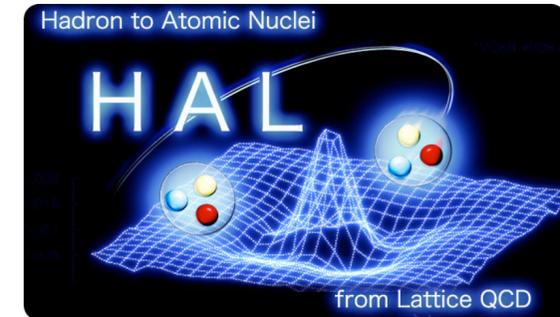# Lattice QCD studies on meson-nucleon interactions and genuine pentaquarks

Kotaro Murakami (村上　耕太郎)
Institute of Science Tokyo/RIKEN iTHEMS

based on

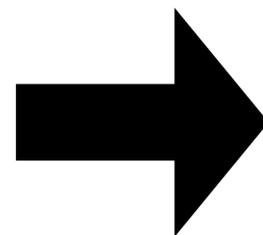KM, S. Aoki, T. Doi, Y. Lyu, W. Yamada (HAL QCD), accepted in PRD [arXiv: 2509.00838]
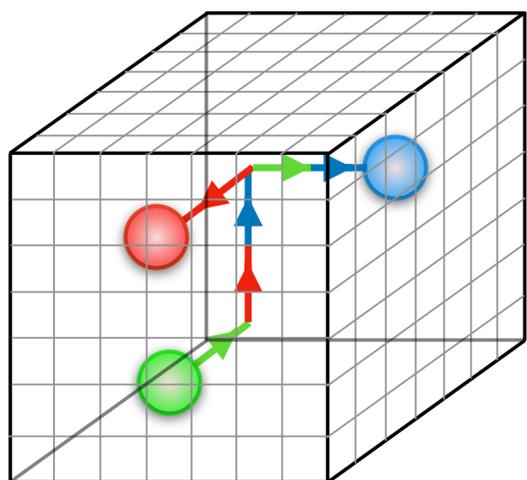W. Yamada, Y. Lyu, KM, T. Doi, (HAL QCD), in preparation
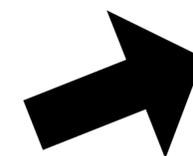
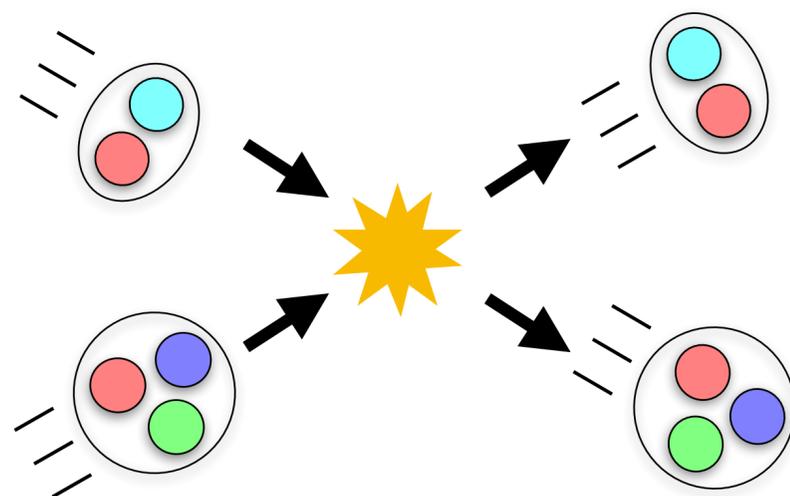核力・ハドロン間相互作用と量子多体計算の進展，京都大学, 2026年2月16-18日

Hadron interactions from lattice QCD

- our goal: understand exotic hadrons/nuclei/matters via hadron interactions using lattice QCD
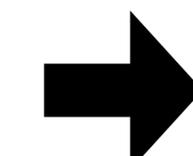
Lattice QCD

hadron interactions (scatterings)

Exotic hadrons

(Exotic) Nuclei

Nuclear matter, Neutron stars

- Finite-volume method [Lüscher, 1991]

- HAL QCD method [Ishii, Aoki, Hatsuda 2007]

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HAL QCD method

- extract an interaction potential

  from Nambu-Bethe-Salpeter (NBS) wave functions:

$$\Psi^W(\mathbf{r}) = \langle 0| \hat{O}_1(\mathbf{r})\hat{O}_2(\mathbf{0}) |1,2;W\rangle \underset{r\to\infty}{\to} A\frac{\sin(kr - \frac{l}{2}\pi + \delta^l(k))}{kr}e^{i\delta^l(k)}Y_{l,m}(\Omega)$$

$$\blacktriangleright \int d^3r' \boxed{U(\mathbf{r},\mathbf{r}')}\Psi^W(\mathbf{r}') = \left(\frac{k^2}{2\mu} + \frac{\nabla^2}{2\mu}\right)\Psi^W(\mathbf{r})$$

interaction potential

[Ishii, Aoki, Hatsuda, PRL (2007)]
[Aoki, Hatsuda, Ishii, PTP (2010)]

- practical calc. : **time-dependent HAL QCD method** [Ishii et al., PLB (2012)]

  + local approximation ($U(\mathbf{r},\mathbf{r}') \approx V(\mathbf{r})\delta^{(3)}(\mathbf{r}-\mathbf{r}')$)

$$R(\mathbf{r},t) = \frac{\langle O_1(\mathbf{r},t)O_2(\mathbf{0},t)\bar{J}(0)\rangle}{\langle O_1(t)\bar{O}_1(0)\rangle\langle O_2(t)\bar{O}_2(0)\rangle} \approx \sum_n C_{\bar{J},n}\underline{\Psi^{W_n}(\mathbf{r})e^{-(W_n-m_1+m_2)t}}$$

NBS wave function

$$\blacktriangleright V(\mathbf{r}) \simeq \frac{1}{R(\mathbf{r},t)}\left(\frac{\nabla^2}{2\mu} - \frac{\partial}{\partial t} + \frac{1}{8\mu}\frac{\partial^2}{\partial t^2}\right)R(\mathbf{r},t)$$

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Current situation of HAL QCD studies

- ~2024: near-physical-point simulations ($m_\pi \approx 146$ MeV)

  - $\Omega\Omega$ [Gongyo et al., 2018]
  - $N\Omega$ [Iritani et al., 2019]
  - nucleon/hyperon interactions: [S. Aoki and T. Doi, Front. in Phys. **8,** 307 (2020) (review)]
  - H dibaryon [Sasaki et al., 2020]
  - $\Omega_{ccc}\Omega_{ccc}$ [Lyu et al., 2021]
  - T_{cc}^+ [Lyu et al., 2023]
  - $N\phi$, NJ/ψ [Lyu et al., 2022] [Lyu et al., 2025]

- 2025~: **on-physical-point** simulations ($m_\pi \approx 137$ MeV)

  - configuration generation: done [HAL QCD Collab., 2024]

    - $N\Omega_{ccc}$ [Zhang et al., 2025]
    - KN [KM, Aoki, Doi, Lyu, Yamada, [arXiv: 2509.00838]]
    - $\bar{D}N$ [Yamada, Lyu, KM, Doi, in preparation]
    - YN (Talk by Murase-san today)
    - $\Lambda\Lambda, \Xi N$ [Sasaki et al., in preparation]
    - $N\Omega$ [Zhang et al., work in progress]

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    - $N\Omega$ [Zhang et al., work in progress]

  - other on-going HAL QCD projects

    - hyperon int. from HAL QCD
      (Talk by Inoue-san today)
    - negative-parity nuclear force
      (Talk by Sugiura-san yesterday)
    - optimized operator constructions
      [Yan et al., [arXiv:2507.09933]]
      [Yan et al., [arXiv:2507.09930]]
    - $\Lambda(1405)$ in SU(3) limit
   [KM, Aoki, in preparation]

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  - $\bar{D}N$ interactions

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Motivation for meson-nucleon interactions (1/2)

- interactions between a nucleon and $q\bar{Q}$-type meson

  K $\bar{D}$ B
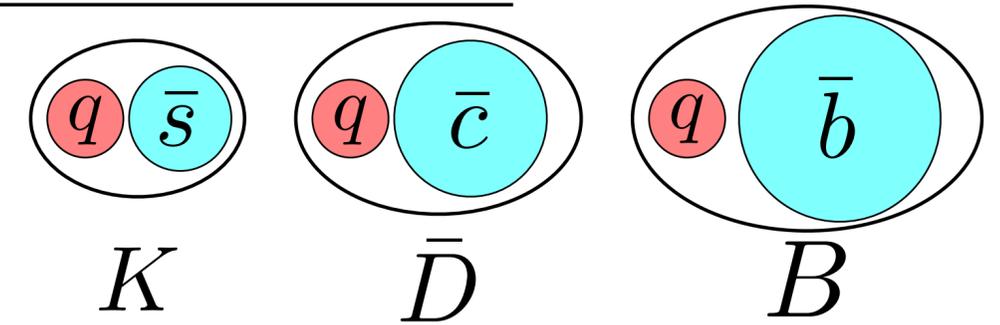
  - no quark-antiquark pair creation/annihilation

