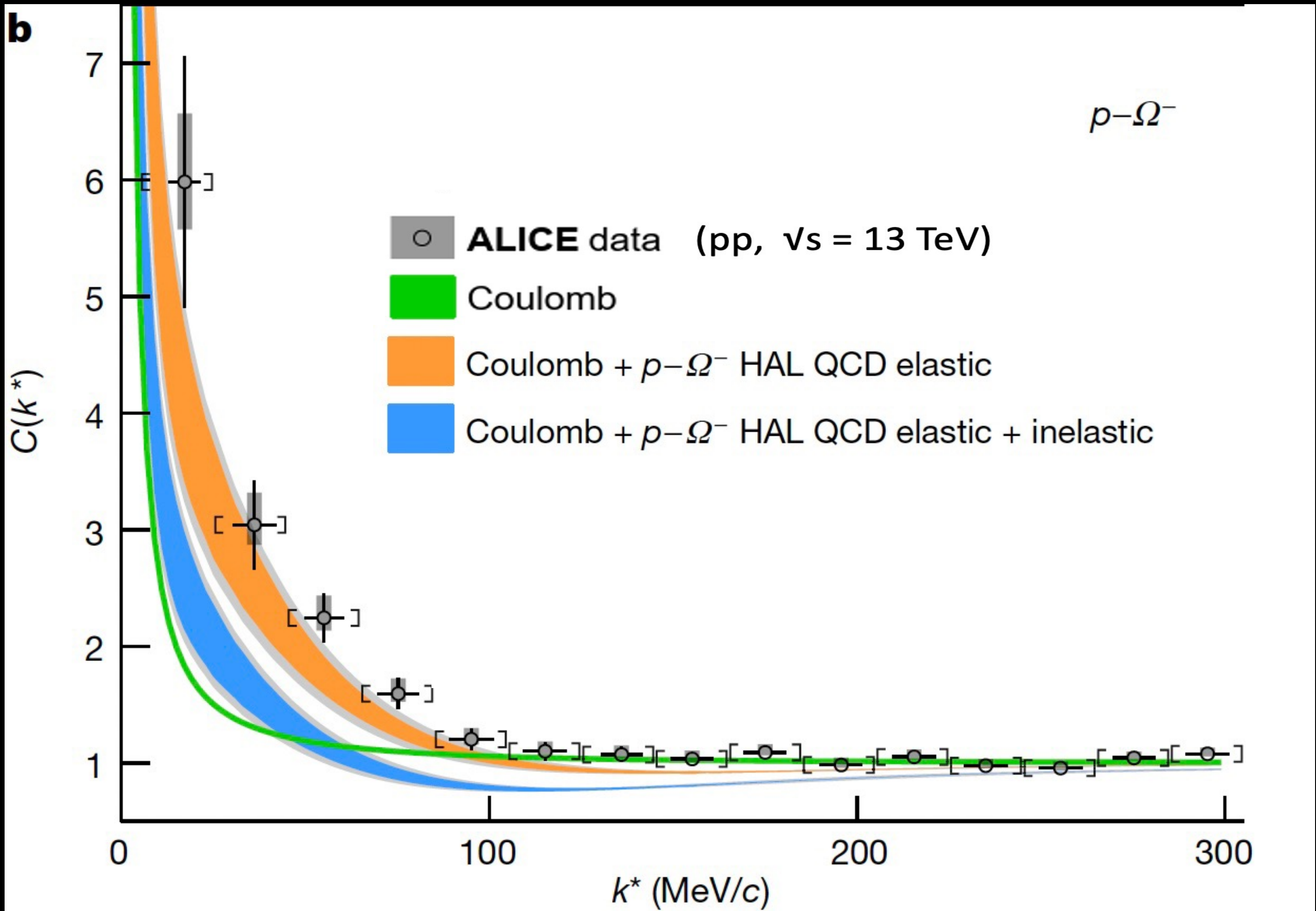
Inoue [HAL QCD Coll.], Few-body Syst. 62 (2021) 106

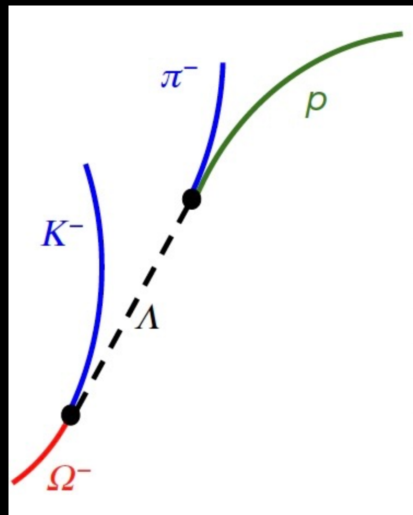
Hiyama, Sasaki, Miyamoto, Doi, Hatsuda, Yamamoto, and Rijken, PRL 124 (2020) 092501

