Universal physics of two neutrons with one flavored meson

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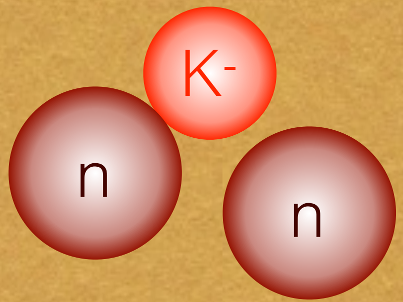
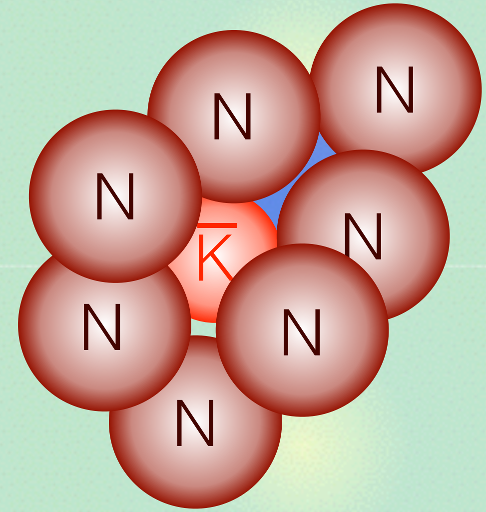


Mesons in nuclei

$\bar{K}$ ($s\bar{u}$, $s\bar{d}$) nuclei



Y. Akaishi, T. Yamazaki, Phys. Rev. C 65, 044005 (2002), …

- **attraction in** $\bar{K}N(I=0)$**:** $\Lambda(1405)$

- **quasibound states up to 7-body systems**

S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara, T. Hyodo, arXiv:1701.07589 [nucl-th]

