Pionless Effective Field Theory for Nuclei and Hypernuclei

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Universality

- Consider particles interacting through 2-body potential with range R.
- Classically, the particles 'feel' each other only within the potential range.
- But, in the case of resonant interaction, the wave function has much larger extent.
- At low energies, the 2-body physics is govern by the scattering length, a.

$$\lim_{k\to 0} k \cot \delta(k) = -\frac{1}{a} + \frac{1}{2} r_0 k^2$$

- When $|a| \gg R$ the potential details has no influence: *Universality*.

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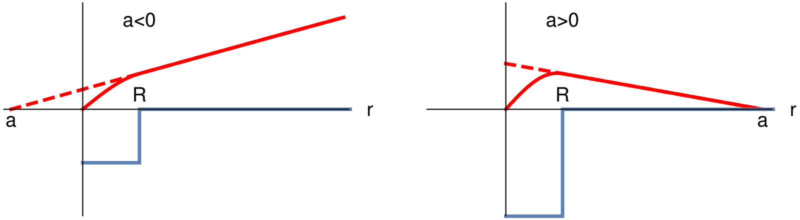

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- Naturally, $a \approx r_0 \approx R$.
  Universal systems are fine-tuned to get $a \gg r_0, R$.
- Corrections to universal theory are of order of r_0/a and R/a.
- For $a > 0$, we have universal dimer with energy $E = -\hbar^2/ma^2$.
- Nucleus: $a_s \approx -23.4$ fm, $a_t \approx 5.42$ fm, $R = \hbar/m_\pi c \approx 1.4$ fm.
  Deuteron binding energy, 2.22 MeV, is close to $\hbar^2/m{a_t}^2 \approx 1.4$ MeV.
- ^{4}He atoms: $a \approx 95$ Å$\gg r_{vdW} \approx 5.4$ Å.
- Ultracold atoms near a Feshbach resonance,

$$a(B) = a_{bg}\left(1 + \frac{\Delta}{B - B_0}\right)$$

S. Inouye *et al.*, Nature **392**, 151 (1998)

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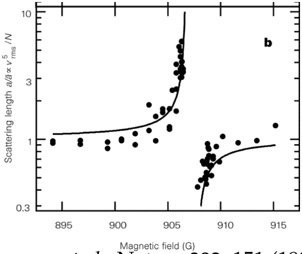

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Effective Field Theory (EFT)

- Typically in physics we have an "underlying" theory, valid at a mass scale M_{hi}, but we want to study processes at momenta $Q \approx M_{lo} \ll M_{hi}$.
- For example, nuclear structure involves energies that are much smaller than the typical QCD mass scale, $M_{QCD} \approx 1$ GeV.
- Effective Field Theory (EFT) is a framework to construct the interactions systematically. The high-energy degrees of freedom are integrated out, while the effective Lagrangian has the same symmetries as the underlying theory.
- The details of the underlying dynamics are contained in the interaction strengths.

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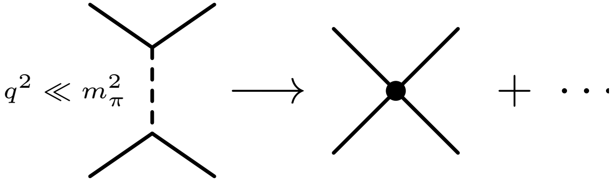

Pionless or Short-Range EFT

- For spinless bosons, the two body-sector has a single term at LO,

$$V_{LO} = a_1.$$

- and another one at NLO,

$$V_{NLO} = b_1(p^2 + p'^2).$$

- The LO term is iterated; the NLO term is treated as perturbation.

- Equivalent to the effective range expansion.

