Dbar-N interaction from Lattice QCD at the physical point

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for HAL QCD collaboration

Paper in Prep.

RIKEN iTHEMS, Science Tokyo

The 42nd International Symposium on Lattice Field Theory

$\bar{D}N$ System: Motivation and Features

- $\bar{D} = \bar{c}q$ and $N = qqq$: no $q\bar{q}$ annihilation channel
  Stable two-body system $\Rightarrow$ possible exotic configurations (e.g., pentaquark)
- Heavy Quark Spin Symmetry (HQSS): relatively small mass gap between $\bar{D}$ and $\bar{D}^*$ meson ~ 140 MeV
  $\Leftrightarrow$ Contrast with KN system ~ 400 MeV
  Attraction gained from $\bar{D}N$-$\bar{D}^*N$ coupling?
- Possible bound states (and excited states) with nuclei (extension of kaonic nuclei, HQSS doublets)

  Y.Yamaguchi, S.Yasui, A.Hosaka, Nuclear Phys. A 927 (2014)
- In-medium properties of (anti-)D mesons
  e.g., Mass modifications in nuclear matter

  A. Hayashigaki Phys.Lett. B487 (2000) 96-103
- Scarce experimental data, strong model dependence

Current status: Models and Experiment

- SU(4) WT contact

  J.Hofmann, M.F.M.Lutz, Nucl.Phys. A763 (2005) 90-139, D.Gamermann, et al, Phys.Rev. D81 (2010) 094016

- Meson exchange models (+short range OGE)

  Y. Yamaguchi, et al, Phys.Rev. D 84 (2011) 014032, J.Haidenbauer, et al, Eur.Phys.J. A33 (2007) 107-117

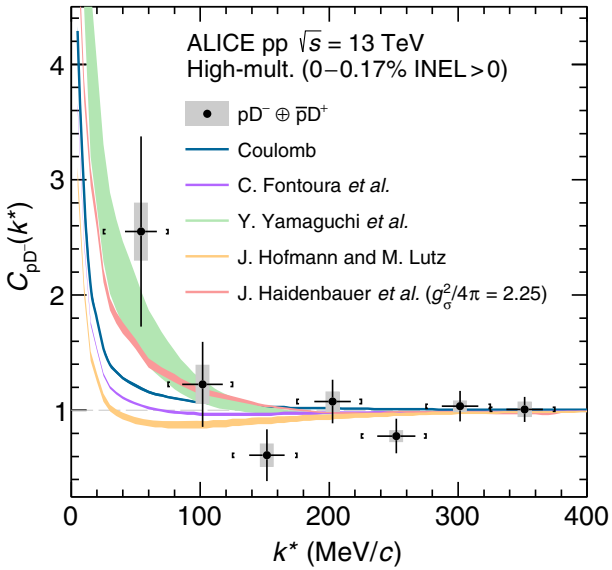
  C.E. Fontoura, et al, Phys.Rev. C 87 (2) (2013) 025206, Y. Yamaguchi, et al, Phys.Rev. D 106, 094001 (2022)

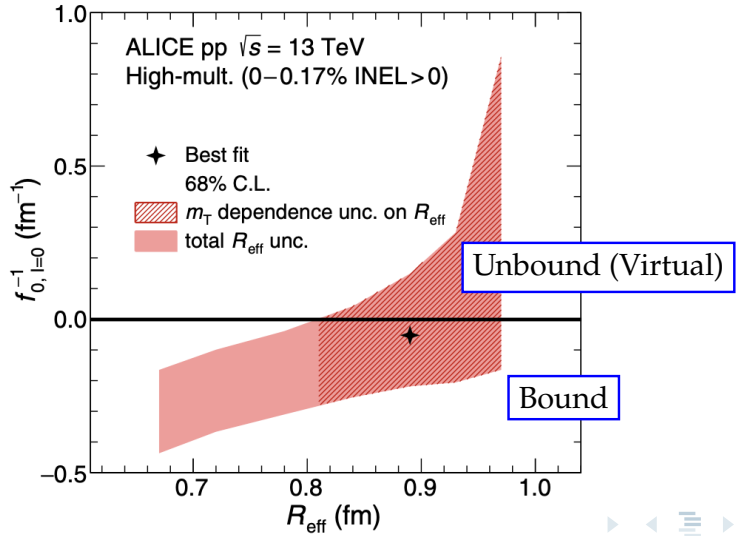
Model	$a_{\bar{D}N}^{I=0}$	$a_{\bar{D}N}^{I=1}$	$a_{\bar{D}}$
SU(4) contact [185]	−0.16	−0.26	−0.24
Meson exchange [194]	0.07	−0.45	−0.32
Pion exchange [192]	−4.38	−0.07	−1.15
Chiral quark model [219]	0.03–0.16	0.20–0.25	0.16–0.23

Tab. from A. Hosaka, et al, Prog.Part.Nucl.Phys. 96 (2017) 88-153

- pD^- momentum correlation from pp collision (ALICE)

S. Acharya et al. ALICE collab. Phys.Rev.D 106 (2022) 5, 052010





HAL QCD Method

N. Ishii, S. Aoki, and T. Hatsuda PRL 99, 022001 (2007)

$$C(t,\vec{r}) = \sum_{\vec{x}} \langle \mathcal{O}_1(t,\vec{x}+\vec{r})\mathcal{O}_2(t,\vec{x})\bar{\mathcal{J}}(0)\rangle = \sum_n A_n \psi(\vec{r};E_n) e^{-E_n t}$$

$$\psi(\vec{r}) \to \frac{\sin(kr - l\pi/2 + \delta(k))}{kr} e^{i\delta(k)} \quad (r \gg R)$$

$$(\nabla^2 + k^2)\psi(\vec{r};E_n) = \int d\vec{r}\,' U(\vec{r},\vec{r}\,')\psi(\vec{r}\,';E_n)$$

- Time-dependent method Ishii et al. (HAL QCD), PLB712, 437(2012)

$$\left[\frac{1+3\delta^2}{8\mu}\frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu}\right] R(t,\vec{r}) = \int d\vec{r}\,' U(\vec{r},\vec{r}\,') R(t,\vec{r}\,')$$

Leading-order of the derivative expansion:

$$U(\vec{r},\vec{r}\,') = V_{\rm LO}(r)\delta^3(\vec{r}-\vec{r}\,') + \mathcal{O}(\nabla^n)$$

- In this study we study $\bar{D}N$ scattering using the LO term of the derivative expansion
- The HAL QCD method reproduces the correct phase shift up to the $\bar{D}^*N$ threshold ($\sim$ 140 MeV above $\bar{D}N$ threshold)

F-conf. Phys. Rev. D 110, 094502 (HAL QCD Collaboration)

