$\bar{D}N$ Scattering at Physical Point by the HAL QCD Method

Wren Yamada

RIKEN Center for Interdisciplinary Theoretical and Mathematical Sciences
(RIKEN iTHEMS)

Collaboration with: Yan Lyu, Kotaro Murakami, Takumi Doi
(and other HAL QCD members)

MULTI-PARTICLE 25

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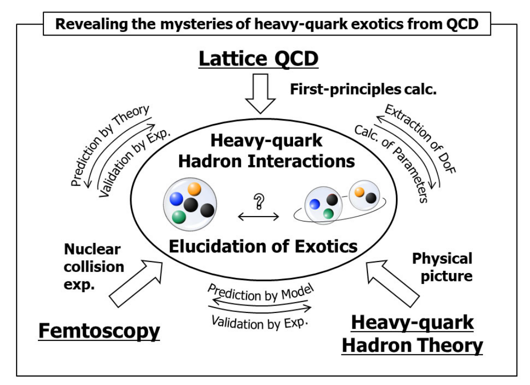
Zooming out a little bit...



T. Doi-san's KIBAN(S) abstract `https://www.jsps.go.jp/.../23h05439.pdf`

HAL QCD works:

- $J/\psi N$-$\eta_c N$ ($m_\pi = 146$ MeV) Yan Lyu et al, Phys.Lett.B 860 (2025) 139178
- $\Omega_{ccc}N$, $\Lambda_c N$ ($m_\pi = 137$ MeV) L. Zhang et al
- $\bar{D}N$ ($m_\pi = 137$ MeV) WY et al, In prep. ← This work

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

- $\bar{D} = \bar{c}q$ and $N = qqq$: no $q\bar{q}$ annihilation channel
  $\Rightarrow$ Stable two-body system; possible exotic configurations (e.g., pentaquark?) cf. T_{cc}, P_c
- Heavy Quark Spin Symmetry (HQSS): relatively small mass gap between $\bar{D}$ and $\bar{D}^*$ meson
  $\Rightarrow$ Contrast with KN system (e.g., Θ^+)
- In-medium properties of (anti-)D mesons:
  - Mass modifications in nuclear matter
  - Possible bound states (and excited states) with nuclei (extension of kaonic nuclei, HQSS doublets)
  - QCD Kondo effect in charm sector?
- Toward heavy-flavor analogues: extension to BN interactions
- 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)

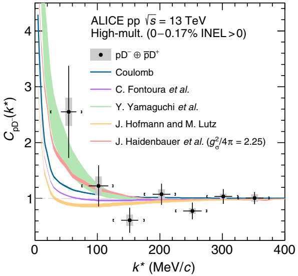
Y. Yamaguchi, et al, Phys.Rev. D 84 (2011) 014032, J.Haidenbauer, et al, Eur.Phys.J. A33 (2007) 107-117
C.E. Fontoura, et al, Phys.Rev. C 87 (2) (2013) 025206, Y. Yamaguchi, et al, Phys.Rev. D 106, 094001 (2022)

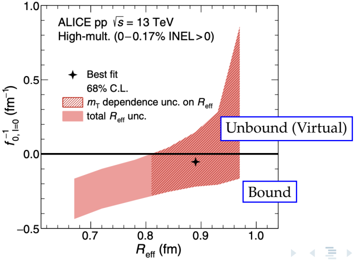
Model	$a^{I=0}_{\bar{D}N}$	$a^{I=1}_{\bar{D}N}$	$a_{\bar{D}}$
SU(4) contact [185]	−0.16	−0.26	−0.24
Meson exchange [194]	0.07	−0.45	−0.32
Pion exchange [192]	−4.38	−0.07	−1.15
Chiral quark model [219]	0.03–0.16	0.20–0.25	0.16–0.23

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

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

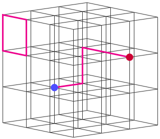
S. Acharya et al. ALICE collab. Phys.Rev.D 106 (2022) 5, 052010

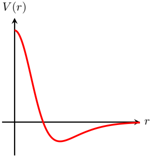


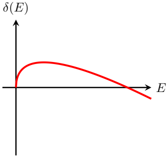


HAL QCD Method

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







$\langle \mathcal{O}(t)\mathcal{O}(0)\rangle$ ⟶ Potential ⟶ Phase Shift

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

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

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

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

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

Setup

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

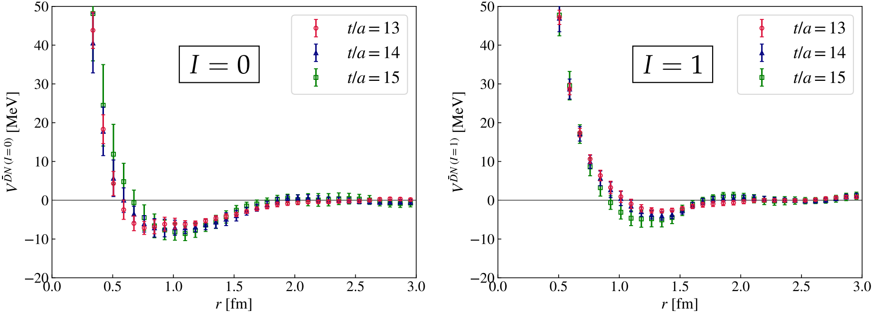
$$\bar{D}_i(x) = \bar{c}(x) i\gamma_5 q_i(x), \quad N_{\alpha,i}(x) = \varepsilon_{abc}\left[u^a(x)^T C\gamma_5 d^b(x)\right] q^c_{\alpha,i}(x)$$