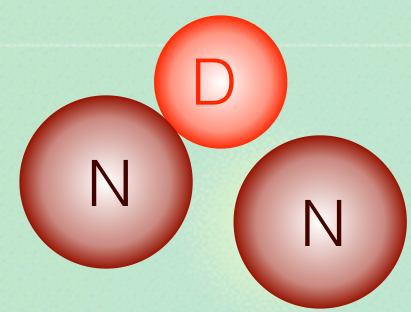
D ($c\bar{u}$, $c\bar{d}$) nuclei

A. Hosaka, T. Hyodo, K. Sudoh, Y. Yamaguchi, S. Yasui, arXiv:1606.08685 [hep-ph]

- **hadronic molecules in** XYZ **—>** D **can be a constituent**

- $\Lambda_c(2595)$ **~** DN(I=0) **molecule? as** $\Lambda(1405)$

T. Mizutani, A. Ramos, Phys. Rev. C 74, 065201 (2006)



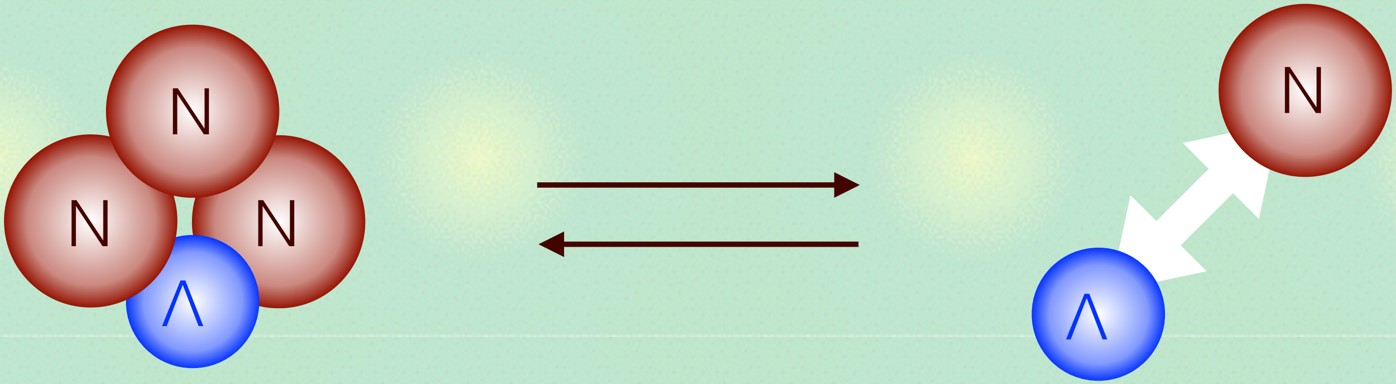
- DNN **quasibound state**

M. Bayar, C.W. Xiao, T. Hyodo, A. Dote, M. Oka, E. Oset, Phys. Rev. C86, 044004 (2012)

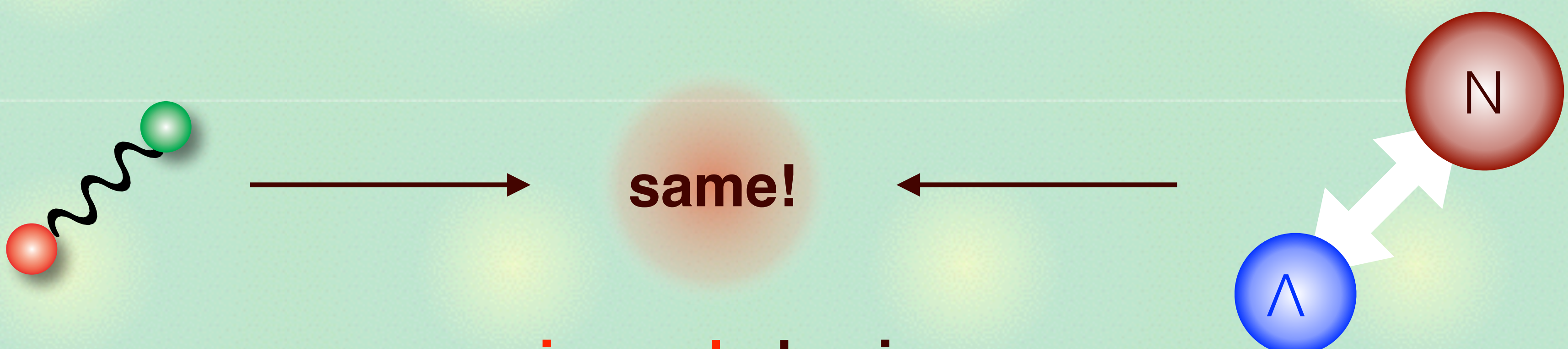
Study of few-body systems

Properties of few-body systems <—> two-body interaction

- c.f. hypernuclei



In some cases, different interactions give the same physics.



universal physics

Two-body universal physics

Universal two-body physics

E. Braaten, H.-W. Hammer, Phys. Rept. 428, 259 (2006)

1) s-wave short range interaction

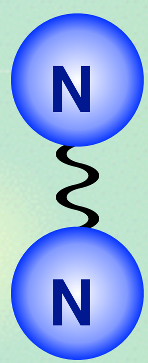
2) scattering length : $|a| \gg r_s$: interaction range

- system is scale invariant
- a shallow bound state exists if $a > 0$

vdW

$$B_2 = \frac{1}{ma^2}\left[1 + \mathcal{O}\left(\frac{r_s}{a}\right)\right]$$

strong



Examples: nucleons and ^{4}He atoms

	N [MeV]	^{4}He [mK]
B_2	**2.22**	**1.31**
$1/ma^2$	**1.41**	**1.12**

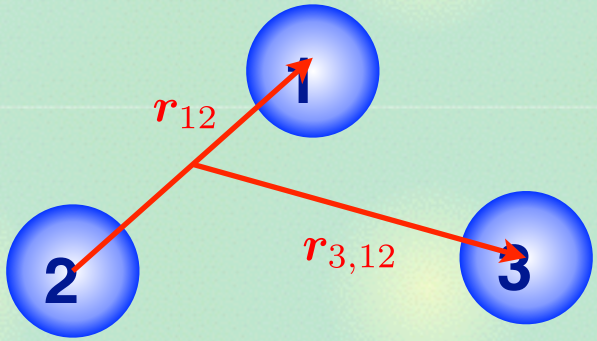
^{4}He

Three-body universal physics

Three-body system in hyperspherical coordinates

$$(\boldsymbol{r}_{12}, \boldsymbol{r}_{3,12}) \leftrightarrow (\underline{R}, \underline{\alpha_3, \hat{\boldsymbol{r}}_{12}, \hat{\boldsymbol{r}}_{3,12}})$$

hyperradius **hyperangular variables Ω (dimensionless)**



If |a| —> ∞, system is scale invariant.