- Iwasaki gauge action ($\beta = 1.82$)
- 2+1 flavor, $\mathcal{O}$(a)-improved Wilson quark action
- $V = 96 \times 96^3$ ($L = 8.1$ fm)

$$a = 0.084372(54)(^{+109}_{-6})\ [\text{fm}],$$

- Relativistic heavy-quark action (RHQ)
  - set-I: slightly heavy c quark
  - set-II: slightly light c quark
- Wall source; Sink operators:

Hadron	Experiment [MeV]	Lattice [MeV]
π	138.04	$137.1(0.3)(^{+0.0}_{-0.2})$
K	495.64	$501.8(0.3)(^{+0.0}_{-0.7})$
N	938.92	$939.7(1.8)(^{+0.2}_{-1.7})$
Λ	1115.68	$1121.4(3.6)(^{+0.5}_{-3.7})$
Σ	1193.15	$1202.5(5.6)(^{+0.3}_{-4.0})$
Ξ	1318.29	$1320.7(2.1)(^{+1.5}_{-1.7})$
Ω	1672.45	Input

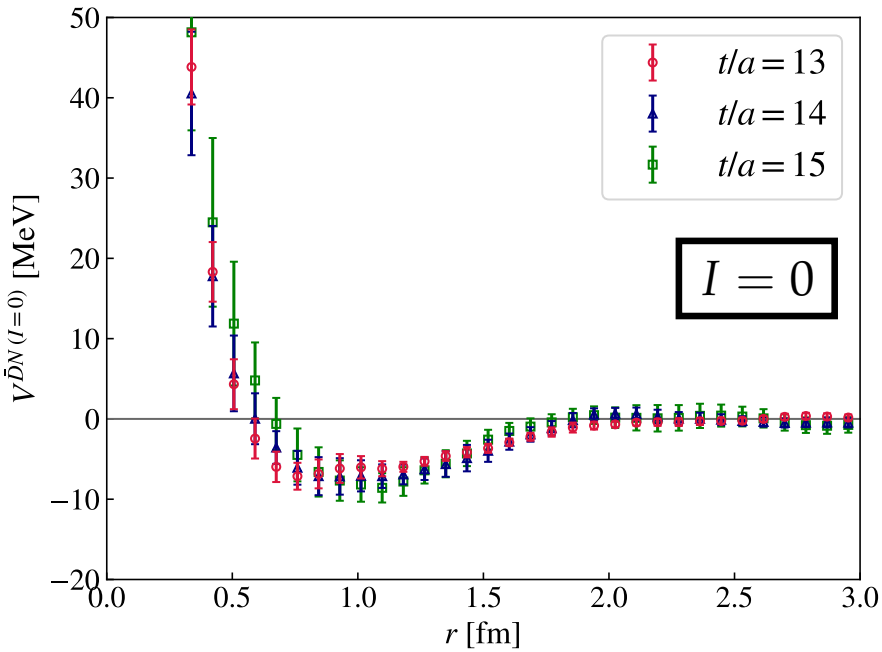
Meson	Set-I [MeV]	Set-II [MeV]	Experiment [MeV]
$\bar{D}$	1880.2 (1)	1854.3 (1)	1864.84 ± 0.05
$\bar{D}^*$	2017.8 (2)	1994.1 (2)	2006.85 ± 0.05

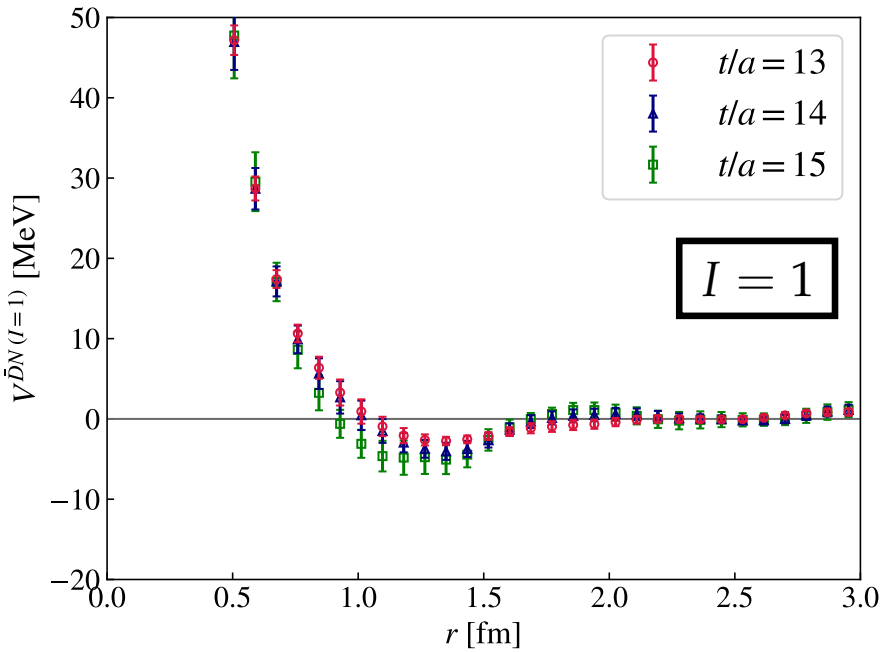
$$\bar{D}_i(x) = \bar{c}(x) i\gamma_5 q_i(x), \quad N_{\alpha,i}(x) = \varepsilon_{abc} \left[u^a(x)^T C\gamma_5 d^b(x) \right] q^c_{\alpha,i}(x)$$

- 360 configs × 96 source pos × 4 rotations × 2 directions of propagation
- A_1^+ projection + Misner method (T. Miyamoto et al., Phys. Rev. D 101, 074514 (2020))
  Suppresses $l = 4, 6, \ldots$ (e.g., Laplacian-induced contamination)

$\bar{D}N$ potential (LO term)

$$V_{\mathrm{LO}}(r) = R(\vec{r},t)^{-1}\left[\frac{1+3\delta^2}{8\mu}\partial_t^2 - \partial_t - H_0\right]R(\vec{r},t)$$

