Low-Energy Dbar-N Scattering from Physical-Point Lattice QCD

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for HAL QCD collaboration

arXiv:2603.12251*

RIKEN iTHEMS, Science Tokyo

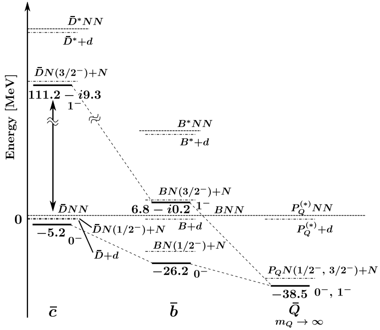
The 43rd International Symposium on Lattice Field Theory

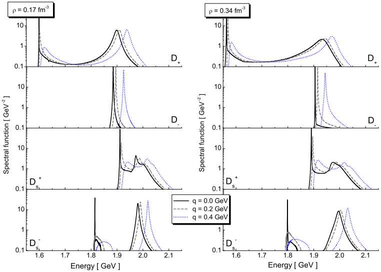
- $\bar{D} = \bar{c}q$ and $N = qqq$: no $q\bar{q}$ annihilation channel
  possible exotic configurations (e.g., pentaquark)
- Possible bound states (and excited states) with nuclei
  (extension of kaonic nuclei, HQSS doublets)

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





- 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)

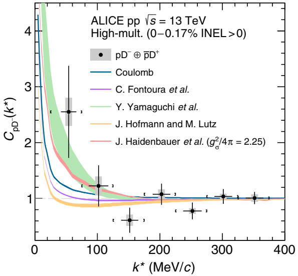
Y. Yamaguchi, et al, Phys.Rev. D 84 (2011) 014032, J.Haidenbauer, et al, Eur.Phys.J. A33 (2007) 107-117
C.E. Fontoura, et al, Phys.Rev. C 87 (2) (2013) 025206, Y. Yamaguchi, et al, Phys.Rev. D 106, 094001 (2022)

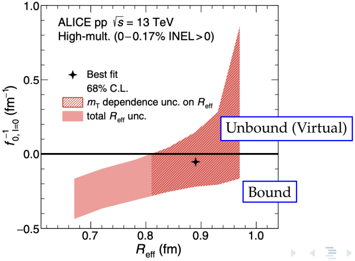
Model	$a^{I=0}_{\bar{D}N}$	$a^{I=1}_{\bar{D}N}$	$a_{\bar{D}}$
SU(4) contact [185]	−0.16	−0.26	−0.24
Meson exchange [194]	0.07	−0.45	−0.32
Pion exchange [192]	−4.38	−0.07	−1.15
Chiral quark model [219]	0.03–0.16	0.20–0.25	0.16–0.23

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





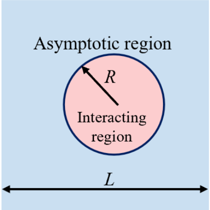
N. Ishii, S. Aoki, and T. Hatsuda PRL 99, 022001 (2007)

Ishii et al. (HAL QCD), PLB712, 437(2012)

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

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

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



- Time-dependent method

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

Leading-order of the derivative expansion:

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

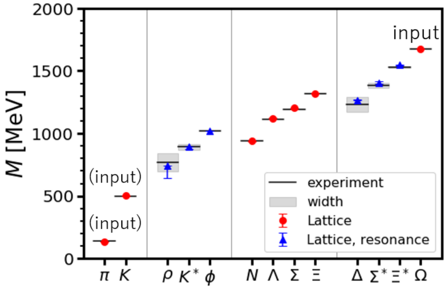
$$V_{\rm LO}(r) = R(\vec{r},t)^{-1}\left[\frac{1+3\delta^2}{8\mu}\partial_t^2 - \partial_t - H_0\right] R(\vec{r},t) \longrightarrow \boxed{\delta(k)}$$

"HAL-conf-2023" 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:

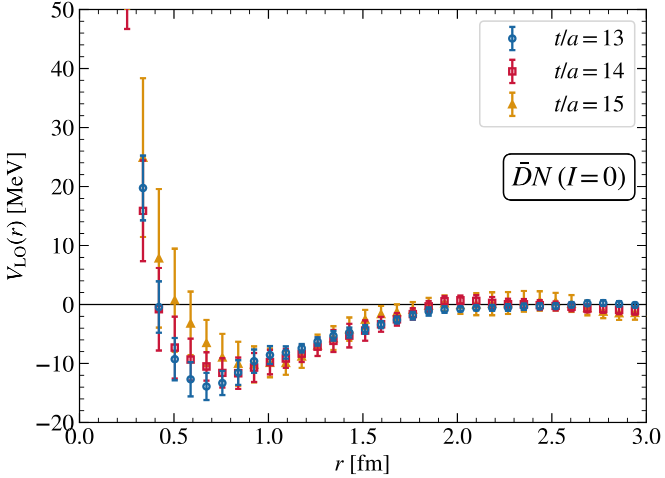


$$\boxed{m_\pi = 137 \text{ MeV}}$$

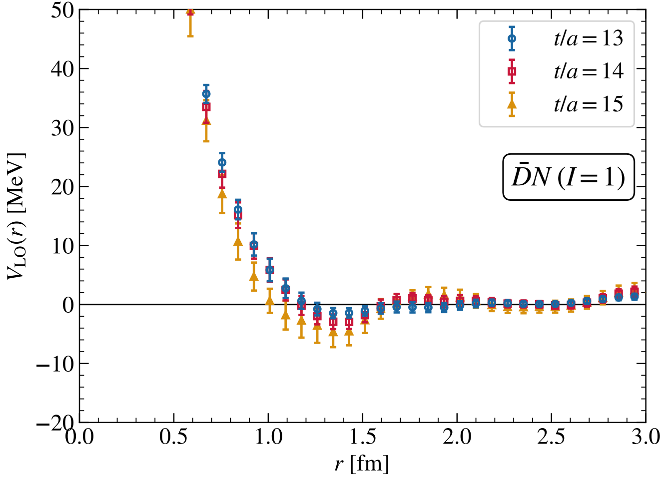
$$\bar{D}_i(x) = \bar{c}(x) i\gamma_5 q_i(x), \quad N_{\alpha,i}(x) = \varepsilon_{abc}\left[u^a(x)^T C\gamma_5 d^b(x)\right] q^c_{\alpha,i}(x)$$

- 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

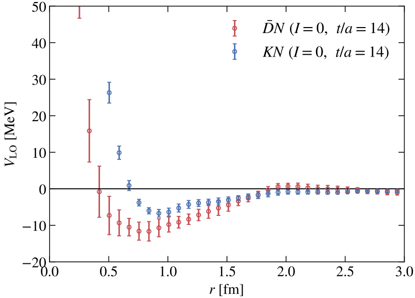


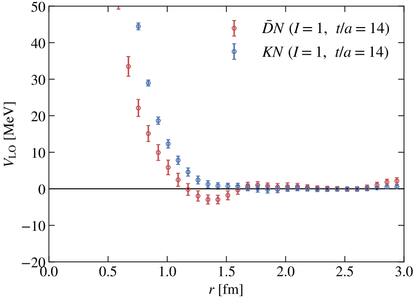
$\bar{D}N$ potential



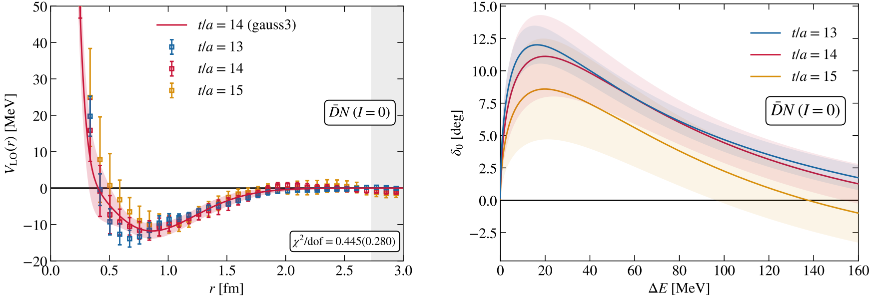
- Stronger attraction in $\bar{D}N$ system than KN (strange analog)
  J. Haidenbauer, G. Krein, U.-G. Meissner, A. Sibirtsev, Eur. Phys. J. A 33 (2007)