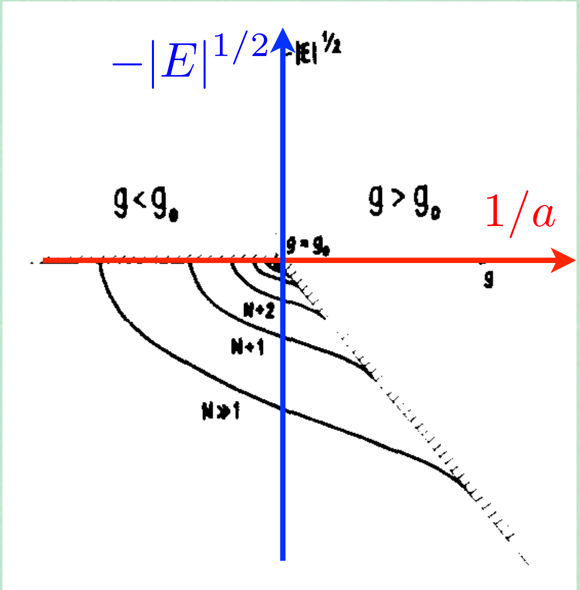
$$V(R, \Omega) \propto \frac{1}{R^2}$$

Efimov effect: attractive $1/R^2$

V. Efimov, Phys. Lett. B 33, 563-564 (1970)

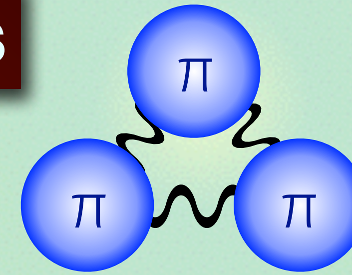
$$B_3^n / B_3^{n+1} \approx 22.7^2$$

- **infinitely many bound states**
- **discrete scale invariance: RG limit cycle**



P.F. Bedaque, H.-W. Hammer, U. van Kolck, Phys. Rev. Lett. 82, 463-437 (1999)