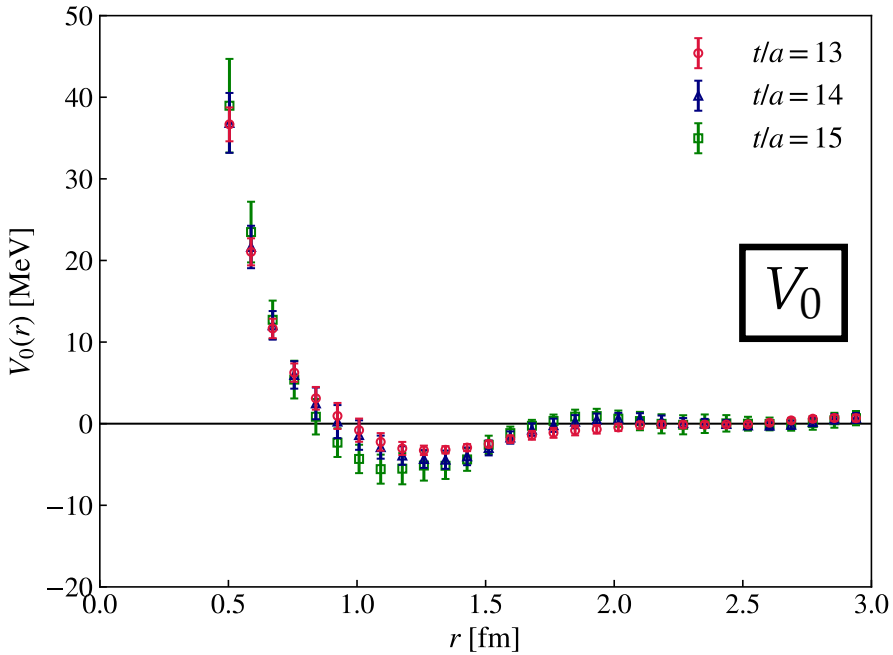


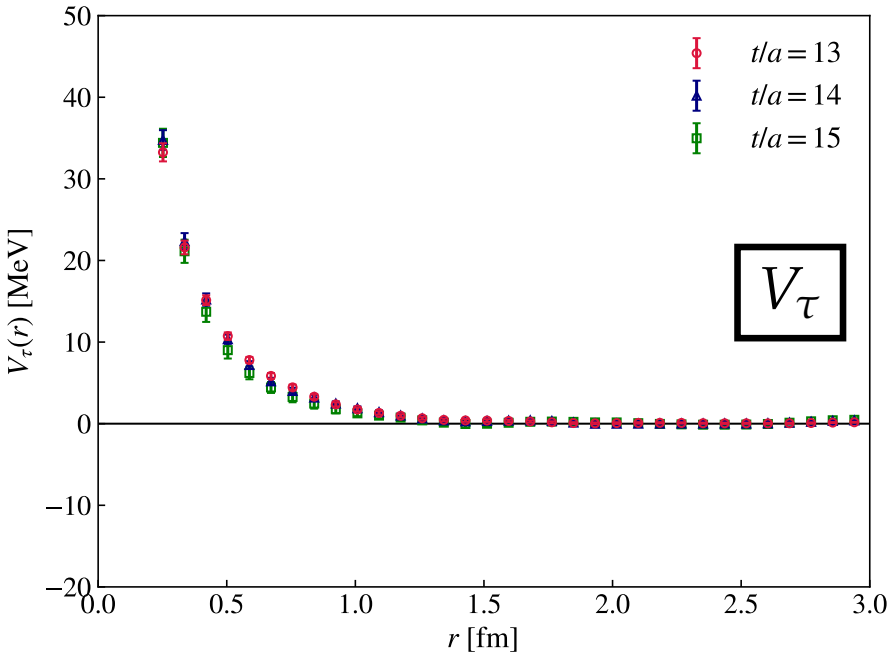


- t-dependence controlled within statistical fluctuations for time slices $t/a = 13$-15
- Repulsive core + Weak attractive pocket (stronger attraction in $I = 0$ channel)

Decompose into isospin-indept and isospin-dependent components:

$$V_{\mathrm{LO}}(r) = V_0(r) + V_\tau(r)\vec{\tau}_{\bar{D}} \cdot \vec{\tau}_N$$





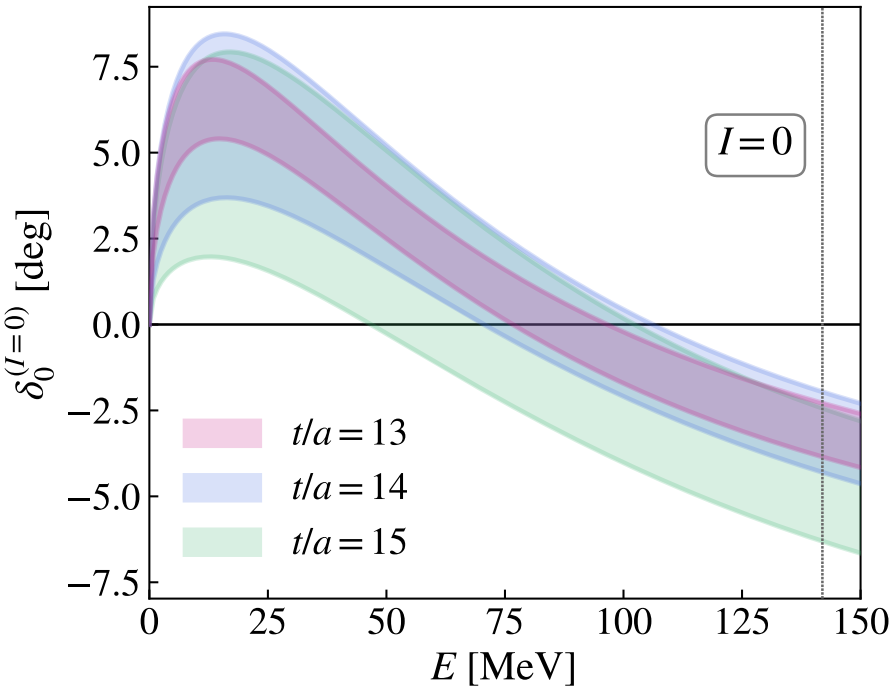
- V_0 attractive pocket, V_τ totally positive
- Attraction from iso-singlet component (e.g., $\pi\pi$, σ- exchange) in meson exchange picture?

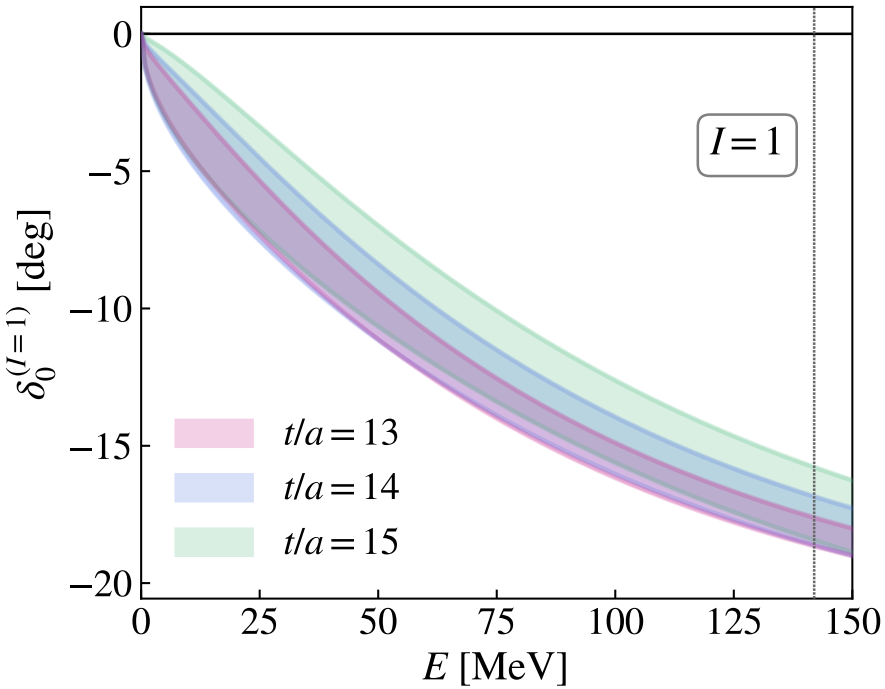
  Qualitatively agree with the results of EFTs: J.Haidenbauer, et al, Eur.Phys.J. A33 (2007) 107-117, Y. Yamaguchi, et al, Phys.Rev. D 106, 094001 (2022)