NΩ correlation in pp

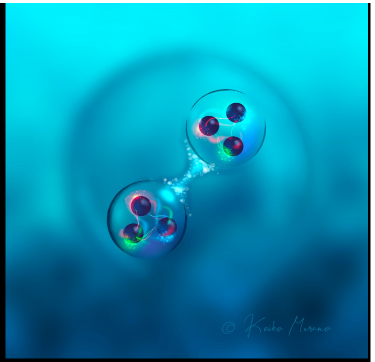
LHC ALICE Coll., Nature 588 (2020) 232

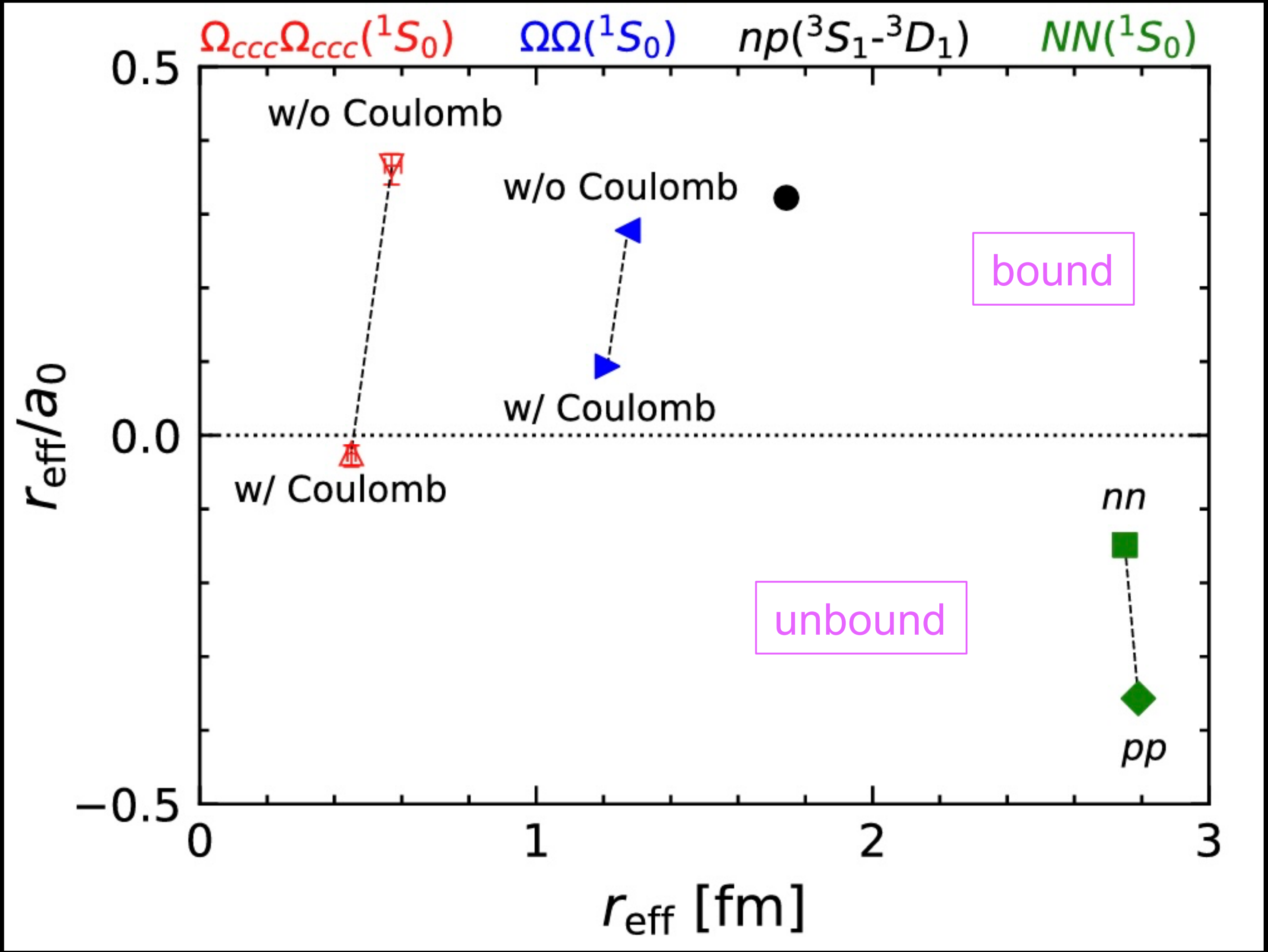






NΩ and ΩΩ systems in LQCD



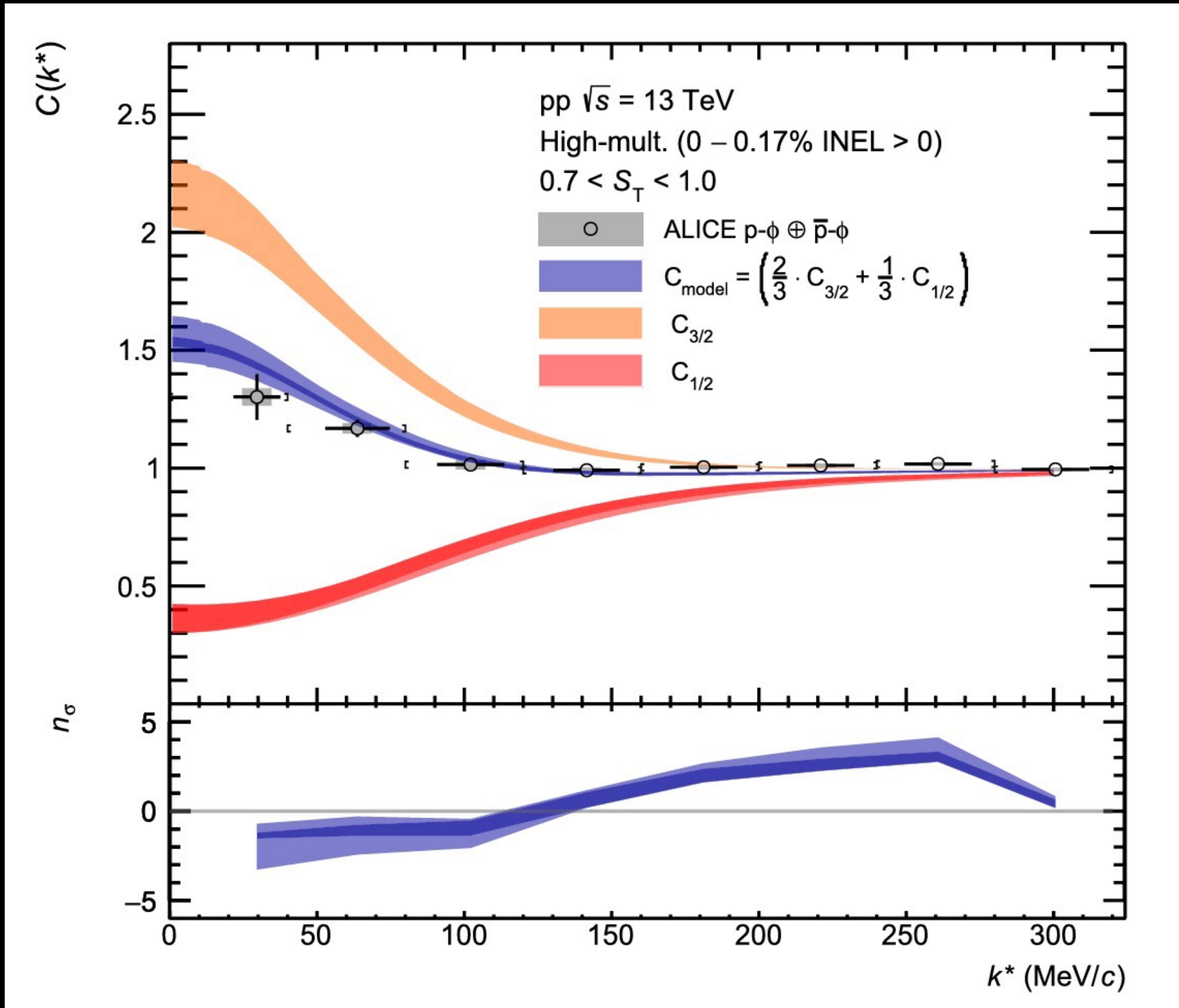


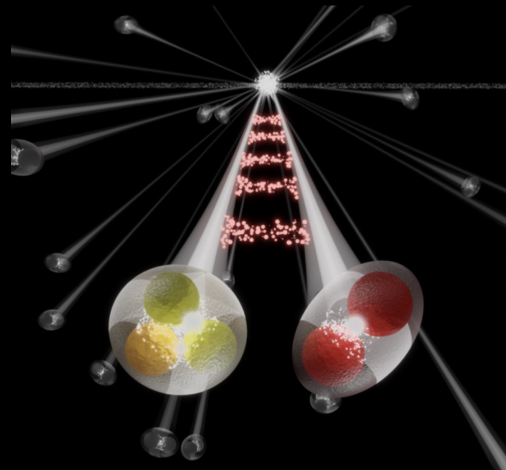