Universal physics of three pions

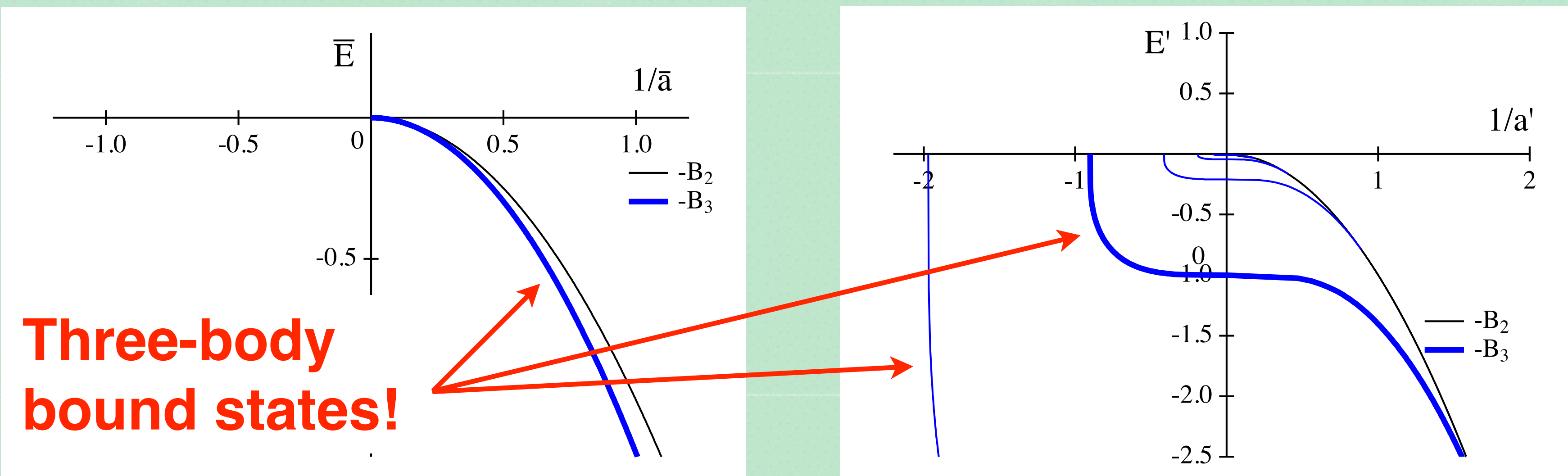


Universal physics <— large scattering length a

T. Hyodo, T. Hatsuda, Y. Nishida, Phys. Rev. C89, 032201(R) (2014)

- I=0 ππ scattering length can be increased by changing m_q

isospin sym. ($\pi^0\pi^0\pi^0$-$\pi^0\pi^-\pi^+$) **isospin breaking** ($\pi^0\pi^0\pi^0$)



- Efimov effect of $\pi^0\pi^0\pi^0$ @ unphysical m_q
- Coupled-channel effect reduces the attraction.

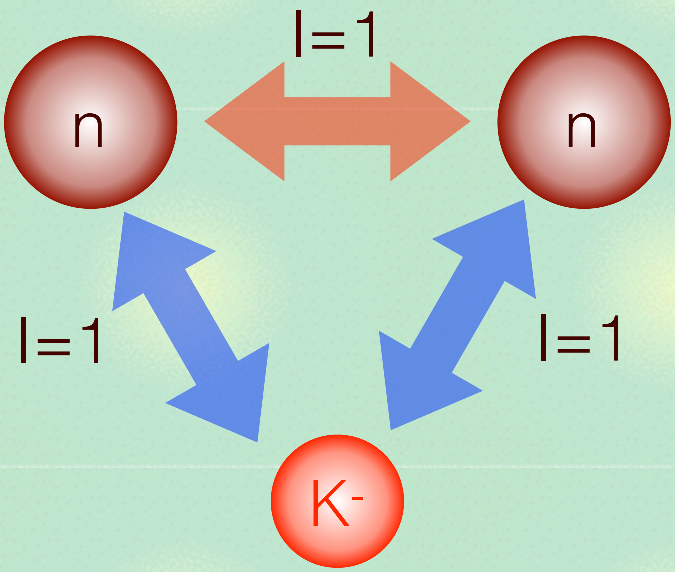
Two neutrons and one flavored meson

K^-nn/D^0nn **system with** $J=0$, $I=3/2$, $I_3=-3/2$

- **different from** $J=0$, $I=1/2$ **(so-called** K^-pp-$\bar{K}^0np$**)**
- **all interactions: isospin** $I=1$ **(no** $\Lambda(1405)$**)**

Desirable features for Efimov effect

- **no coupled channels**
- **no Coulomb interaction**
- $a_{nn} \sim -20$ fm $\gg r_s \sim O(1)$ fm



Two-body K^-n**: unitary? —> yes, with suitable idealization.**

Three-body K^-nn**: Efimov? —> yes, if two-body** K^-n **is unitary.**

Kaon-neutron interaction

Experimental database in $\bar{K}N$ sector

- cross sections of K^-p scattering (elastic, inelastic)
- threshold branching ratios
- kaonic hydrogen by SIDDHARTA —> a_{K^-p}

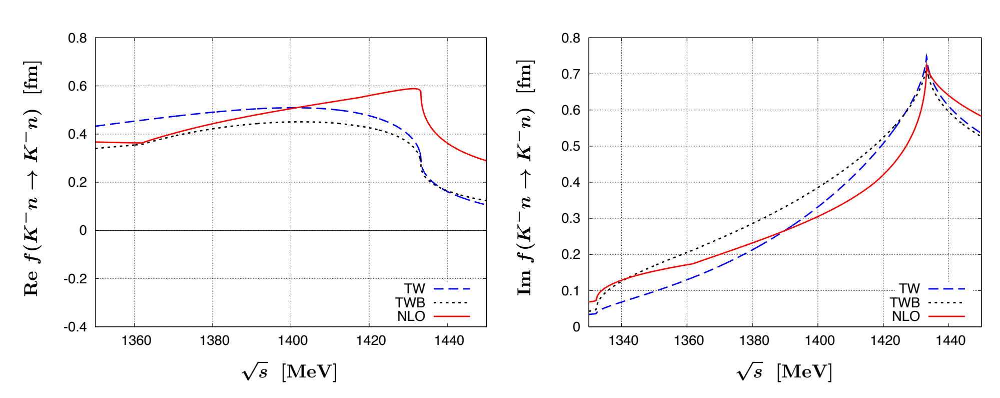
M. Bazzi, *et al.*, Phys. Lett. B704, 113 (2011); Nucl. Phys. A881, 88 (2012),
U.G. Meissner, U. Raha, A. Rusetsuky, Eur. Phys. J. C35, 349 (2004).