- Lattice calculation at physical point
  K. Murakami et. al., (HAL QCD), Phys. Rev. D 113 (2026)
  K. Murakami's talk (Fri 31st, 15:20-)
  same configs, statistics





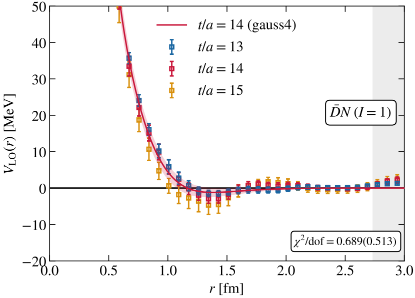
3-gaussian fit

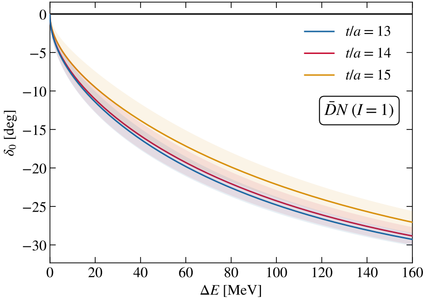


	a0 [fm]	r0 [fm]
t/a=13	0.519 (92)	4.88 (36)
t/a=14	0.425 (163)	4.53 (76)
t/a=15	0.320 (164)	5.56 (189)

- Small attraction, no bound state

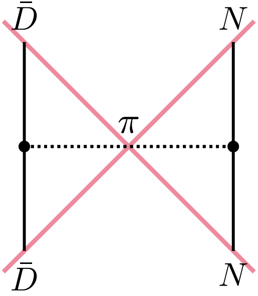
4-gaussian fit

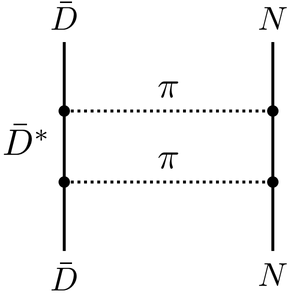




	a0 [fm]	r0 [fm]
t/a=13	-0.242 (41)	0.62 (105)
t/a=14	-0.234 (46)	0.63 (109)
t/a=15	-0.197 (60)	1.11 (222)

- Totally repulsive, no bound state



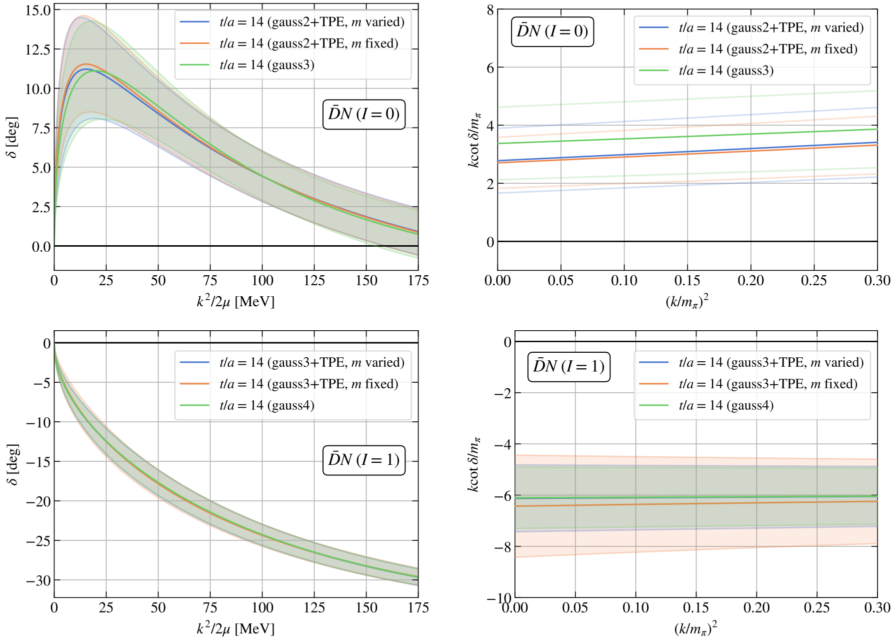


TPE-motivated fit (OPE forbidden by parity conservation)