S-wave Phase shift $\bar{D}N$ (4-Gauss Potential Fit)

Purely phenomenological fit (4-Gauss)

$$V_{\text{fit}}^{\text{4G}}(r) = \sum_{i=1}^{4} a_i \exp(-b_i^2 r^2)$$





- Attraction in $I = 0$, repulsion in $I = 1$
- No bound states found

  (Virtual pole found $\sim$ 30 MeV in the $I = 0$ channel)

S-wave Phase shift $\bar{D}N$ (TPE-motivated fit)

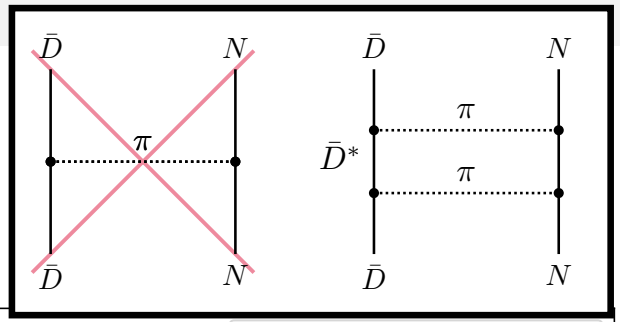
TPE-motivated fit (OPE forbidden by parity conservation)

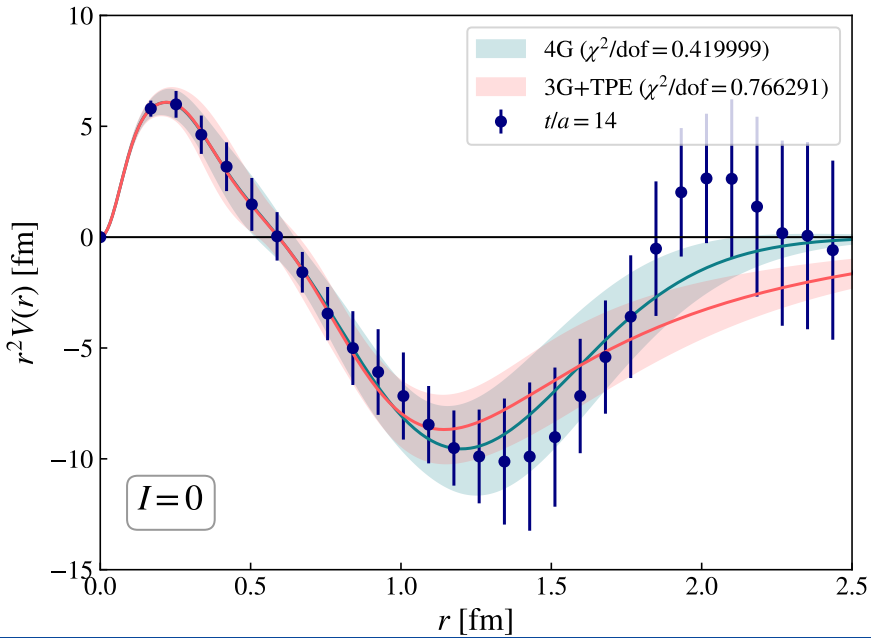
J.Tarru Castellá and G.a.Krein, Phys.Rev.D 98 (2018) 1, 014029

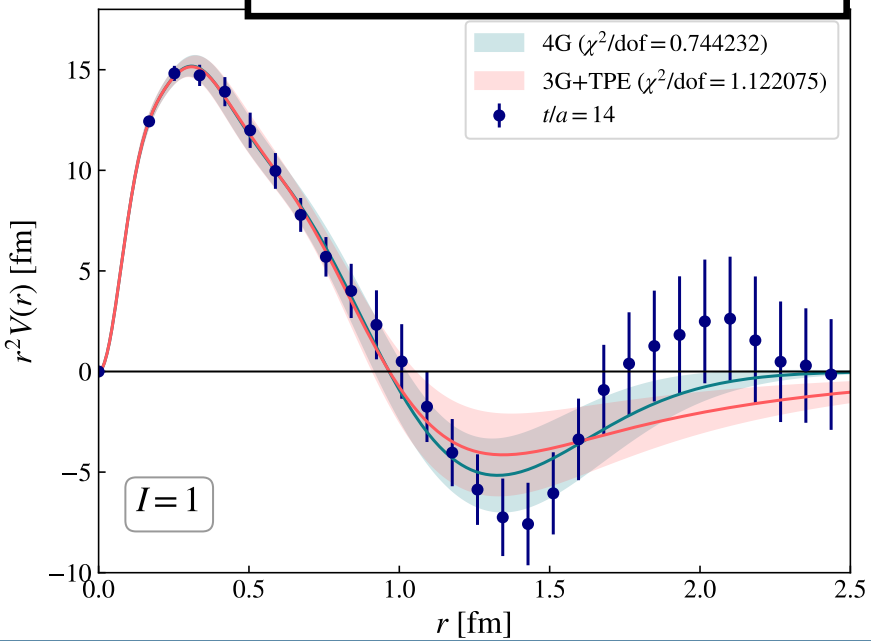
$$V_{\text{fit}}^{\text{3G+TPE}}(r) = \sum_{i-=1}^{3} a_i \exp(-b_i^2 r^2) + a^{\text{TPE}}(1-\exp(-\Lambda^2 r^2))^2 \frac{e^{-2m_\pi r}}{r^2}$$