Tong+ [HAL QCD Coll.], PRL (2021)

Indication of a p–ϕ bound state from a correlation function analysis

Emma Chizzali [a,b,*], Yuki Kamiya [c,d,*], Raffaele Del Grande [b], Takumi Doi [d], Laura Fabbietti [b], Tetsuo Hatsuda [d], Yan Lyu [e,d]

Phys. Lett. B 848 (2024) 138358





φp bound state
in spin ½ channel?
(B = 12.8- 56.1 MeV)

Energy levels

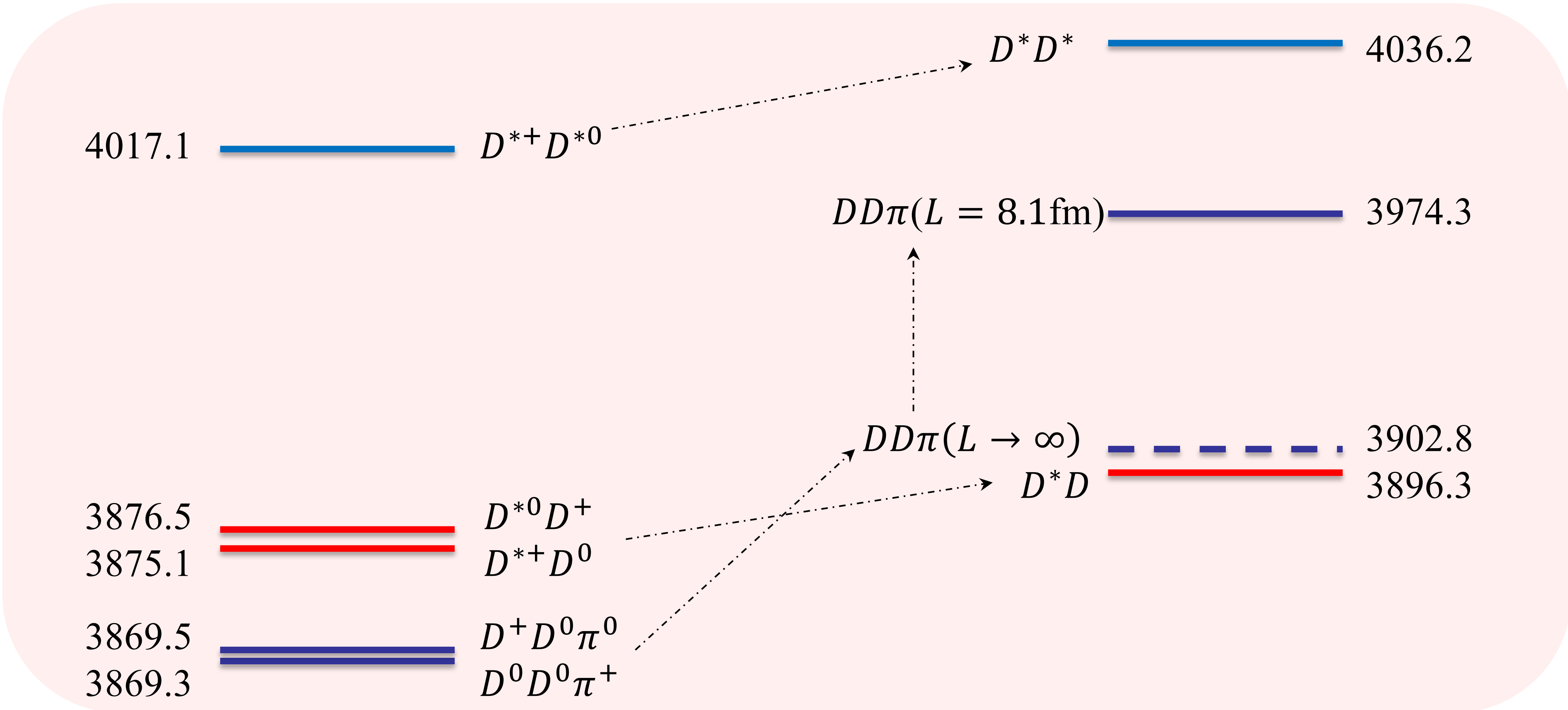
Nature

$\pi^0(134.98)$ $\pi^+(139.57)$
$D^0(1864.84)$ $D^+(1869.66)$
$D^{*0}(2006.85)$ $D^{*+}(2010.26)$