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

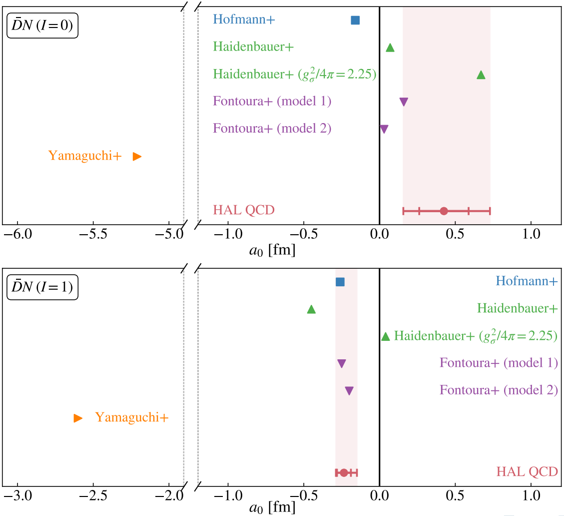
$$V_{\text{fit}}^{\text{3G+TPE}}(r) = \sum_{i-=1}^{3} a_i \exp(-b_i^2 r^2) + a^{\text{TPE}}(1 - \exp(-\Lambda^2 r^2))^2 \frac{e^{-2m_\pi r}}{r^2}$$

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

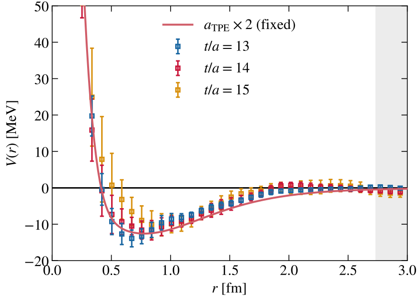


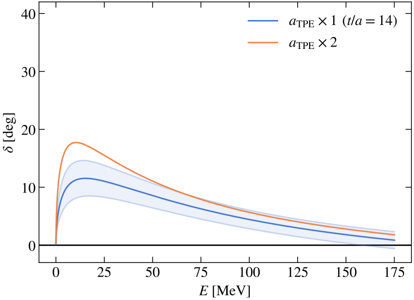
Scattering length vs EFTs

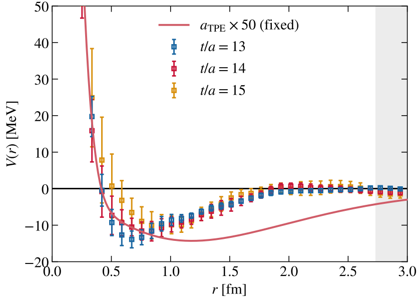
J.Hofmann, M.F.M.Lutz, Nucl.Phys. A763 (2005) 90-139, J.Haidenbauer, et al, Eur.Phys.J. A33 (2007) 107-117, C.E. Fontoura, et al, Phys.Rev. C 87 (2) (2013) 025206, Y. Yamaguchi, et al, Phys.Rev. D 106, 094001 (2022)

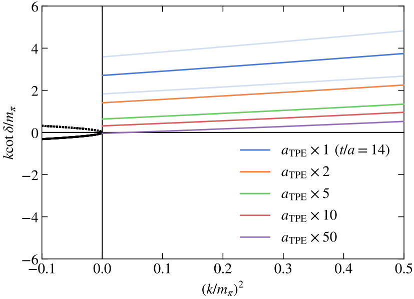


S-wave Phase shift $\bar{D}N$ (TPE-motivated fit)