- 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)

Leading-order of the derivative expansion:

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

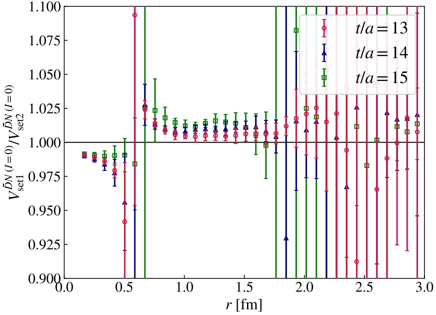
LO potential (set-I):

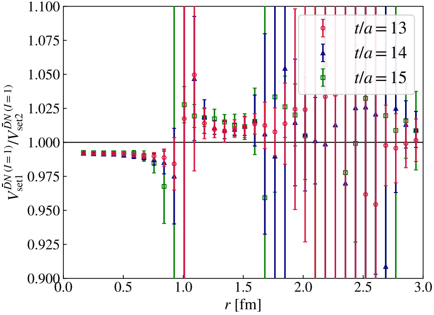


- t-dependence controlled within statistical fluctuations
- Repulsive core + Weak attractive pocket (stronger for $I = 0$)

LO HAL Potential: m_c dependence

$V_{\mathrm{LO}}(r)$: 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

Fitting

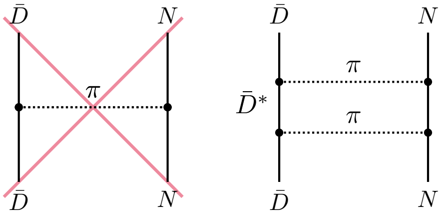
- Fit A: purely phenomenological fit

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

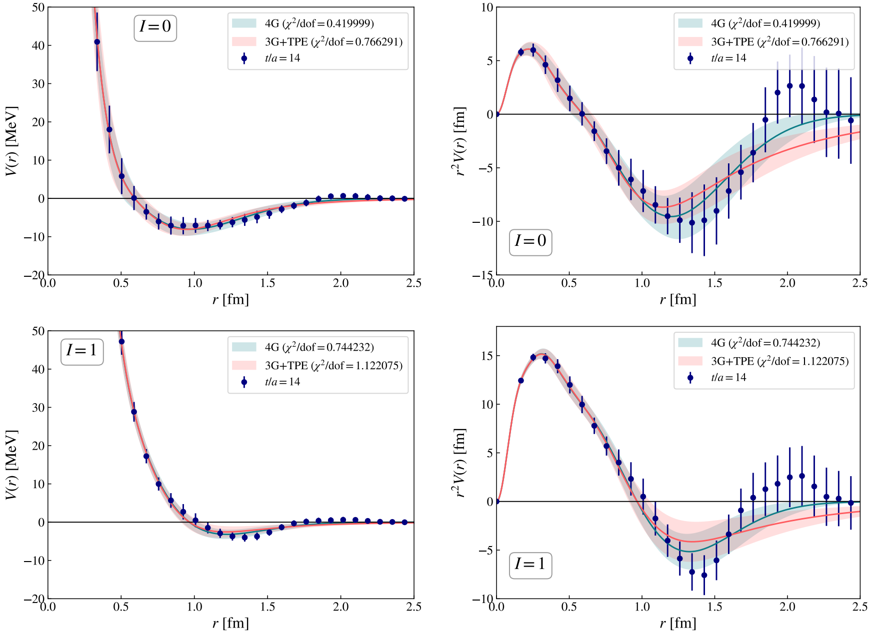
- Fit B: TPE-motivated fit (OPE forbidden by parity conservation)