  - can provide **understandings of quark/hadron dynamics**

    1. restoration of chiral symmetry in medium

    2. possible existence of genuine pentaquark

1. **restoration of chiral symmetry in medium**

- $\langle \bar{u}u + \bar{s}s \rangle^*(\rho_N)$ from KN scattering data

  [Iizawa, Jido, Hübsch, PTEP (2024)]

- rich scattering experimental data since 1960s

- **no data near threshold** due to the experimental difficulty

  ➡ **large ambiguity** (especially for I=0)

[Iizawa, Jido, Hübsch, PTEP (2024)]

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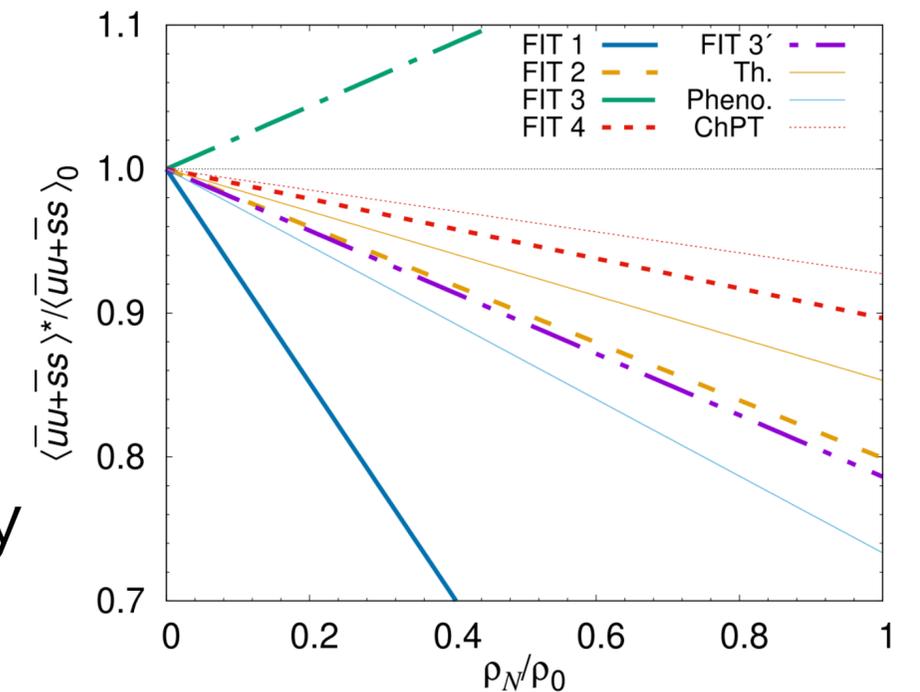
Motivation for meson-nucleon interactions (2/2)

2. possible existence of open-strange/charm genuine pentaquark
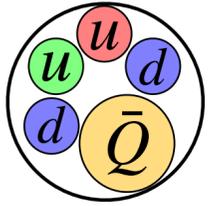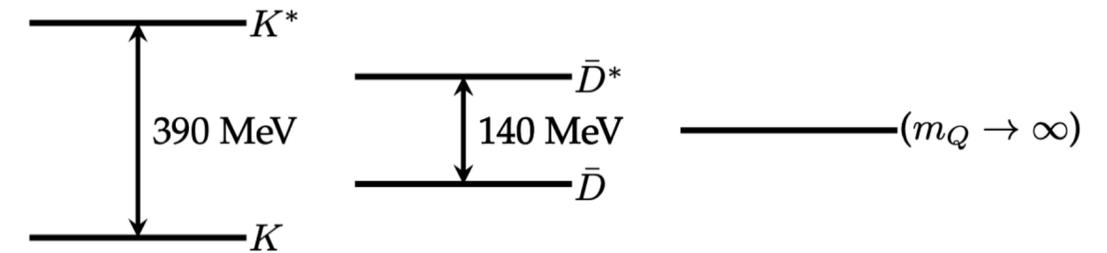
- Θ^+ ($uudd\bar{s}$) pentaquark in KN

  - most experiments after the LEPS gave negative results
    [LEPS, PRL (2003)]

  - **no definitive conclusion from theoretical side**
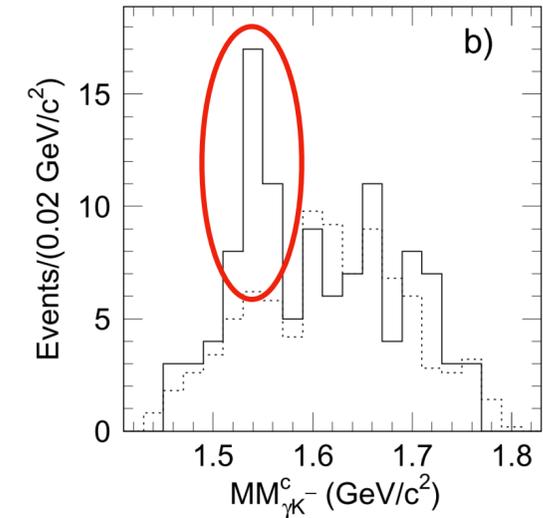
[LEPS, PRL (2003)]

- Θ_c^+ ($uudd\bar{c}$) pentaquark in $\bar{D}N$

 - $\bar{D}N$ would be attractive due to $\bar{D}^*N$-$\bar{D}N$ coupling

    ➡ bound state?

  - scarce experimental data for $\bar{D}N$ (only by ALICE)
    [ALICE, PRD (2022)]

  - **phenomenological-model prediction is uncertain**

Model	$\bar{D}N(I=0)$	$\bar{D}N(I=1)$
SU(4) contact [185]	None	None
SU(8) contact [193]	2805	None
Meson exchange [194]	None	None
Pion exchange [192]	2804	None
Chiral quark model [195]	None	None

[Hosaka et al., Prog. Part. Nucl. Phys. (2017)]

$KN/\bar{D}N$ interactions in lattice QCD
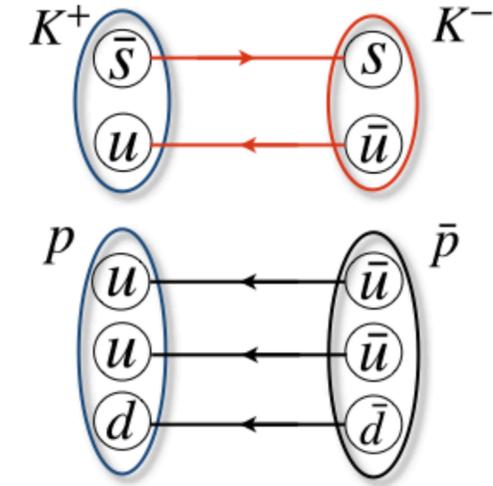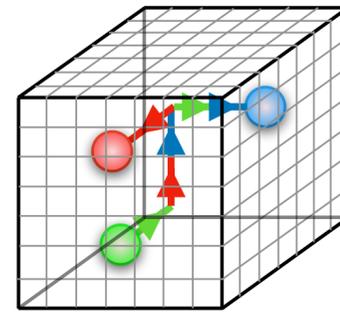
- $KN/\bar{D}N$: relatively easy to calculate

    - no annihilation diagram ➡ cheap computational cost

    - no need for coupled-channel analysis

    - **physical point simulations are now possible** (for S-wave component)
        $(m_\pi \approx 137 \text{ MeV})$ [HAL QCD, PRD (2024)]

    Lattice QCD compensates the missing profiles of $KN/\bar{D}N$

- this talk: theoretical study on $KN/\bar{D}N$ interactions

  using **lattice QCD on physical point**

    - how does the $KN/\bar{D}N$ **interactions** behave?

    - what are $KN/\bar{D}N$ scatterings like **near the threshold**?

    - does the **genuine pentaquarks** exist?

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Calculation strategy

- u, d, s quarks: $N_f = 2 + 1$ gauge configurations ($m_u = m_d < m_s$)

[HAL QCD, PRD (2024)]

on the physical point

- clover fermion + Iwasaki gauge w/ stout smearing

- $V = (96a)^4 \approx (8.1 \text{ fm})^4$, $a = 0.084372(54)\binom{+109}{-6}$ fm

- $m_\pi \approx 137 \text{ MeV}$, $m_K \approx 502 \text{ MeV}$, $m_N \approx 940 \text{ MeV}$

- c quark: quench approximation for the sea quark, action w/ physical mass for the valence quark