- common exponents for short-range region

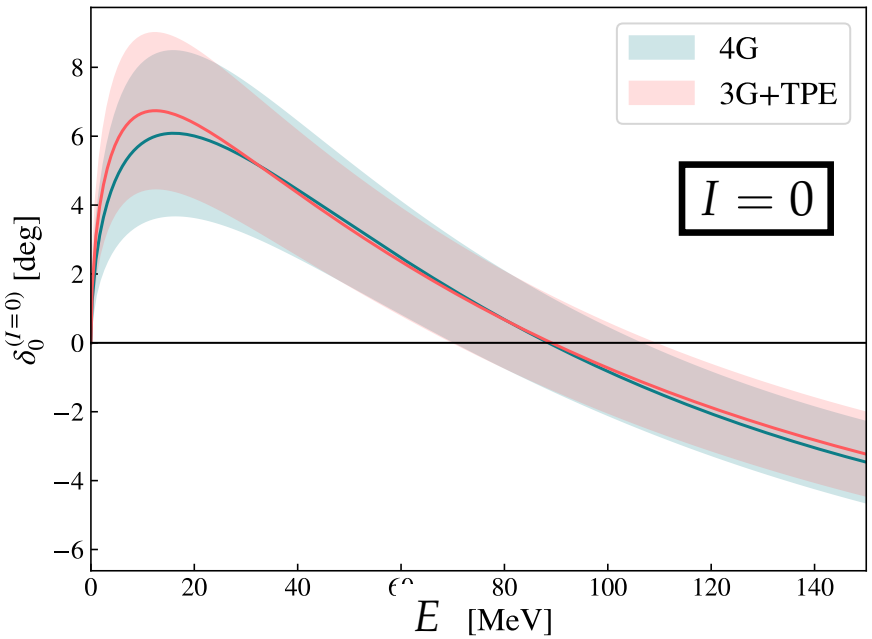
  i.e., $b_1^{(4G)} = b_1^{(3G+TPE)}$, $b_2^{(4G)} = b_2^{(3G+TPE)}$

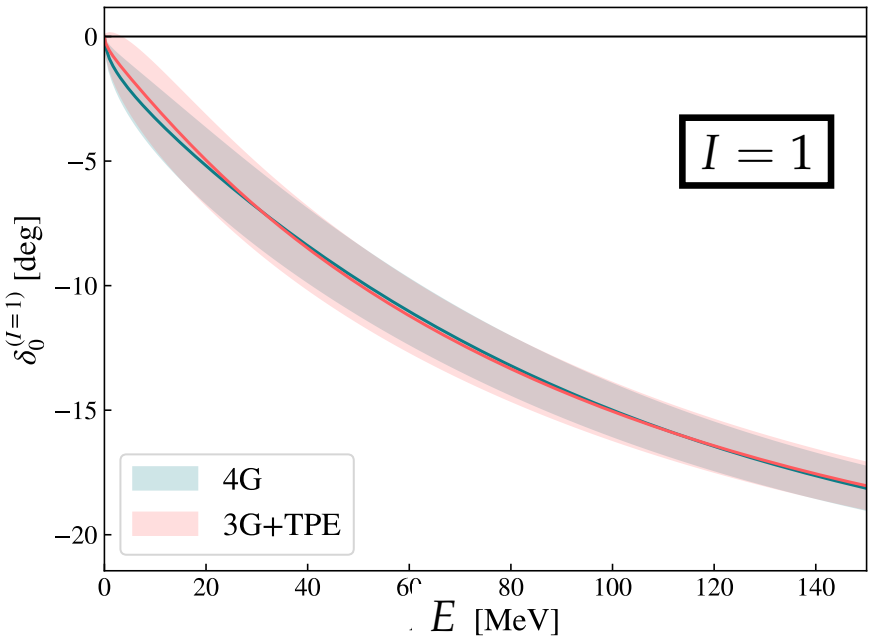






S-wave Phase shift $\bar{D}N$ (TPE-motivated fit)





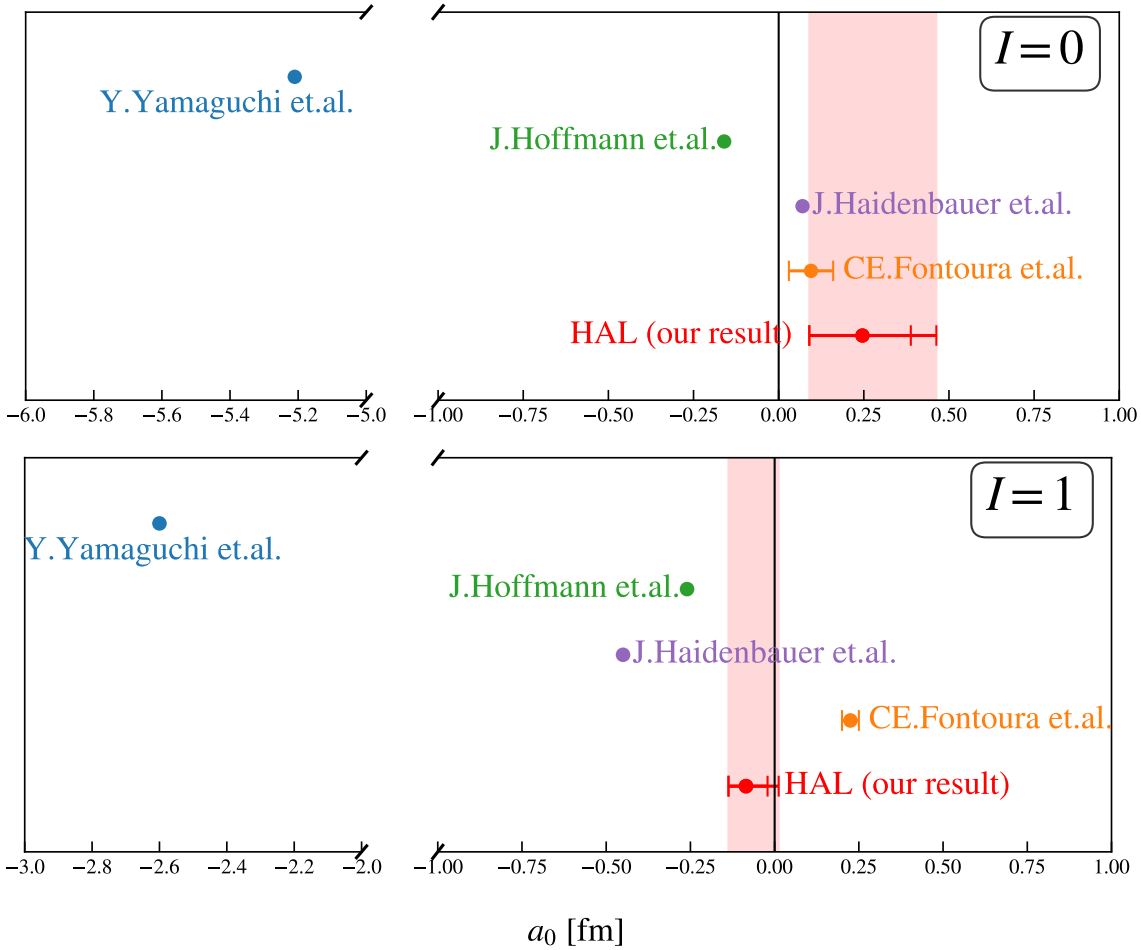
- Discrepancy in the low energy region
- TPE motivated fit: increase of scattering length by $\sim 30\%$ in both channels

Scattering lengths
(stat. err. + timeslice dept.(13-15) + diff. between two potential fits)

$$a_0^{I=0} = 0.246 \pm 0.105(^{+0.112}_{-0.051})\ \text{fm}$$
$$a_0^{I=1} = -0.086 \pm 0.050(^{+0.049}_{-0.001})\ \text{fm}$$