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

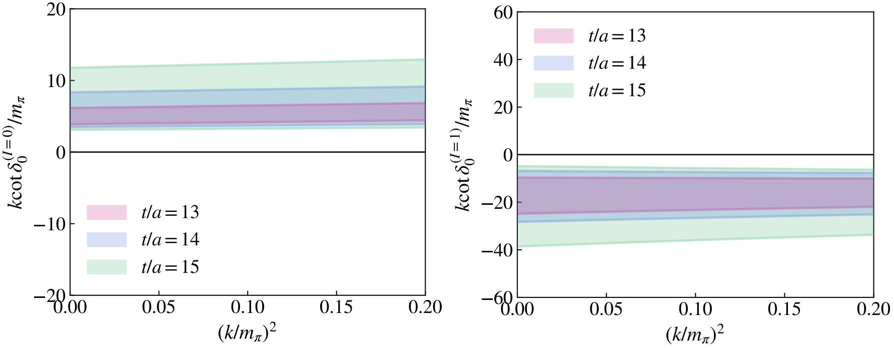
$$V_{\rm fit}^{\rm 3G+TPE}(r) = \sum_{i-=1}^{3} a_i \exp(-b_i^2 r^2) + a^{\rm TPE}(1 - \exp(-\Lambda^2 r^2))^2 \frac{e^{-2m_\pi r}}{r^2}$$



Fitting: Example $t/a = 14$



s-wave Phase Shift (Fit A)



- t-dependence controlled within statistical fluctuations
- $I = 0$ weak attraction, $I = 1$ weak repulsion
- No bound state (or virtual state) in both channels

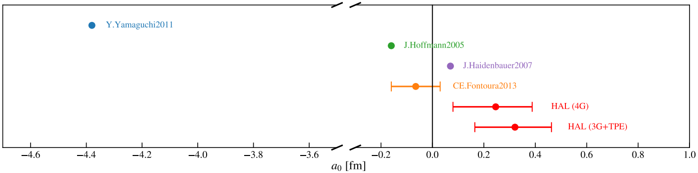
$$k\cot\delta_0 = \frac{1}{a_0} + \frac{1}{2}r_0k^2 + \mathcal{O}(k^4)$$

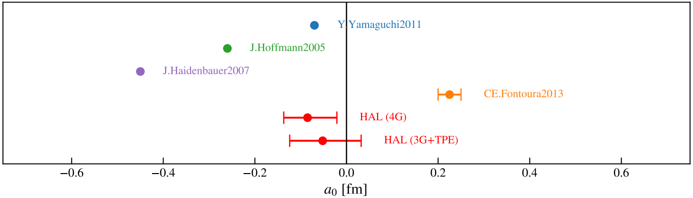
- Fit A

$$a_0^{I=0} = 0.246 \pm 0.105(^{+0.037}_{-0.051})\ \mathrm{fm} \quad a_0^{I=1} = -0.085 \pm 0.050(^{+0.014}_{-0.002})\ \mathrm{fm}$$

- Fit B

$$a_0^{I=0} = 0.321 \pm 0.116(^{+0.026}_{-0.040})\ \mathrm{fm} \quad a_0^{I=1} = -0.052 \pm 0.071(^{+0.013}_{-0.001})\ \mathrm{fm}$$





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

Finite Volume Energy and Effective Mass

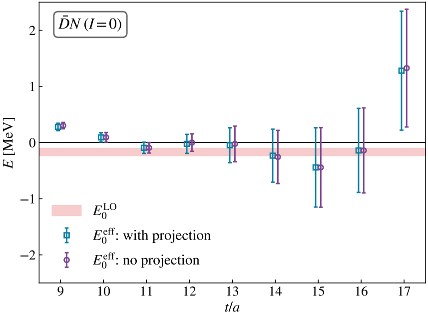
- LO HAL QCD potential in FV

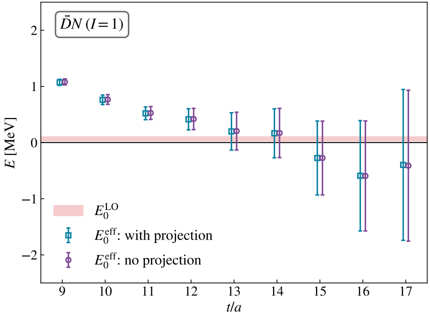
$$H\psi_n(\vec{r}) = E_n^{\mathrm{LO}}\psi_n(\vec{r}), \qquad H = -\nabla^2/2\mu + V_{\mathrm{LO}}^{4\mathrm{G}}(r)$$

- Effective mass:

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

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





- Energy level of LO HAL QCD potential (4G) lies well within statistical error
- GS projection on the R-correlator does not change result
  → Strong ground-state overlap in the R-correlator

Summary

- $\bar{D}N$ system: relevance for pentaquark states, charmed nuclei, ...
- Very limited experimental input $\Rightarrow$ lattice QCD is essential
- This work: LO analysis in derivative expansion using fitted potential
  - Attractive interaction 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 fits
    $\rightarrow$ relatively small compared to model dependence
  - FV energy levels consistent with R-correlator effective masses
    $\rightarrow$ LO truncation effects are under control

- Coupled-channel analysis of $\bar{D}N$–$\bar{D}^*N$ system
  $\rightarrow$ essential for explaining the attraction
- Study of multi-body systems ($\bar{D}NN$, $\bar{D}A$) via HAL QCD potential
- Possible Coulomb-assisted bound states?
- Extension to BN–B^*N system