- (approximated) S-wave component of wave functions are extracted

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  - $\bar{D}N$ interactions
    - W. Yamada, Y. Lyu, KM, T. Doi (HAL QCD), in preparation
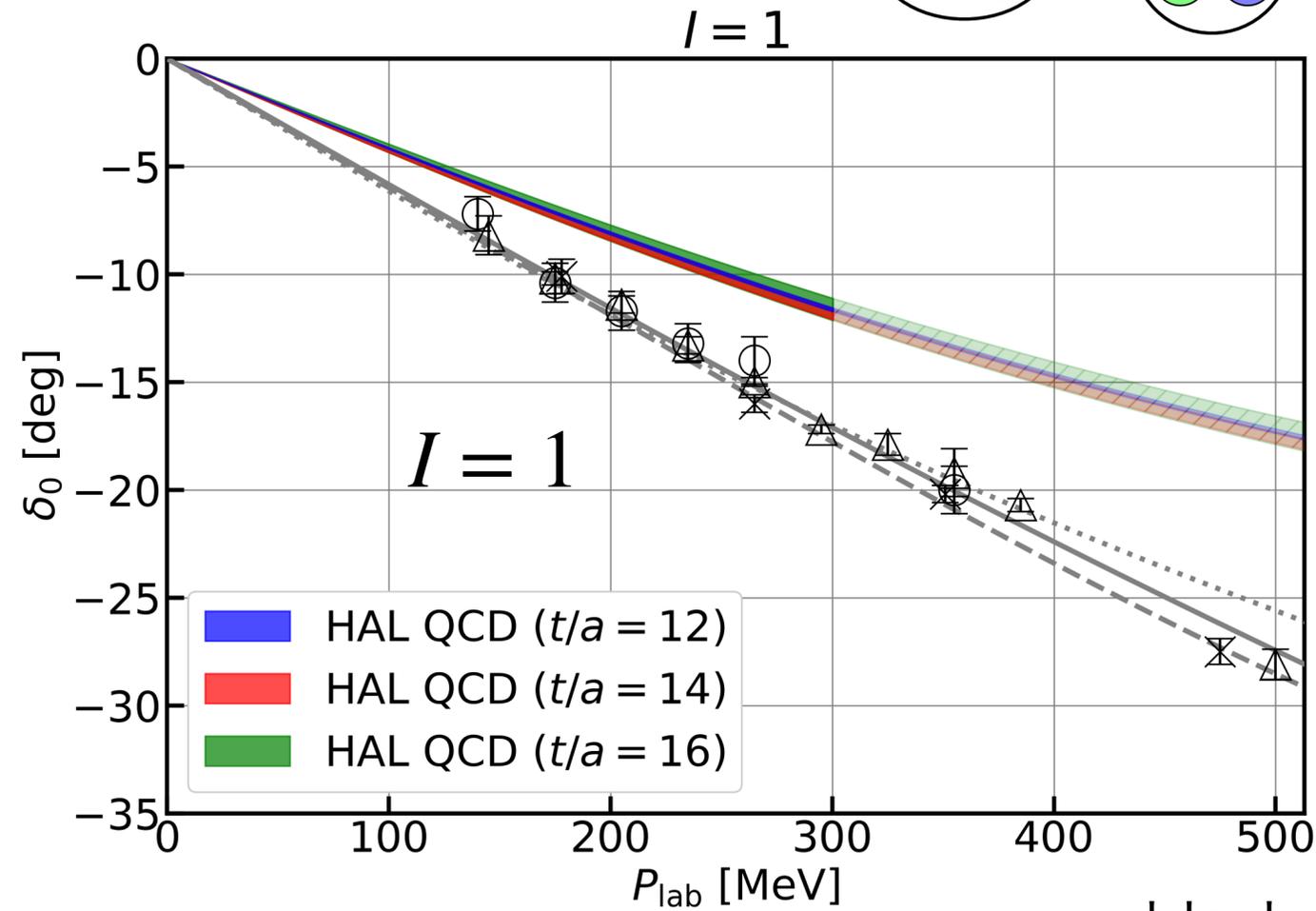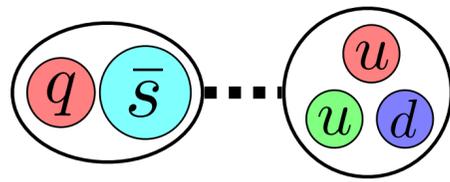
KN local potentials
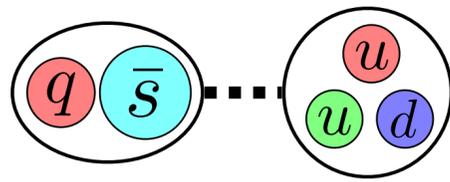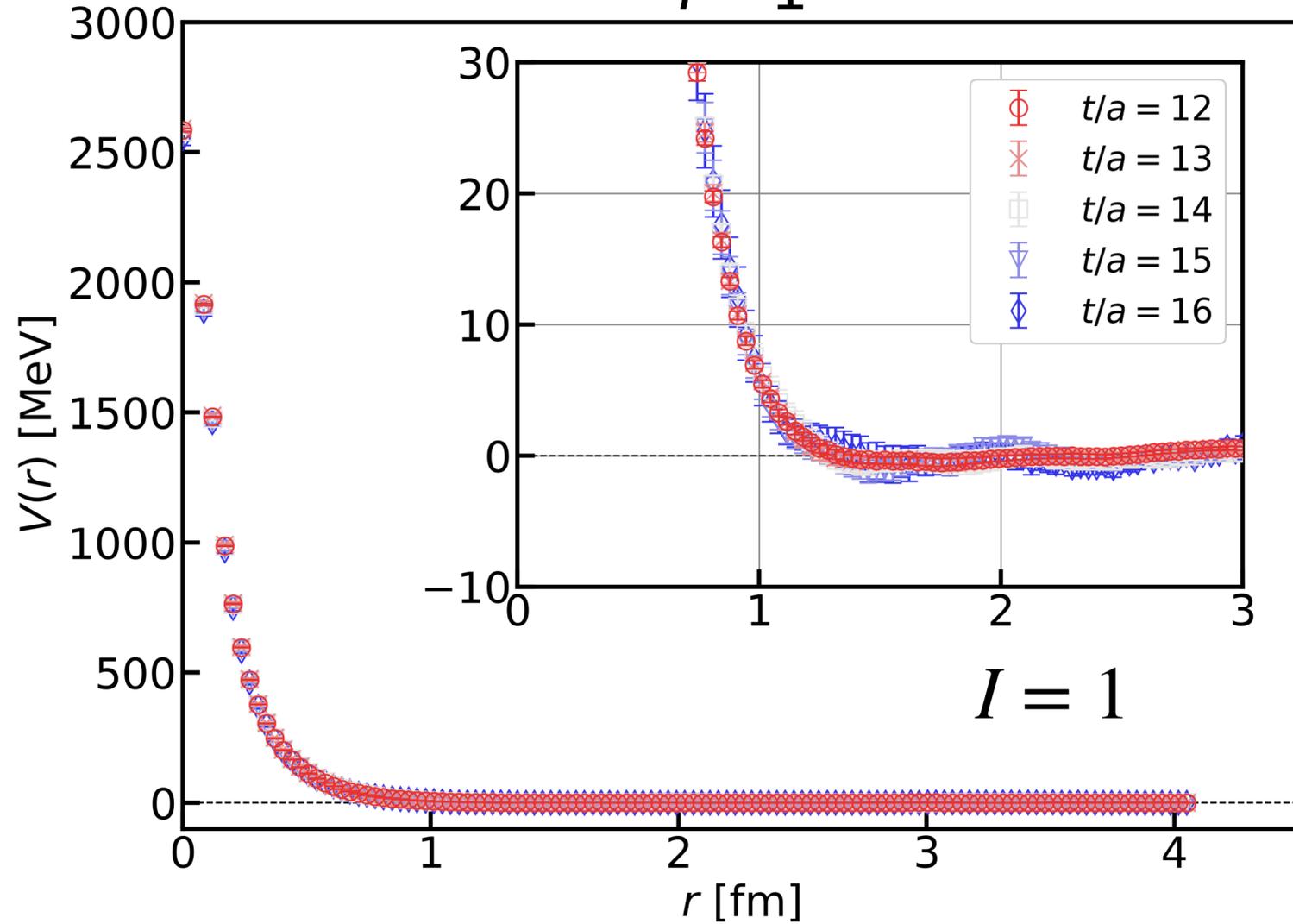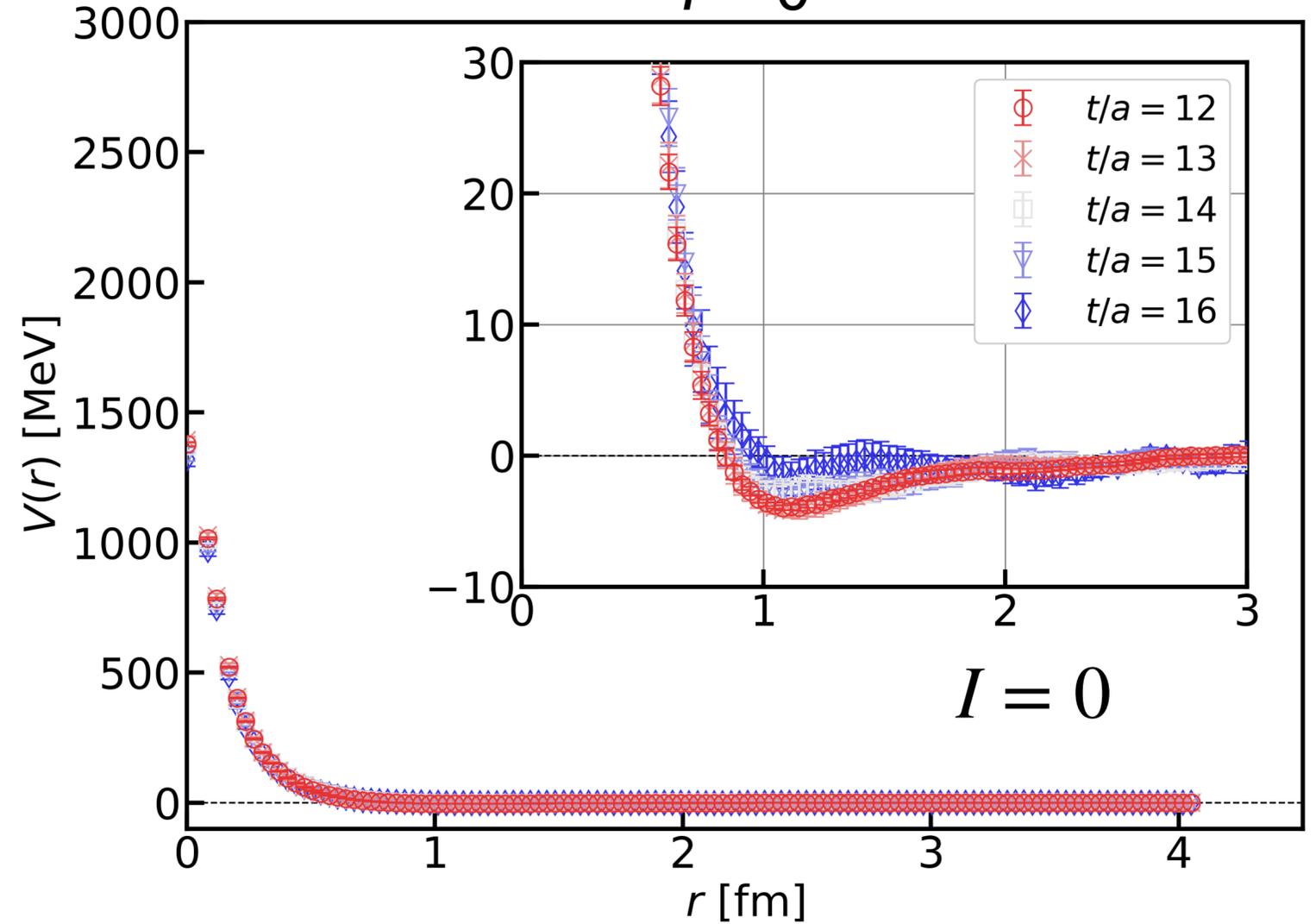
- I=1: repulsive core