Scattering length vs EFTs

J.Hofmann, M.F.M.Lutz, Nucl.Phys. A763 (2005) 90-139, J.Haidenbauer, et al, Eur.Phys.J. A33 (2007) 107-117, C.E. Fontoura, et al, Phys.Rev. C 87 (2) (2013) 025206, Y. Yamaguchi, et al, Phys.Rev. D 106, 094001 (2022)



- In the context of EFT, $I = 1$ channel is more sensitive to the coupling between σ and $\bar{D}$ (which is unknown)

Finite Volume Energy and Effective Mass

Check of the systematics from LO truncation of the interaction kernel $U(\vec{r},\vec{r}')$

- Solve schrödinger equation in FV with LO potential

JHEP 03, 007, arXiv:1812.08539

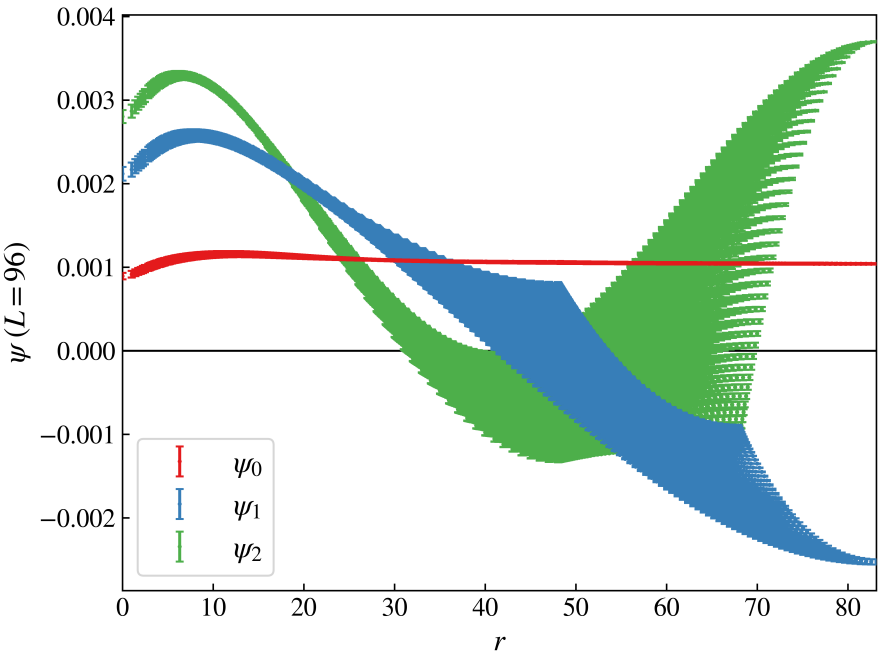
$$H\psi_n(\vec{r}) = E_n^{\mathrm{LO}}\psi_n(\vec{r}), \qquad H = -\nabla^2/2\mu + V_{\mathrm{LO}}^{\mathrm{fit}}(r)$$

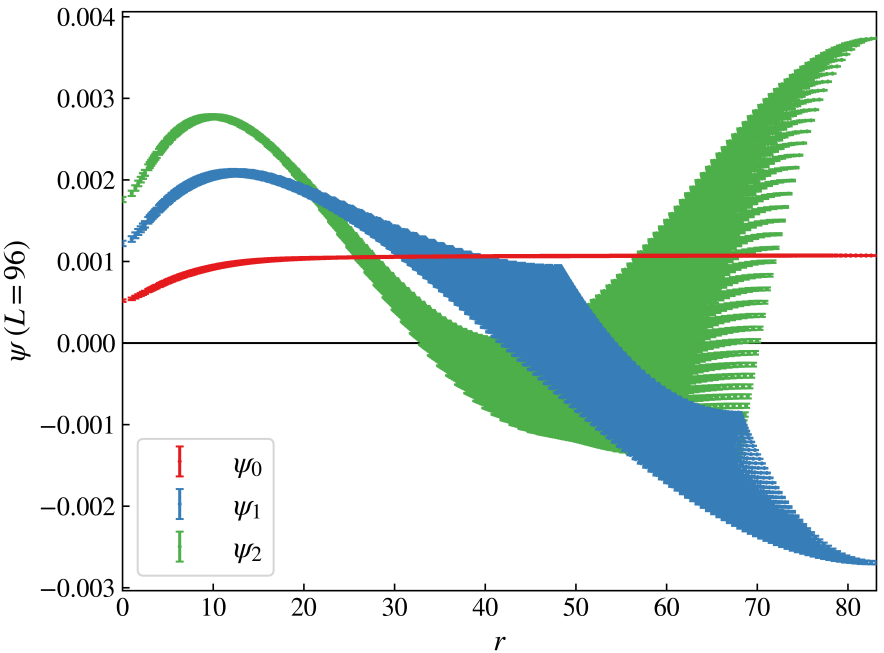
- Effective mass from (projected/unprojected) R-correlators

$$E_0^{\mathrm{eff}}(t) = \frac{1}{a}\log\left[\frac{R^{(\mathrm{opt})}(t)}{R^{(\mathrm{opt})}(t+1)}\right]$$

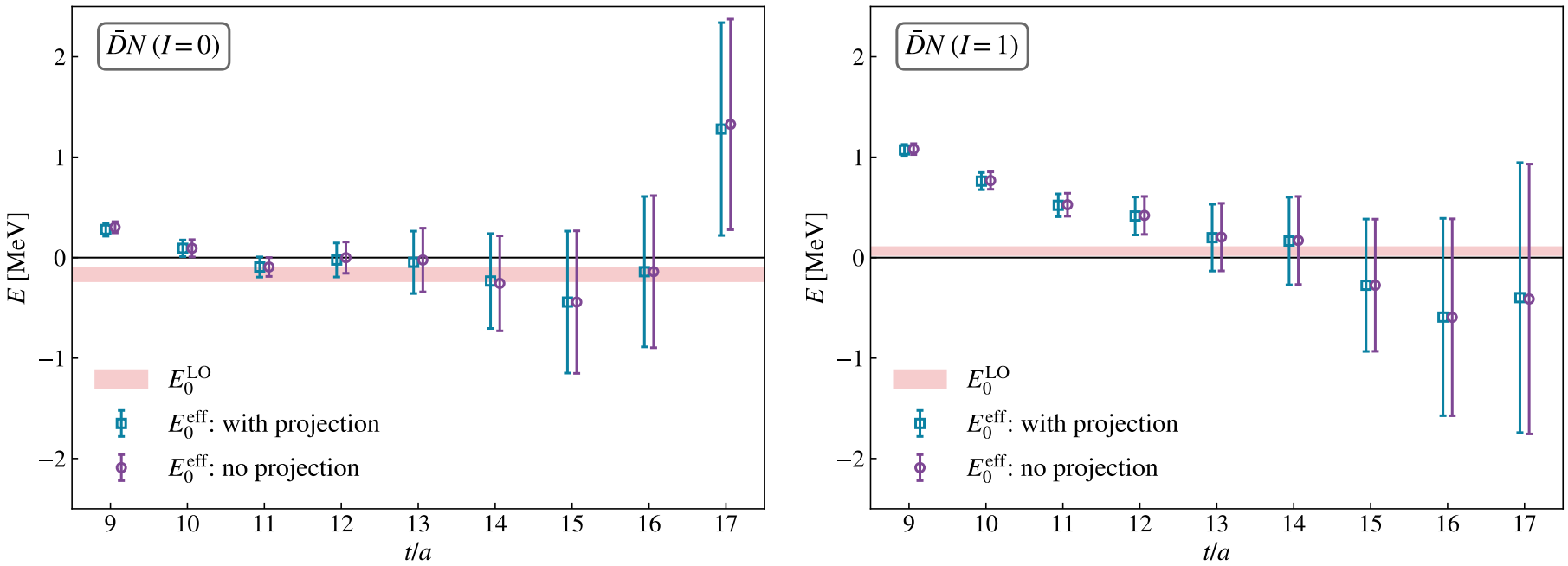
$$R(t) = \sum_{\vec{x}} R(\vec{x},t), \qquad R_0^{\mathrm{opt}}(t) = \sum_{\vec{x}} \psi_0^\dagger(\vec{x})R(\vec{x},t)$$