Analysis in NLO chiral SU(3) dynamics

Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B (2012); Nucl. Phys. A881, 98 (2012)

- data fitted as χ^2/d.o.f. ~ 1

$$a_{0,K^-n} = -0.57^{+0.21}_{-0.04} - i0.72^{+0.41}_{-0.26}\ \mathrm{fm}$$



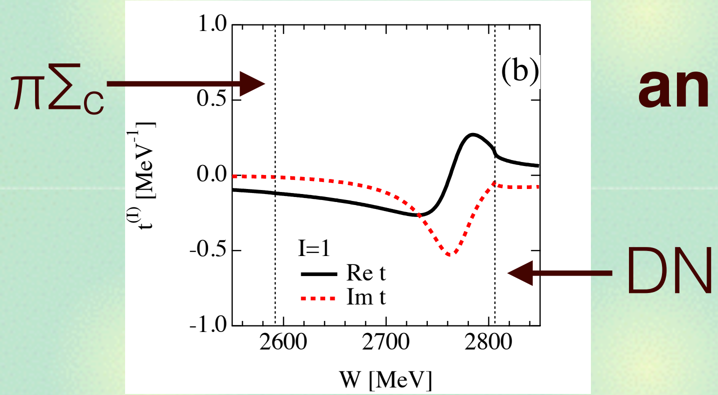
K^-p scattering length is attractive (no quasi-bound state).

D-neutron interaction

No experimental information of scattering length

- SU(4) contact interaction model (Λ_c(2595) fixed)

T. Mizutani, A. Ramos, Phys. Rev. C 74, 065201 (2006),
M. Bayar, C.W. Xiao, T. Hyodo, A. Dote, M. Oka, E. Oset, Phys. Rev. C86, 044004 (2012)



an I=1 resonance around 2760 MeV

- Σ_c(2800) as a quasi-bound state (DN threshold ~ 2804 MeV)

C. Patrignani *et al.*, (Particle Data Group) Chin. Phys. C40, 100001 (2016)

$$M_{\Sigma_c^0(2800)} = 2806^{+5}_{-7}\ \text{MeV}, \quad \Gamma_{\Sigma_c^0(2800)} = 72^{+22}_{-15}\ \text{MeV}$$

D^0n scattering length is repulsive (with quasi-bound state).