- I=0: repulsive core + attractive pocket

KN Phase shifts
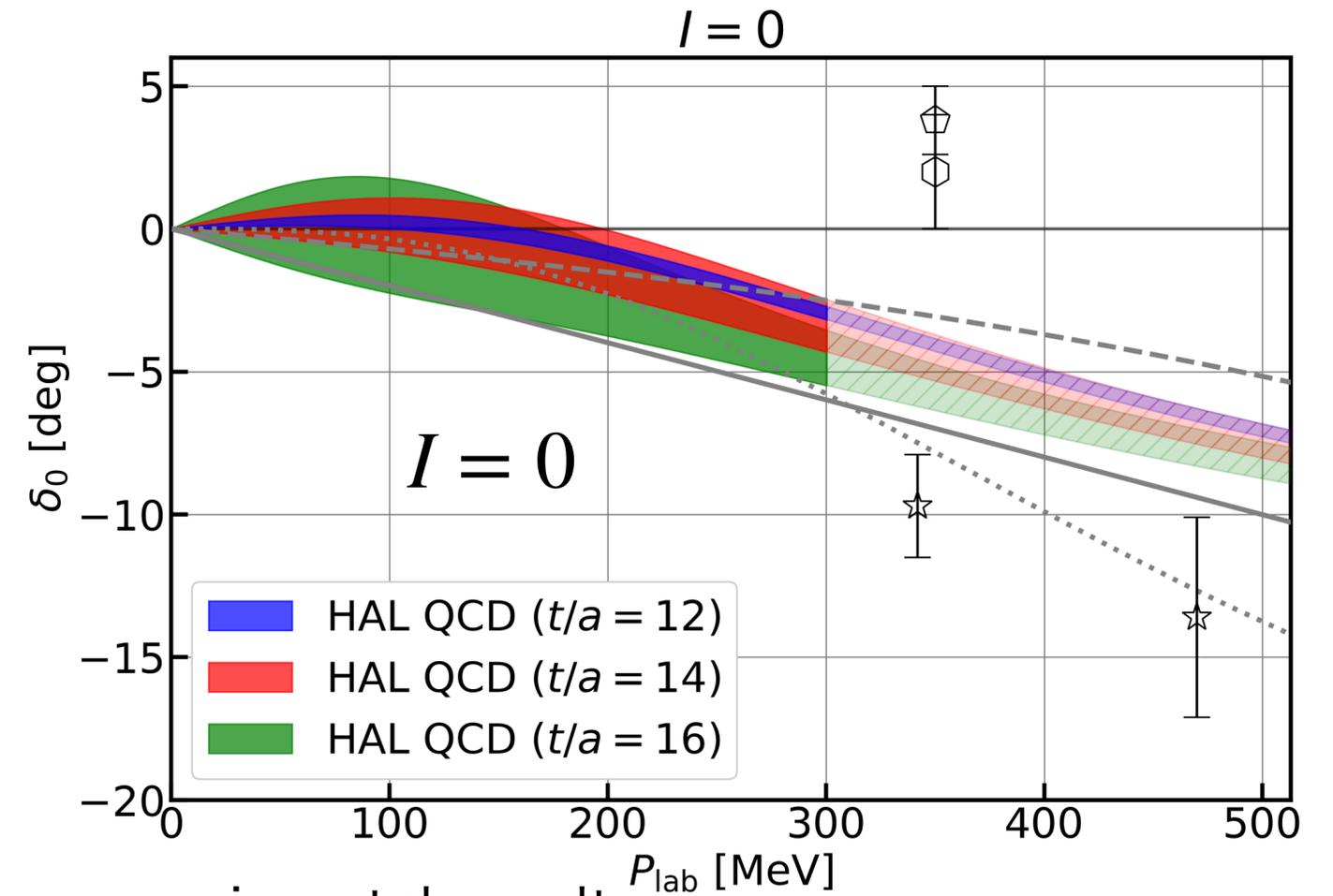
- black plots: experimental results
- gray lines: partial-wave analysis (parameterization method)

- **no bound states or resonances found**

- larger in magnitude than experimental data for I=1
    - more careful determination is required both in experiment and theory
    - necessary to see the lattice discretization effect in future