Finite Volume Energy and Effective Mass

Check of the systematics from truncation of the interaction kernel $U(\vec{r}, \vec{r}')$
T. Iritani, et.al., JHEP 03 (2019) 007

- Solve schrödinger equation in FV with LO potential

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

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

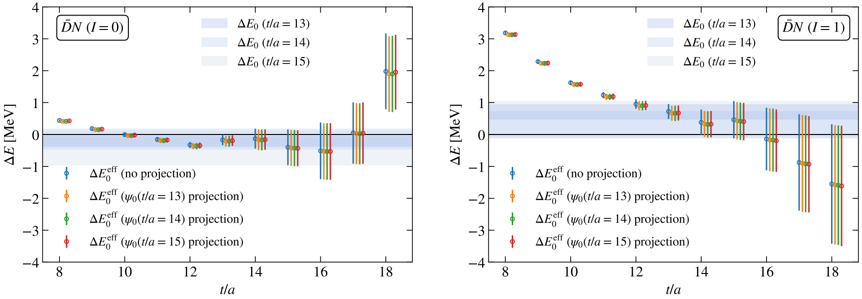
$$E_0^{\mathrm{eff}}(t) = \frac{1}{a}\log\left[\frac{R^{(\mathrm{opt})}(t)}{R^{(\mathrm{opt})}(t+1)}\right]$$

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

$$\longrightarrow \boxed{\text{Compare } E_0^{\mathrm{LO}} \text{ and } E_0^{\mathrm{eff}}}$$

Finite Volume Energy and Effective Mass

Ground state energy level in FV

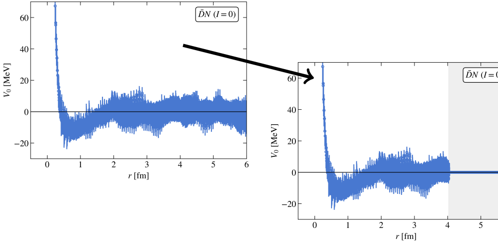


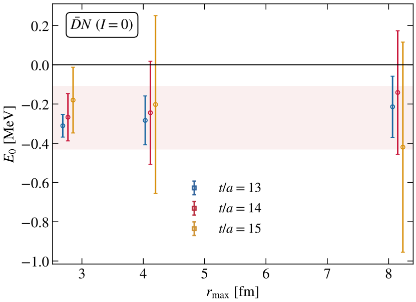
- GS projection on the R-correlator does not change result
  $\rightarrow$ Strong ground-state overlap in the R-correlator
- Energy level of the leading-order potential coincides with the statistical error of the energy level obtained directly from the R-correlators

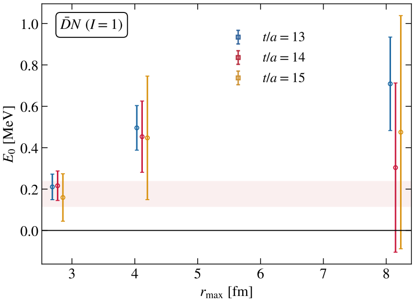
Finite Volume Energy

$$H\psi_n(\vec{r}) = E_n^{\mathrm{LO}}\psi_n(\vec{r})$$

$$V(r) = \begin{cases} V_{\mathrm{LO}}(r), & r < r_{\max} \\ 0, & r > r_{\max} \end{cases}$$







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
  - Attractive phase shift in $I = 0$, repulsive in $I = 1$
  - No bound states observed in either $I = 0$ or $I = 1$ channels
  - Systematic uncertainties estimated via gaussian fit and gauss + two-pion exchange fit
  - FV energy levels consistent with R-correlator effective masses

- calculation of related channels on going...
  - coupled-channel $\bar{D}N$–$\bar{D}^*N$ system
  - $\bar{D}^*N$ in s-wave $I(J^P) = 0(3/2^-)$ Possible Feshbach resonance?

    Phys. Rev. D 84, 014032 (2011)
  - BN–B^*N system, more attraction predicted in pheno