Lattice

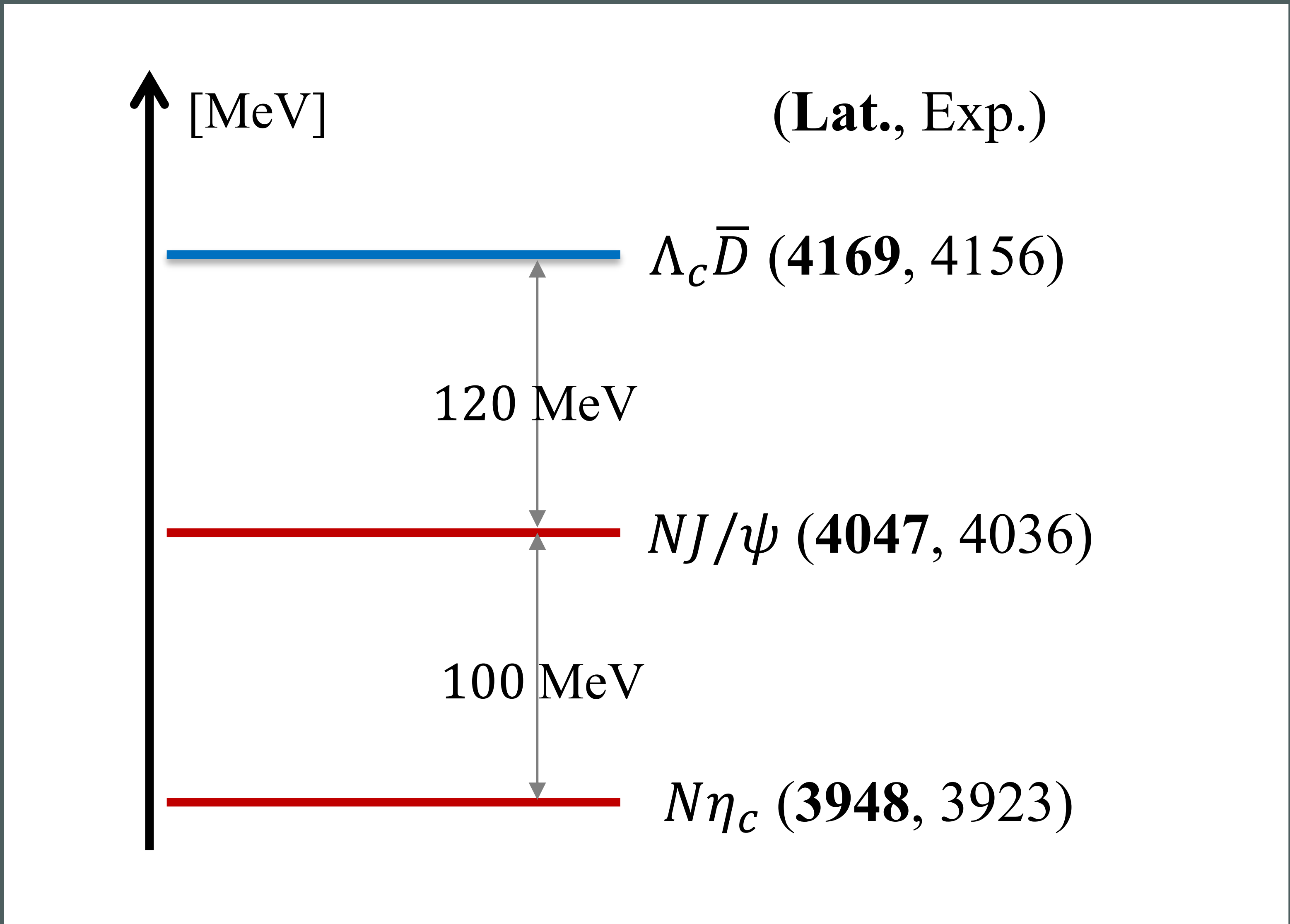
[MeV]