solutions for the 4-Gauss potential





Ground state energy level in FV



- GS projection on the R-correlator does not change result
  $\rightarrow$ Strong ground-state overlap in the R-correlator
- Energy level of the leading-order potential lies well within statistical error of the energy level obtained directly from the R-correlators

Summary and Outlook

- $\bar{D}N$ system: relevance for pentaquark states, charmed nuclei, ...
- Very limited experimental input $\Rightarrow$ lattice QCD is essential
- This work: LO analysis in derivative expansion
  - Attraction of potential may come from meson exchange (isospin-singlet components)
  - Attractive phase shift (at low energy) in $I = 0$, repulsive in $I = 1$
  - No bound states observed in either $I = 0$ or $I = 1$ channels
  - Systematic uncertainties estimated via 4G vs. 3G+TPE
  - FV energy levels consistent with R-correlator effective masses $\rightarrow$ LO truncation effects are under control

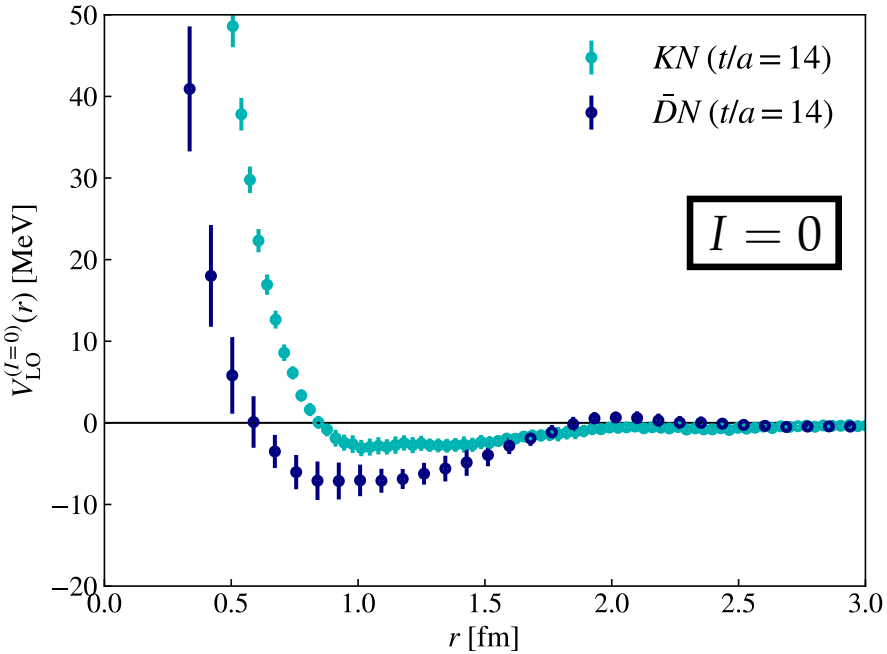
- Coupled-channel analysis of $\bar{D}N$–$\bar{D}^*N(\bar{D}\pi N)$ system
- $\bar{D}^*N$ in s-wave $I(J^P) = 0(3/2^-)$ Possible Feshbach resonance?

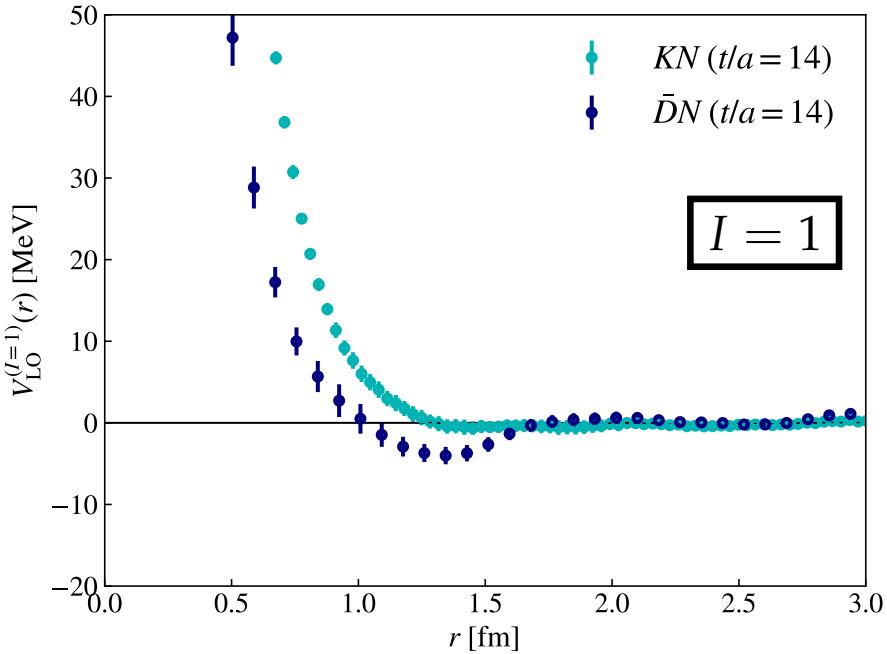
  Phys. Rev. D 84, 014032 (2011)
- Possible $\bar{D}_sN$ bound state? Phys. Rev. D 112 7, 074026 (2025)
- Study of multi-body systems ($\bar{D}NN$, $\bar{D}A$), Femtoscopy
- Extension to BN–B^*N system

vs KN potential ($t/a = 14$)

Comparison to KN LO potential (Same configuration, same statistics)