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S-wave total cross sections

$I = 1$

$I = 0$
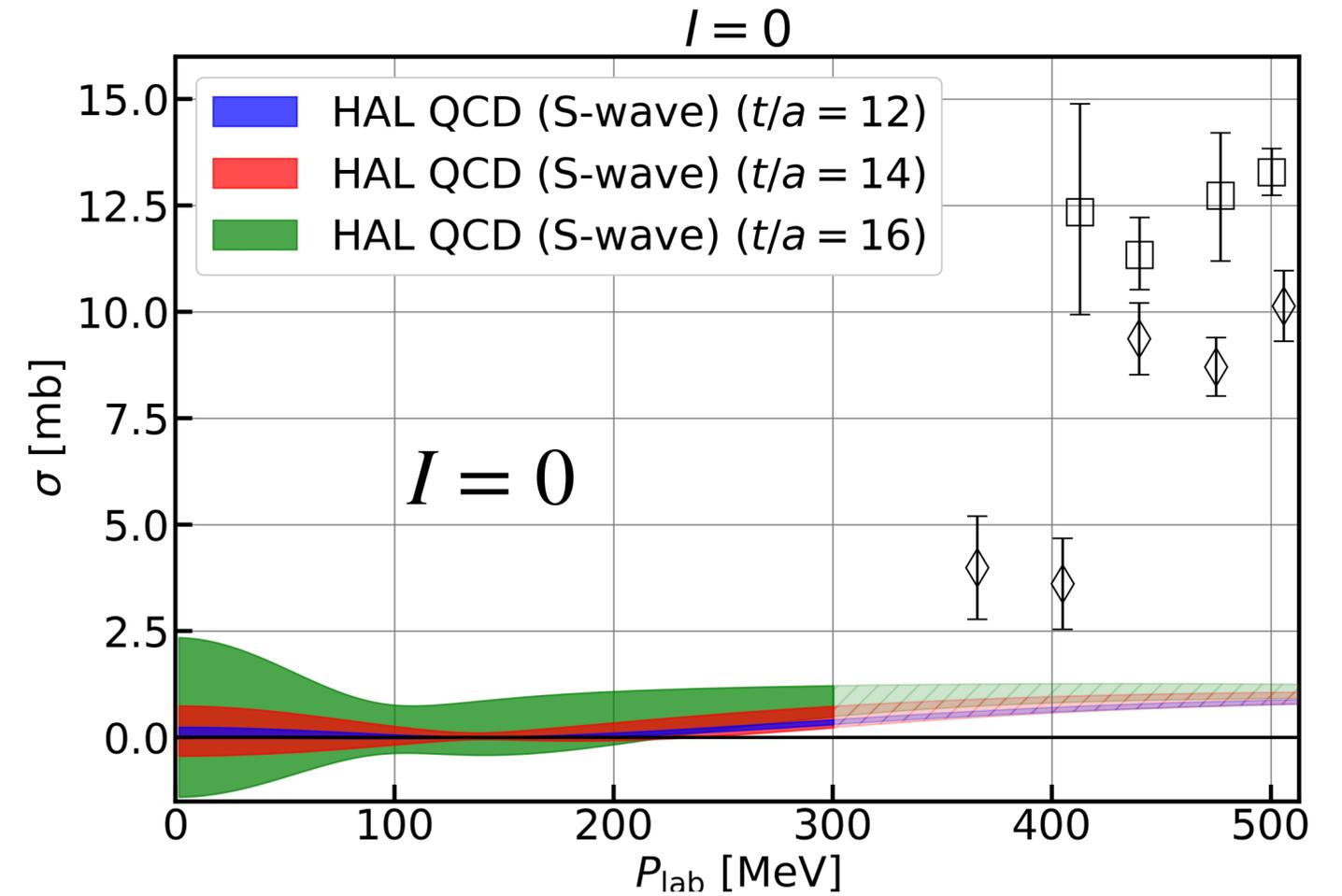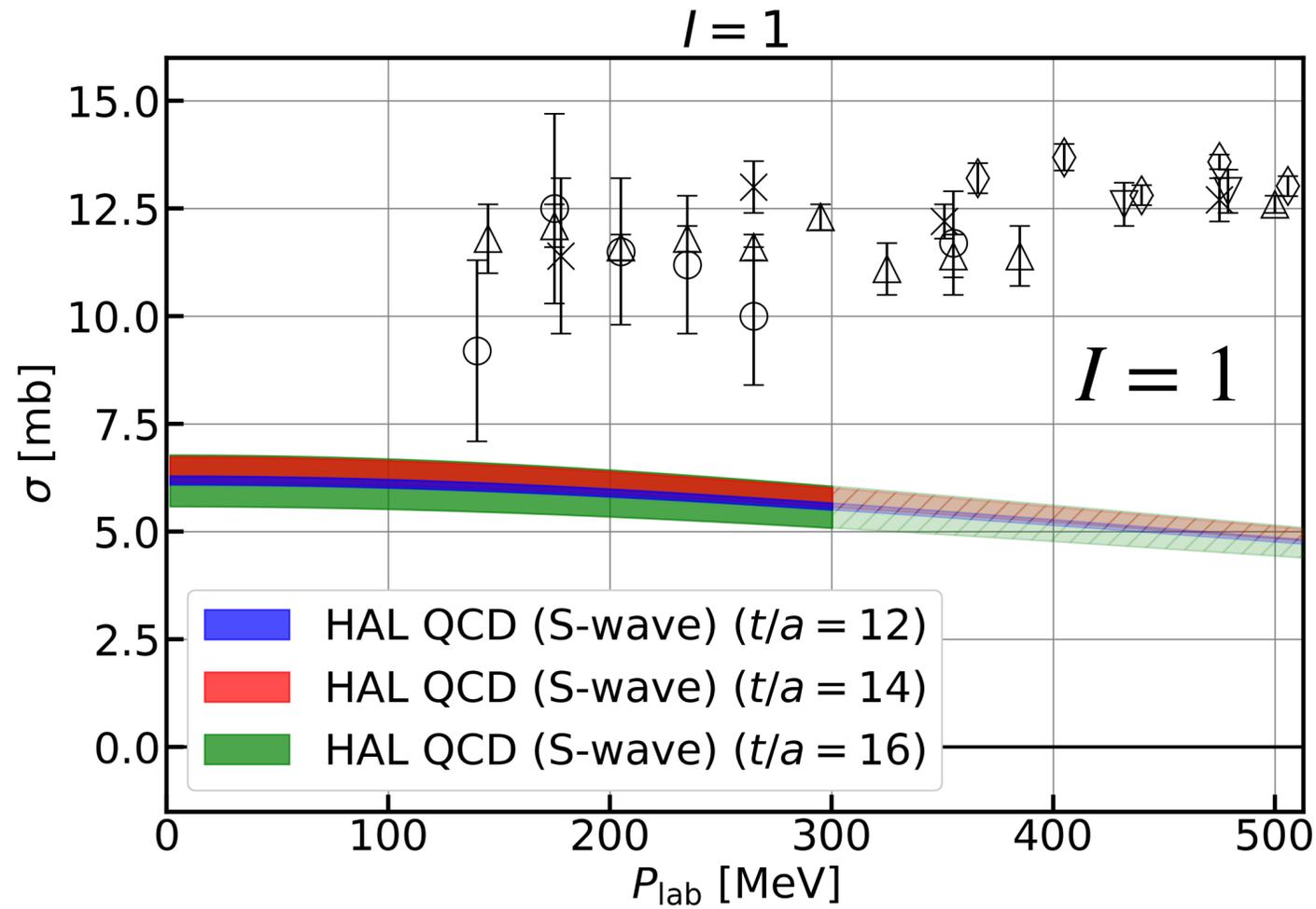
- color bands: our results (**only S-wave component**)
- black plots: experimental results (**including all partial waves**)

- I=0: consistent with (u)ChPT [Aoki, Jido, PTEP (2019)]

  ➡ I=0 cross section is dominant by P-wave?
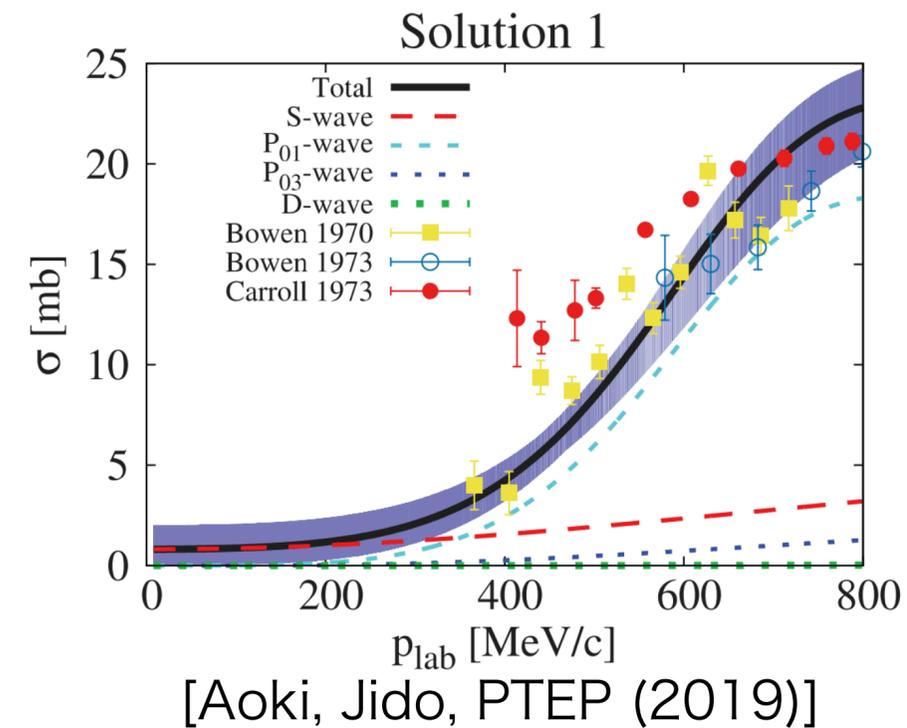
Solution 1

[Aoki, Jido, PTEP (2019)]