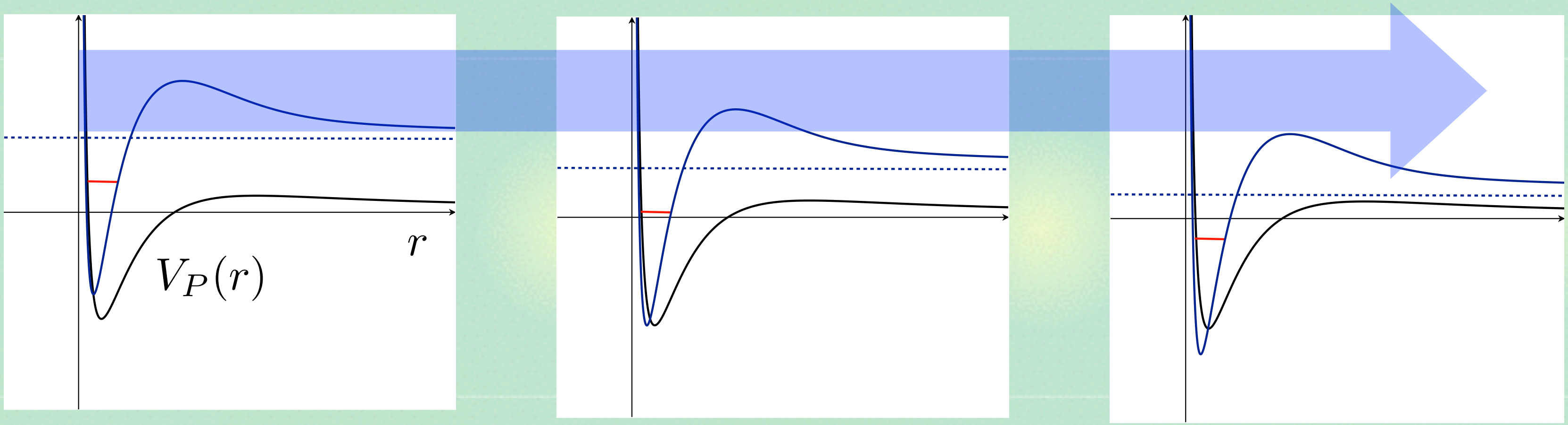
Idealization

When decay channels ($\pi\Sigma$-$\pi\Lambda$, $\pi\Sigma_c$-$\pi\Lambda_c$) are neglected:

- $a_{K^-n} < 0$ **(attractive),** $a_{D^0n} > 0$ **(repulsive, with bound state)**

Extrapolation in quark mass

strange, unbound **charm, bound**



$|a| \longrightarrow \infty$

unitary limit

Unitary limit: neglecting decay channels and tuning $m_{s/c}$

Contact interaction model

Model for $\bar{K}N/DN$ scattering

T. Mizutani, A. Ramos, Phys. Rev. C 74, 065201 (2006),
Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B (2012); Nucl. Phys. A881, 98 (2012)

$$T(W) = [V^{-1}(W) - G(W)]^{-1}$$

- **four channels:** K^-n-$\pi^-\Lambda$-$\pi^0\Sigma^-$-$\pi^-\Sigma^0$, D^0n-$\pi^-\Lambda_c$-$\pi^0\Sigma_c^0$-$\pi^-\Sigma_c^+$
- $V(W)$**: flavor symmetric contact interaction**

$$V_{ij}(W) = -\frac{C_{ij}}{f_i f_j}(2W - M_i - M_j)\sqrt{\frac{M_i + E_i}{2M_i}}\sqrt{\frac{M_j + E_j}{2M_j}}$$

- **cutoff in** $G(W)$ **<— Experiments (**$\bar{K}N$**),** $\Sigma_c(2800)$ **(**DN**)**