KN data: K. Murakami et.al. (HALQCD) arXiv:2509.00838



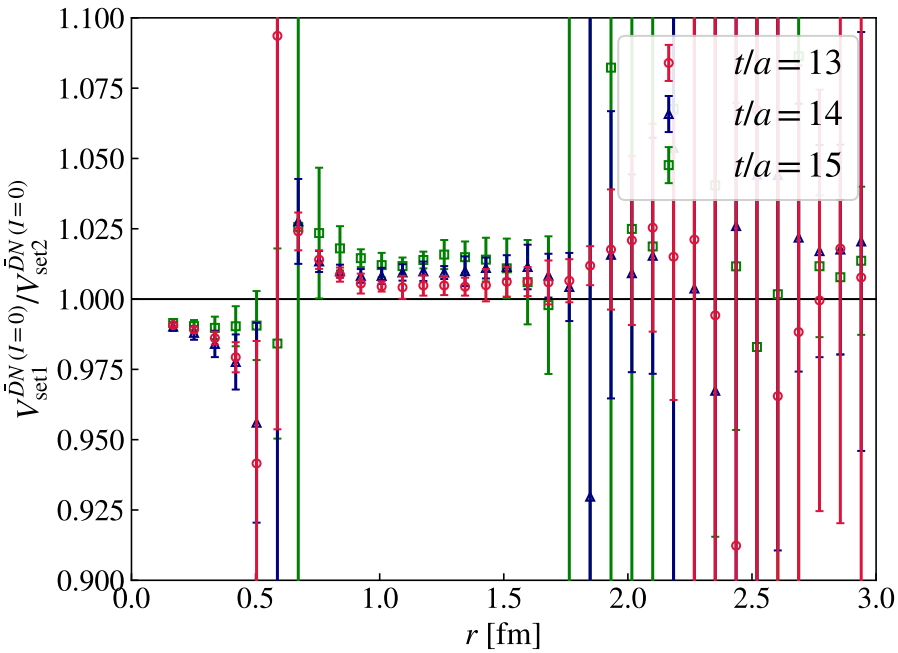


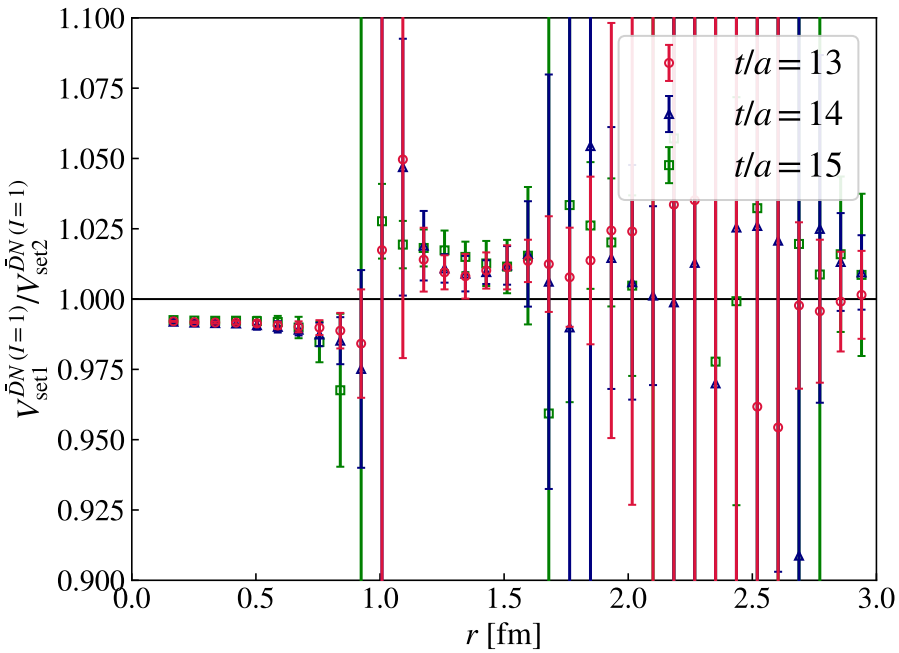
- $\bar{D}N$ is more attractive than KN
- Possible sign of effective attraction generated by the coupling to the $\bar{D}^*N$ channel?

  Results from J.Haidenbauer, et al, Eur.Phys.J. A33 (2007) 107-117 imply that the $\bar{D}N$ gains more attraction via $\bar{D}^*N$ coupling than the KN case.

LO HAL Potential: m_c dependence

$V_{\rm LO}(r)$: set-I vs set-II





$$V_{\text{set-I}}/V_{\text{set-II}}(I=0) = 1.0115(9) \quad V_{\text{set-I}}/V_{\text{set-II}}(I=1) = 1.010(3)$$

- Heavier the D meson mass, the more attractive cf. $m_D^{\text{set-I}}/m_D^{\text{set-II}}$=1.014
- Linear interpolation to physical D_0 mass

Mass shift of $\bar{D}$ with Linear Density Approximation

- Linear Density Approximation

$$\Delta m_{\bar{D}} = -2\pi \frac{m_N + m_{\bar{D}}}{m_N m_{\bar{D}}} \rho_N \bar{a}_0, \quad \bar{a}_0 = \frac{1}{4} a_0^{(I=0)} + \frac{3}{4} a_0^{(I=1)}$$

Input HAL scattering amplitude:

$$\Delta m_{\bar{D}}^{(4G)} \sim +0.14\ \text{MeV} \quad \Delta m_{\bar{D}}^{(3G+TPE)} \sim -2.7\ \text{MeV}$$

Analysis	Ref.	Mass shift of $\bar{D}$ (MeV)	Density ρ (fm^{-3})
QMC model (QMC: quark-meson coupling)	[18]	−62 **attractive**	0.15
QCD sum rule	[19]	-48 ± 8 **attractive**	0.17
	[23]	+45 (averaged mass shift of D and $\bar{D}$) **repulsive**	0.15
	[28]	-46 ± 7 (averaged mass shift of D and $\bar{D}$) **attractive**	0.17
	[30]	−72 (averaged mass shift of D and $\bar{D}$) **attractive**	0.17
	[31]	+38 **repulsive**	0.17
Coupled channel analysis	[21]	+18 **repulsive**	0.17
	[22]	+(11–20) **repulsive**	0.16
	[26]	+35 **repulsive**	0.17
	[15]	$\simeq -$(20–27) **attractive**	0.17
Chiral effective model	[20]	$\simeq -$(30–180) **attractive**	0.15
	[25]	−27.2 **attractive**	0.15
	[16]	−35.1 **attractive**	0.17
	[37]	+97 (parity doublet model), +120 (skyrmion crystal) **repulsive**	0.16
	Our result*	+74 **repulsive**	0.095

*D. Suenaga, S. Yasui., M. Harada, Phys. Rev. C96, 015204 (2017) [See this paper for the reference numbers.]

Yasui-san's slide