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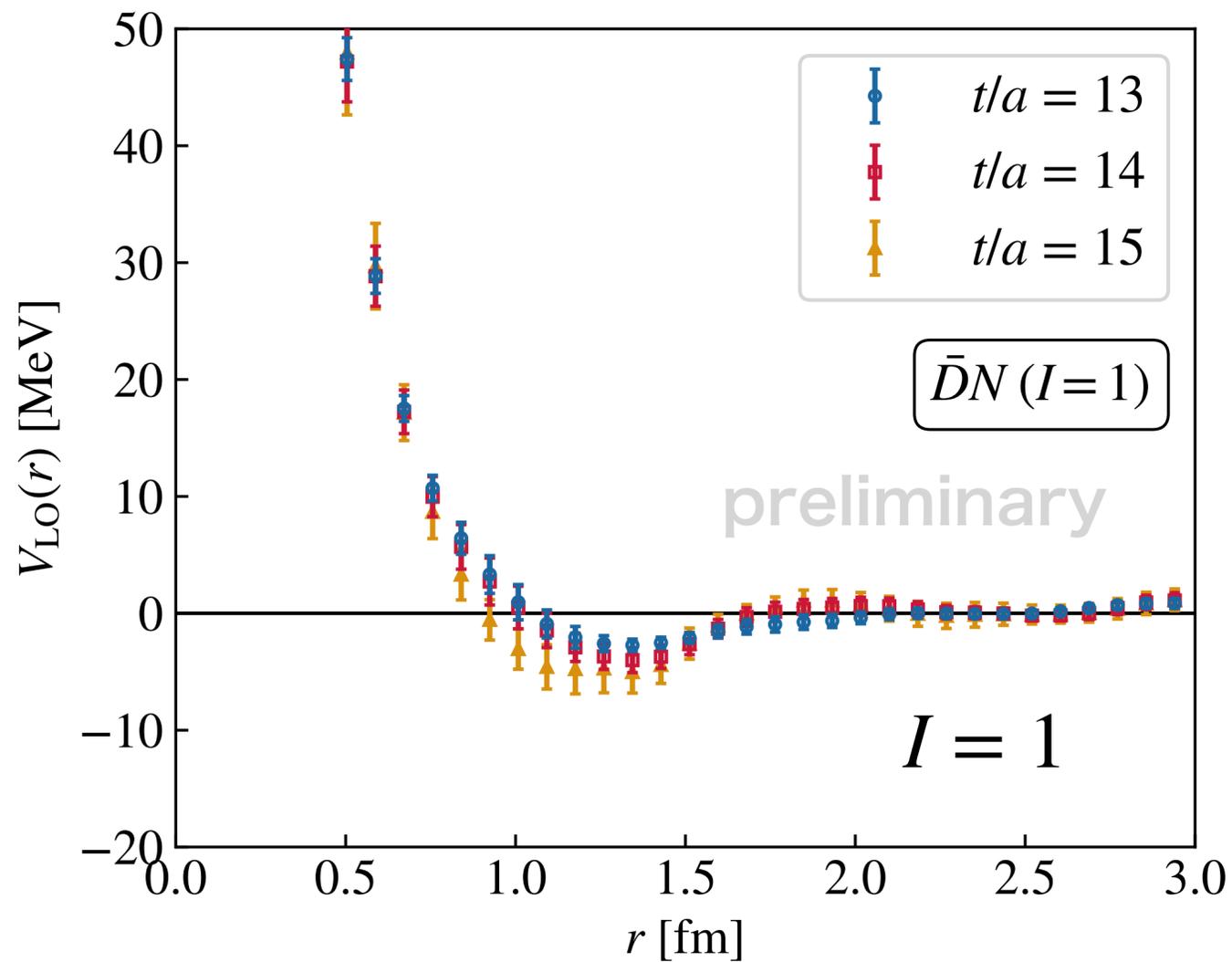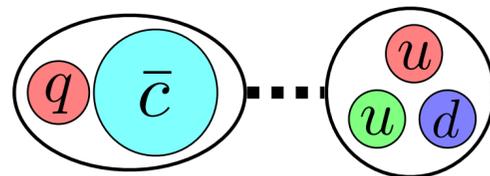- Motivation for $KN/\bar{D}N$ interactions

- Numerical results

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    KM, S. Aoki, T. Doi, Y. Lyu, W. Yamada (HAL QCD), [arXiv: 2509.00838]
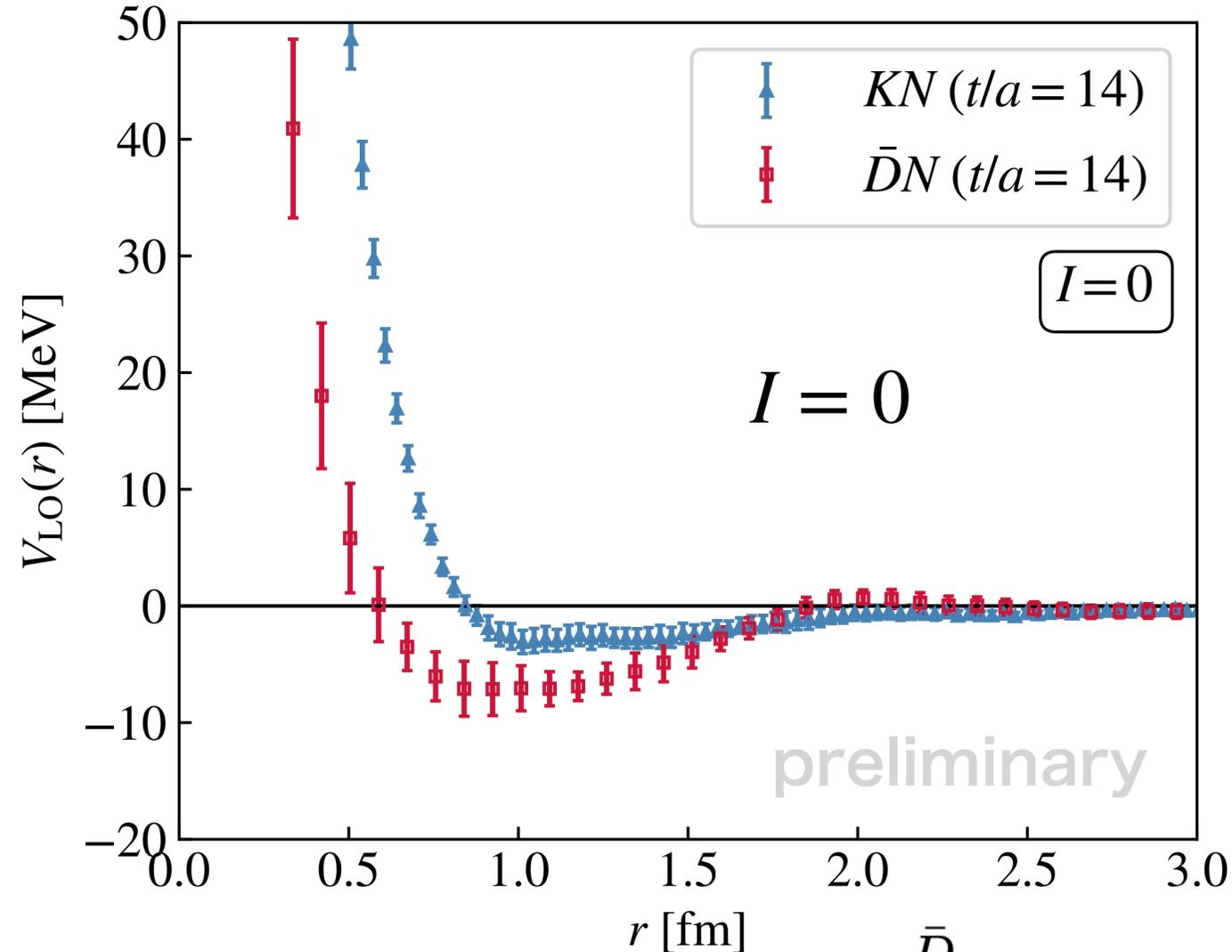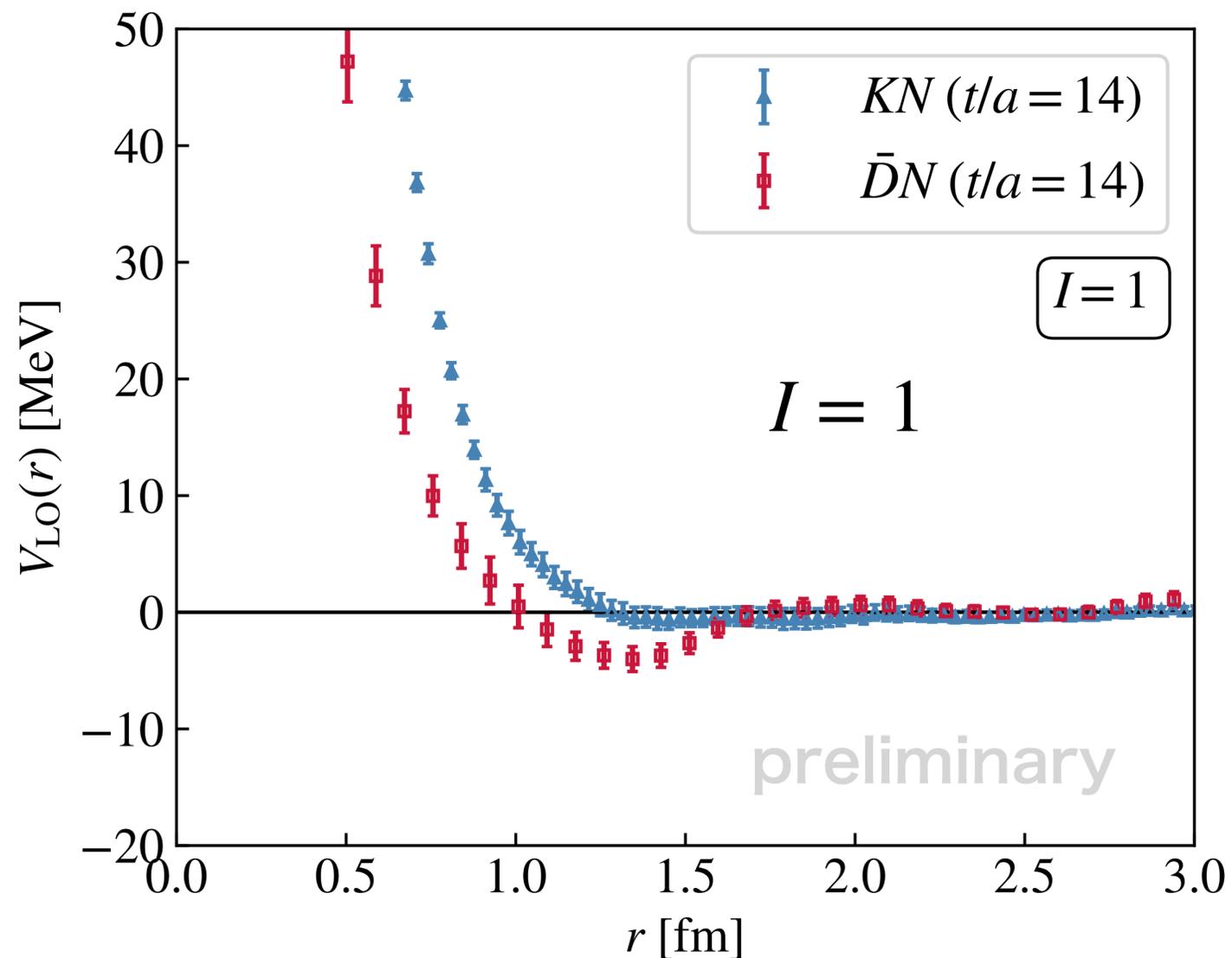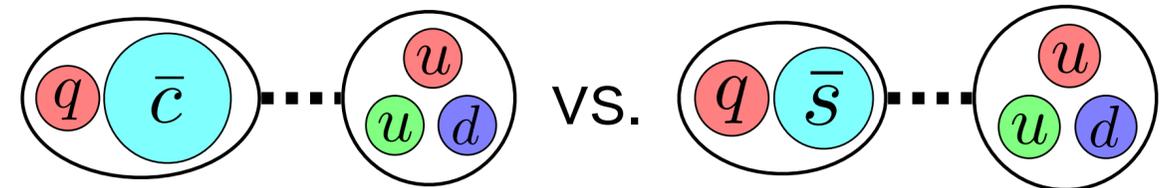
  - $\bar{D}N$ interactions