$\pi(146.4)$
$D(1878.2)$
$D^*(2018.1)$



- The lowest energy level of $DD\pi$ (D^*D^*) is around 78 (140) MeV above on the lattice

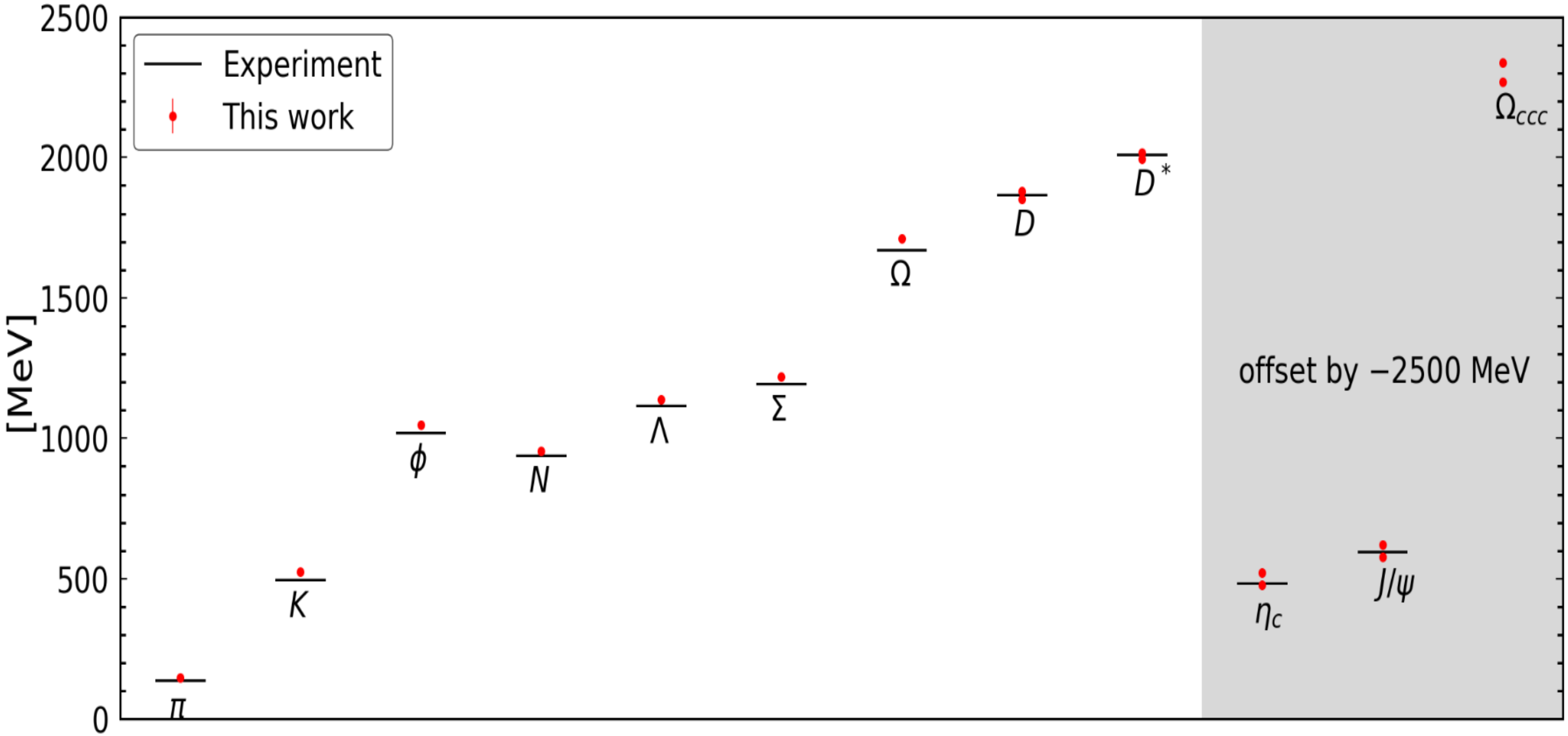
Thresholds



[MeV]
(**Lat.**, Exp.)
$\Lambda_c\bar{D}$ (**4169**, 4156)
120 MeV
NJ/ψ (**4047**, 4036)
100 MeV
$N\eta_c$ (**3948**, 3923)

Hadron masses with “K-configuration”

$L^3 \times T$	a [fm]	La [fm]	m_π [MeV]	m_K [MeV]
$96^3 \times 96$	0.0846	8.1	146	525



PACS Coll. (2016, 2017)