Extrapolation parameter x

$$m(x) = m_K(1-x) + m_D x, \quad \text{etc.}$$

- $x=0$ **(**$x=1$**) corresponds to the** $\bar{K}N$ **(**DN**) scattering.**

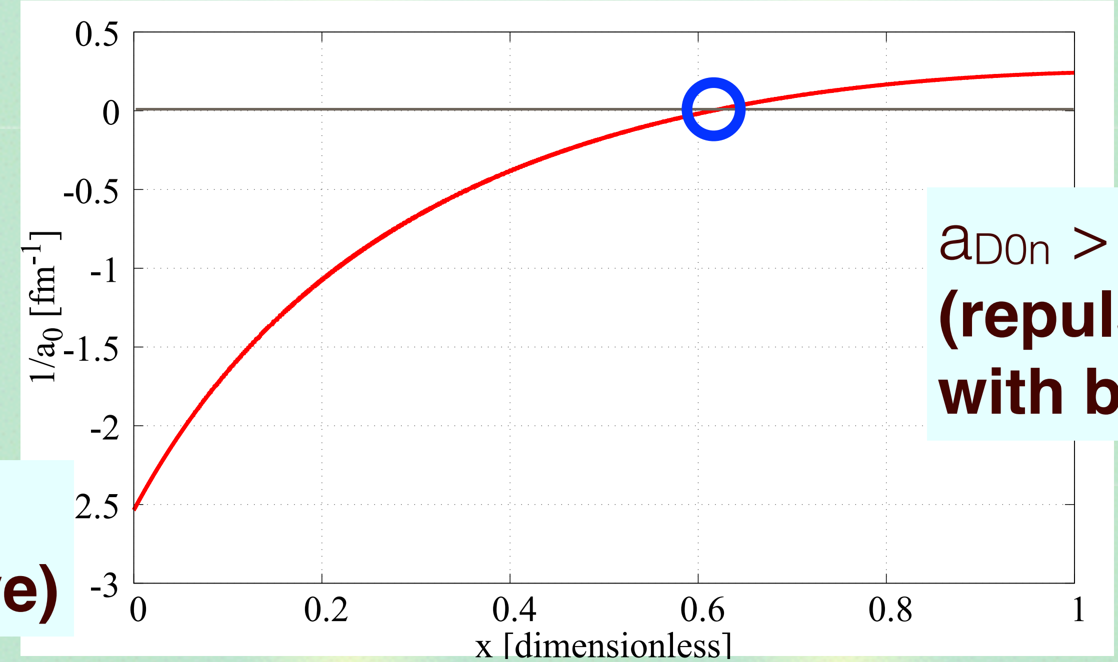
Model extrapolation

Extrapolation

- **eliminate couplings to decay channels**

$$C_{1i} = C_{i1} = 0 \quad \text{for } i = 2, 3, 4$$

- **vary extrapolation parameter** x **to calculate** $1/a_{K^-n}$



$a_{K^-n} < 0$
(attractive)

$a_{D^0n} > 0$
(repulsive, with bound state)

Unitary limit at $m_K = 1337$ **MeV (**$x=0.62$**)**

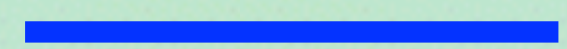
Effective field theory

Effective field theory with dihadron fields

P.F. Bedaque, H.-W. Hammer, U. van Kolck, Phys. Rev. Lett. 82, 463-437 (1999)
S.-I. Ando, U. Raha, Y. Oh, Phys. Rev. C 92, 024325 (2015)

$$\mathcal{L} = \mathcal{L}_n + \mathcal{L}_K + \mathcal{L}_{s(nn)} + \mathcal{L}_{d(nK)} + \mathcal{L}_{\text{3-body}}$$

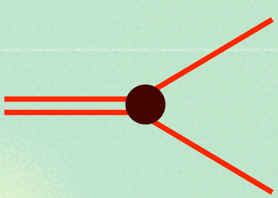
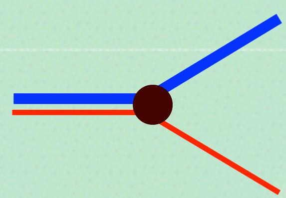
- **hadron fields**

n K^- 

- **dihadron fields**

$s_{(nn)}$  $d_{(nK)}$ 

- **interactions**

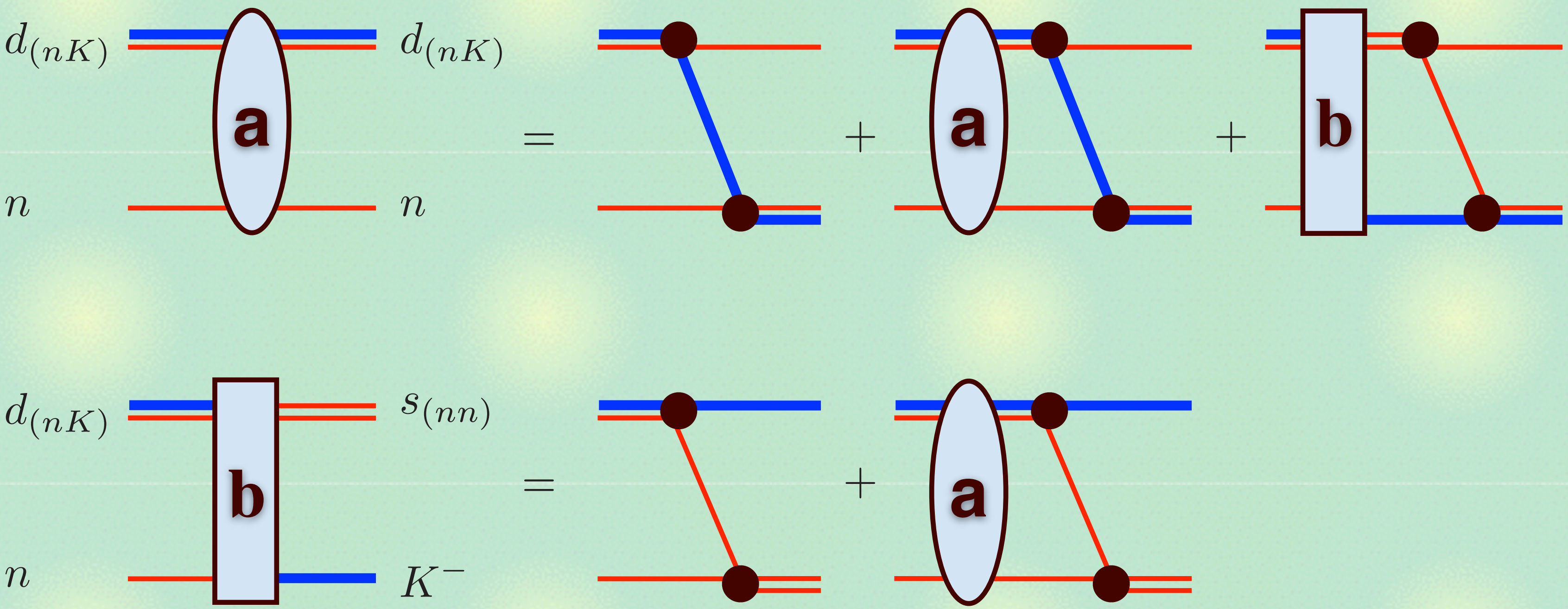
Renormalization in two-body sector (dressing $s_{(nn)}$, $d_{(nK)}$)