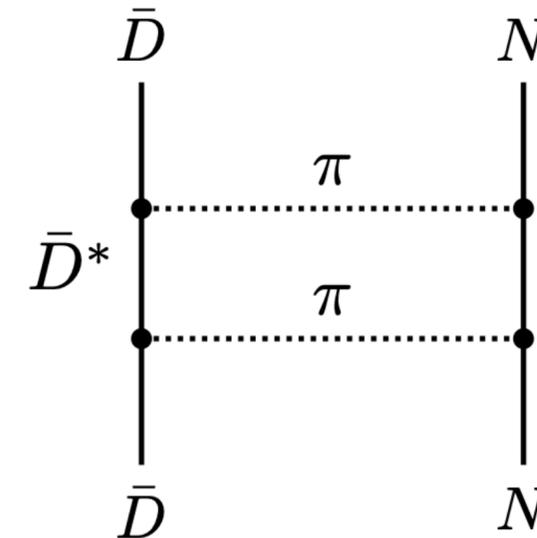   W. Yamada, Y. Lyu, KM, T. Doi (HAL QCD), in preparation

$\bar{D}N$ local potentials
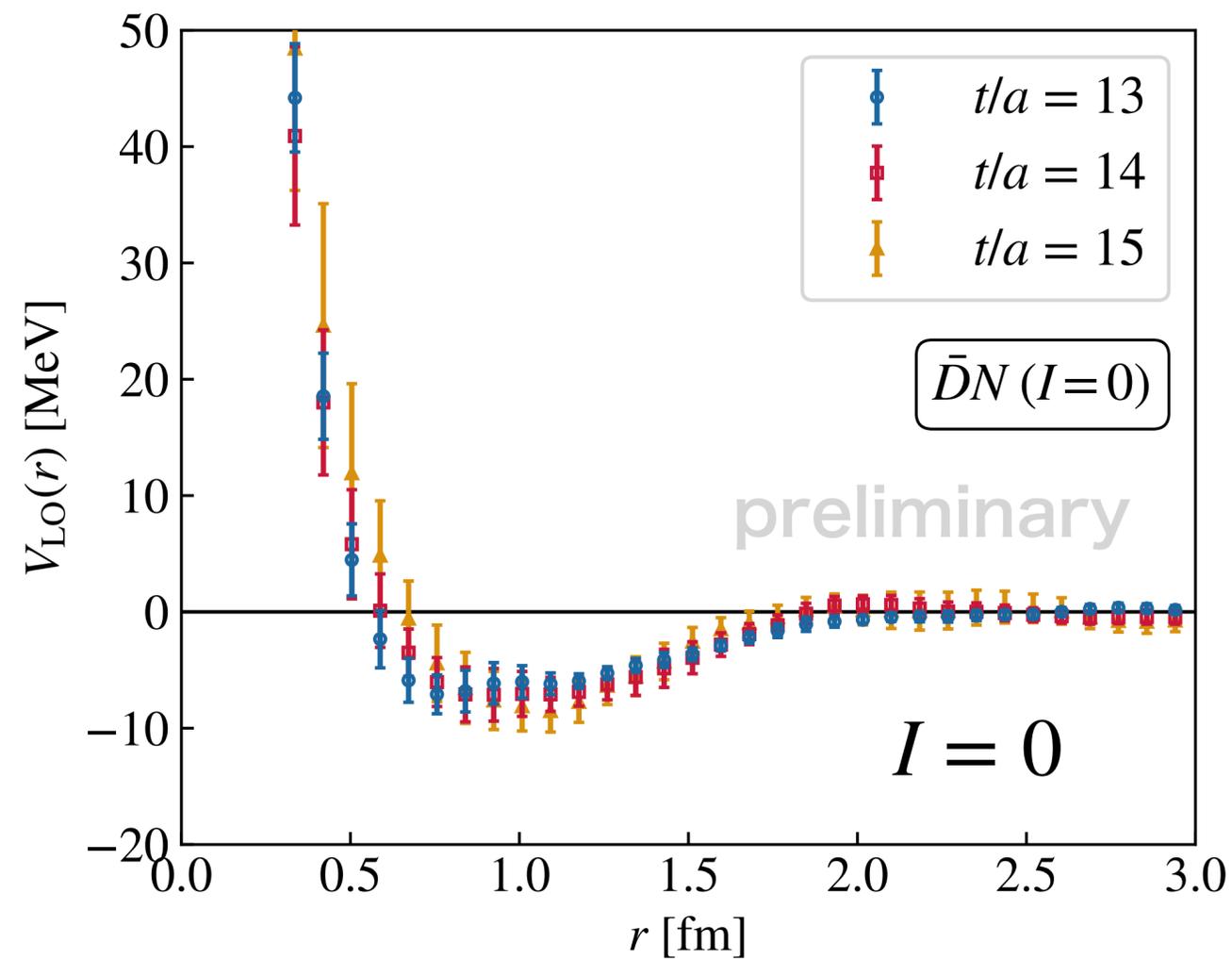
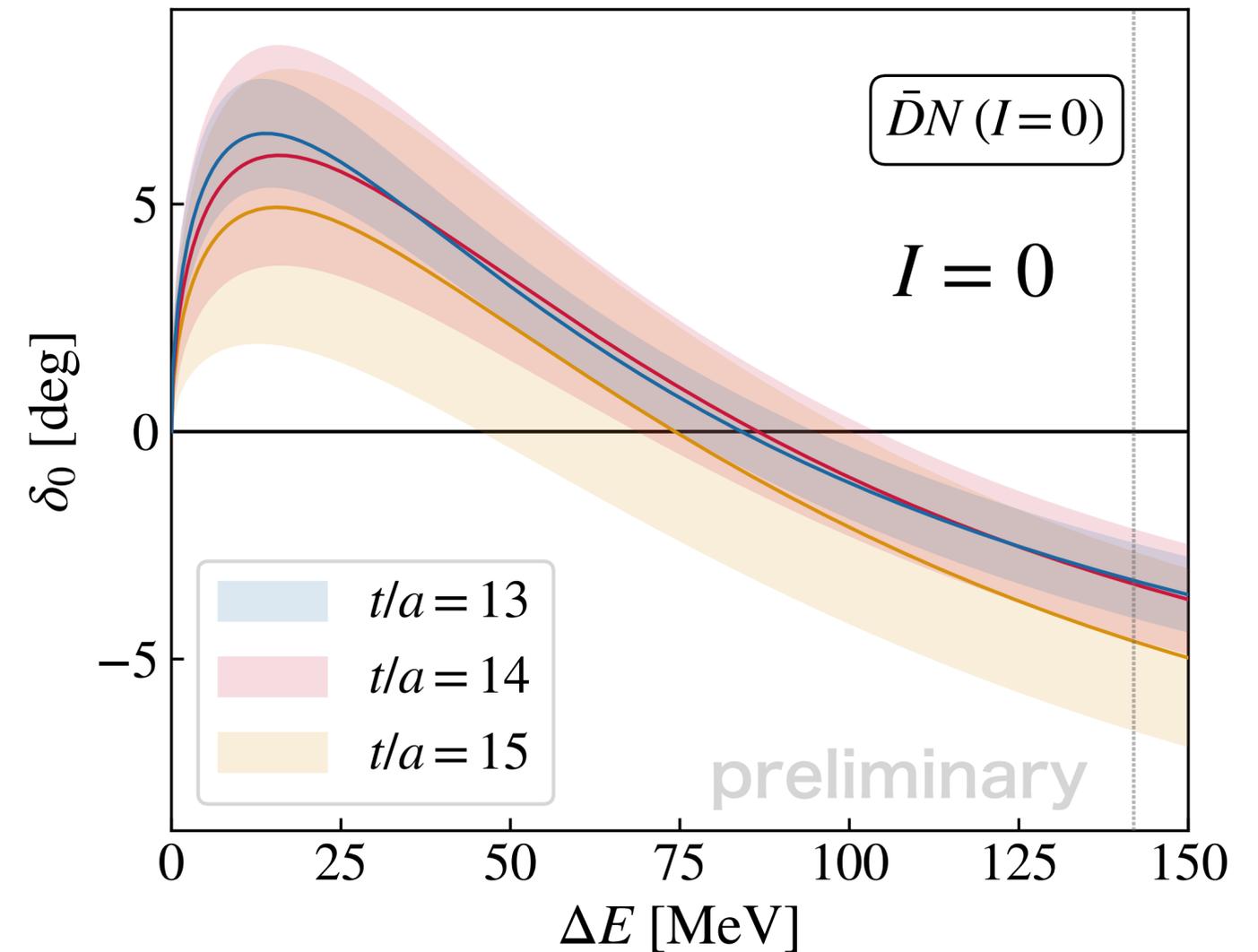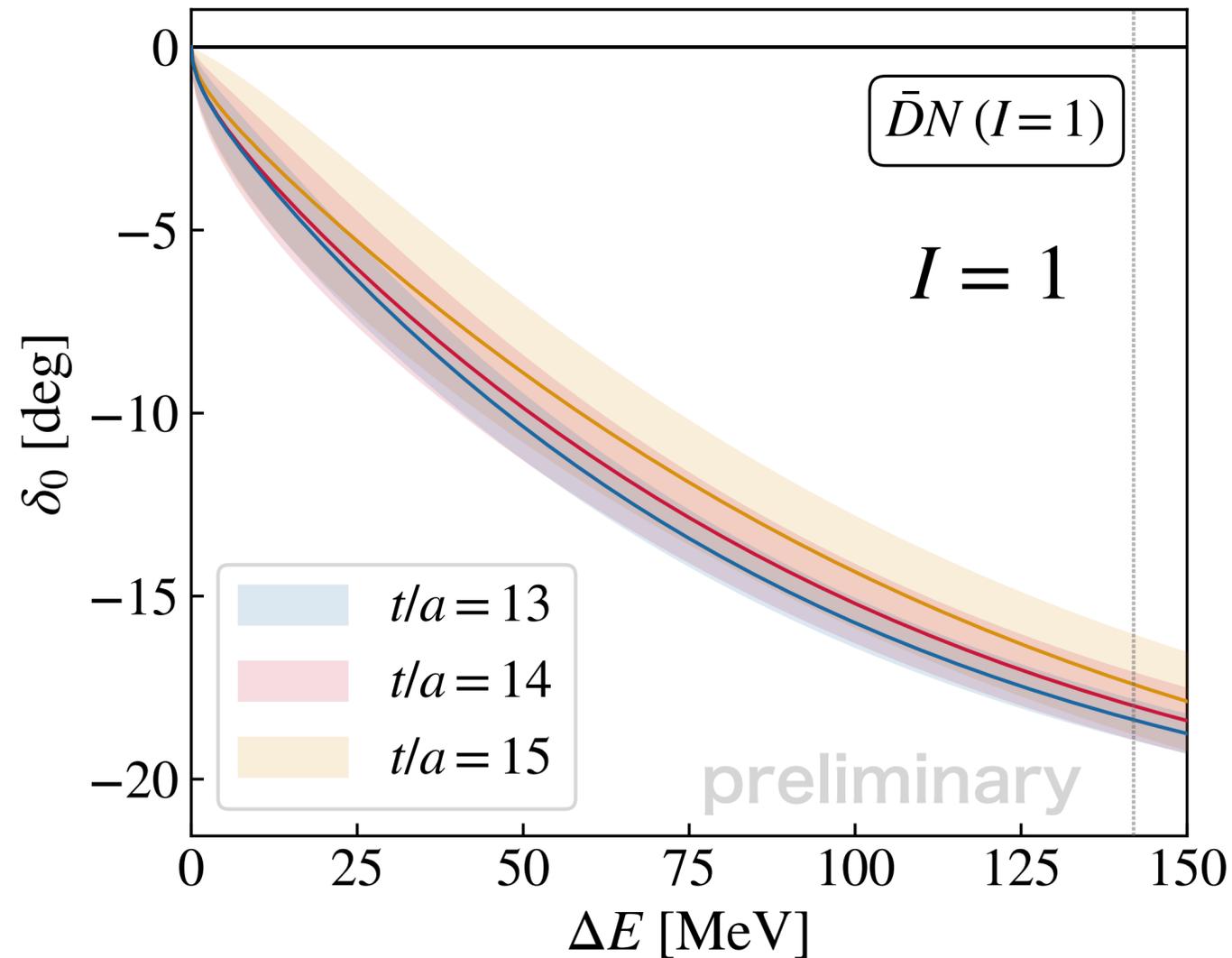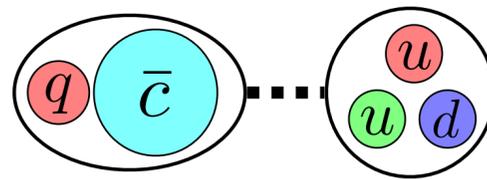- repulsive core + attractive pocket for both isospins

Comparison between $\bar{D}N$ and KN

- $\bar{D}N$ is more attractive than KN

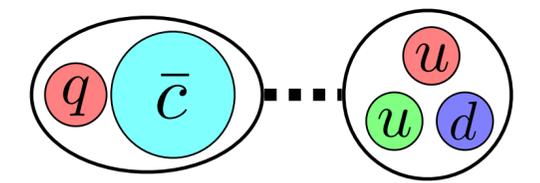- sign of attraction attributed to coupling of $\bar{D}^*N$?
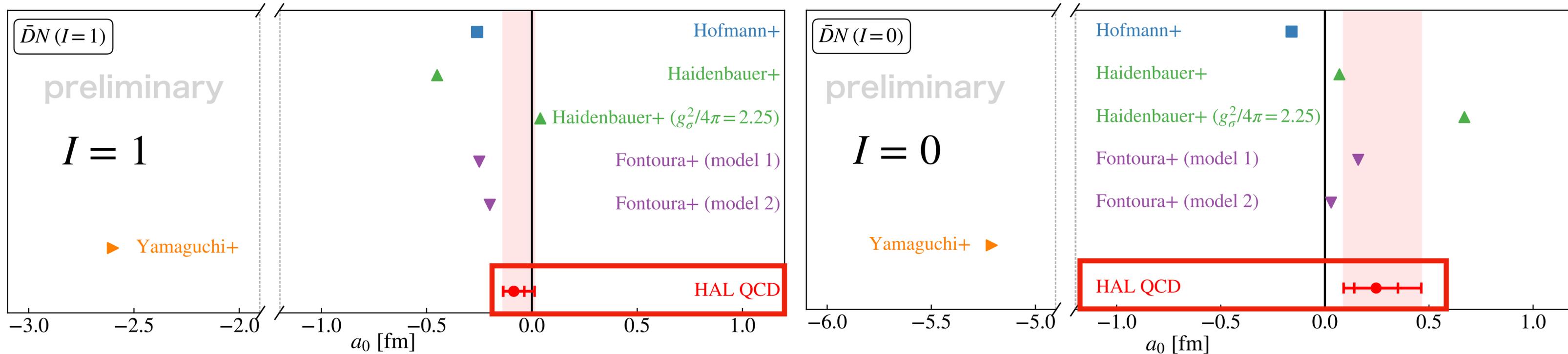
$\bar{D}N$ Phase shifts

- **no bound states or resonances found**

- more attractive behavior compared with KN

Comparison with $\bar{D}N$ phenomenological studies

- scattering lengths a_0

$$k \cot \delta_0(k) = \frac{1}{a_0} + \frac{1}{2} r_{\text{eff}} k^2 + \mathcal{O}(k^4)$$

$\bar{D}N\,(I=1)$

preliminary

$I = 1$

	Hofmann+
	Haidenbauer+
	Haidenbauer+ $(g_\sigma^2/4\pi = 2.25)$
	Fontoura+ (model 1)
	Fontoura+ (model 2)
Yamaguchi+	
	HAL QCD

$\bar{D}N\,(I=0)$

preliminary

$I = 0$

Hofmann+	
Haidenbauer+	
Haidenbauer+ $(g_\sigma^2/4\pi = 2.25)$	
Fontoura+ (model 1)	
Fontoura+ (model 2)	
Yamaguchi+	
HAL QCD	

a_0 [fm]

a_0 [fm]

- same order as those in the models that do not exhibit bound state

- our results can constrain the model parameters?

Summary

- we study S-wave $KN/\bar{D}N$ interactions in lattice QCD
  using HAL QCD method on the physical point

- KN interactions exhibit repulsive behavior in short distance

- KN $I = 1$ phase shifts are larger than experiment

- $\bar{D}N$ is more attractive than KN, which may be a sign of attraction
  attributed to coupling of $\bar{D}^*N$

- our lattice results

- **no resonance or bound state in** KN **and** $\bar{D}N$

Future prospects

- (KN) need estimation of systematics by simulation
  w/ different lattice spacing

- ($\bar{D}N$) $\bar{D}^*N$-$\bar{D}N$ coupled channel analysis might change the results

- (KN, $\bar{D}N$) P-wave calculations (at heavier quark masses)

- meson-nucleon w/ a bottom quark ($BN - B^*N$)