- **system is determined by** m_K, M_n, $a_{s(nn)}$, $a_{d(nK)}$.

Three-body equation

Three-body equation for K-nn **system**

- **coupled integral equations (quasi two-body)**
- **dressed dihadron propagators**



If Efimov effect occurs, we need three body contact term.

Asymptotic expressions

$|a| \longrightarrow \infty$ limit: check whether Efimov effect occurs

- **transcendental equation for three identical bosons**

P.F. Bedaque, H.-W. Hammer, U. van Kolck, Phys. Rev. Lett. 82, 463-437 (1999)

$$1 = \frac{8}{\sqrt{3}s}\frac{\sin(\pi s/6)}{\cos(\pi s/2)} \quad \Rightarrow \quad s = \pm i s_0, \quad s_0 = 1.00624$$

- **imaginary** s**: RG limit cycle with factor** $\exp[\pi/s_0] \sim 22.7$

For K^-nn/D^0nn system at $x=0.62$:

- $a_{s(nn)} \longrightarrow \infty$ **and** $a_{d(nK)} \longrightarrow \infty$

$$1 = C_1 \frac{2\pi}{s}\frac{\sin[s\,\mathrm{arcsin}(a/2)]}{\cos(\pi s/2)} + C_2 \frac{4\pi^2}{s^2}\frac{\sin^2[s\,\mathrm{arccot}(\sqrt{4b-1})]}{\cos^2(\pi s/2)} \quad \Rightarrow \quad s_0 = 1.01156$$

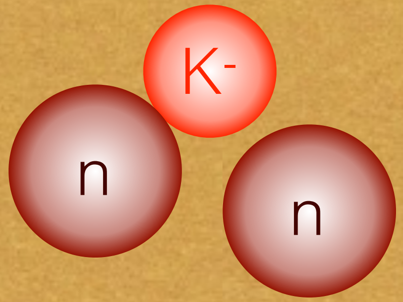
- $a_{s(nn)}$ **fixed and** $a_{d(nK)} \longrightarrow \infty$

$$1 = C_1 \frac{2\pi}{s}\frac{\sin[s\,\mathrm{arcsin}(a/2)]}{\cos(\pi s/2)} \quad \Rightarrow \quad s_0 = 0.327675$$

RG limit cycle in the asymptotic expressions: Efimov effect

Summary

- **Universal physics of the** K^-nn/D^0nn **system.**
- **Two-body sector: meson-neutron scattering length can be infinitely large with suitable idealization (tune** m_q**, neglect decay channels).**
- **Three-body sector: Efimov effect occurs when two-body interaction is unitary.**
- **Implication at physical point: three-body resonance?**



U. Raha, Y. Kamiya, S.-I. Ando, T. Hyodo, in preparation