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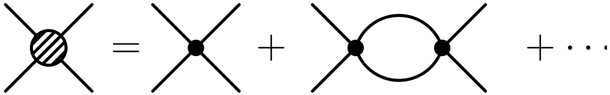

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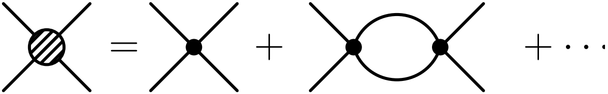

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Regularization

- In coordinate space, we have at LO a contact interaction,

$$V(r_{ij}) = \tilde{C}^{(0)}\delta(r_{ij}).$$

- This interaction needs regularization and renormalization.
- The bound state of two identical bosons ($\hbar = c = 1$),

$$-\frac{1}{m}\nabla^2\psi(r) + \tilde{C}^{(0)}\delta(r)\psi(r) = -B_2\psi(r)$$

and in momentum space,

$$\frac{p^2}{m}\phi(p) + \tilde{C}^{(0)}\int\frac{d^3p'}{(2\pi)^3}\phi(p') = -B_2\phi(p)$$

- Therefore,

$$\frac{1}{\tilde{C}^{(0)}} = \int\frac{d^3p'}{(2\pi)^3}\frac{1}{p'^2/m + B_2}$$

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- To regularize, we can smear the interaction over a range of $1/\Lambda$,

$$\delta_\Lambda(r) \equiv \frac{\Lambda^3}{8\pi^{3/2}} \exp[-(\Lambda r/2)^2], \quad \delta_\Lambda(r) \xrightarrow{\Lambda\to\infty} \delta(r).$$

- Doing so for the incoming and outcoming momenta we have,

$$\frac{1}{\tilde{C}^{(0)}(\Lambda)} = \int \frac{d^3p'}{(2\pi)^3} \frac{exp(-2p'^2/\Lambda^2)}{p'^2/m + B_2}$$

- Which can be expand by powers of Q_2/Λ, ($Q_2 = \sqrt{mB_2}$)

$$\tilde{C}^{(0)}(\Lambda) = \frac{4\sqrt{2}\pi^{3/2}}{m\Lambda} \left(1 + \sqrt{2\pi}\frac{Q_2}{\Lambda} + ...\right).$$

- ...therfore our Low Energy Constant (LEC) $\tilde{C}^{(0)} = \tilde{C}^{(0)}(\Lambda)$ is now renormalized by some experimental data, here B_2.

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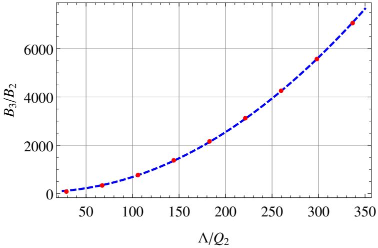
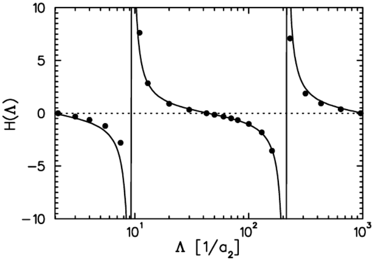
Three-boson system

Trying to calculate the trimer binding energy we get the Thomas collapse:

$$B_3 \propto \frac{\hbar^2 \Lambda^2}{m}$$



To stabilize the system, a 3-body counter term must be introduced at LO

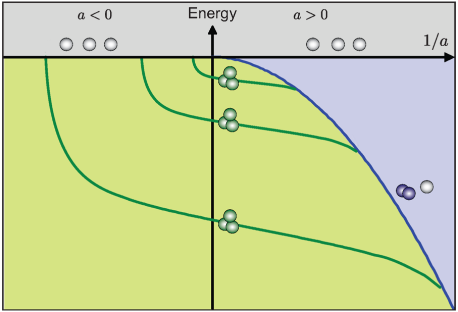


LO: Bedaque, Hammer, and van Kolck, PRL **82**, 463 (1999).

NLO: Ji, Phillips, and Platter, Ann. Phys. **327**, 1803 (2012).

Efimov Physics

- Actually we see here the Efimov effect.
- discrete scale invariance: $\lambda_n = e^{-\pi n/|s|}$
- infinite number of bound states $E_n = E_0 e^{-2\pi n/|s_0|}$ with $e^{2\pi/|s_0|} \approx 515$
- Borromean binding

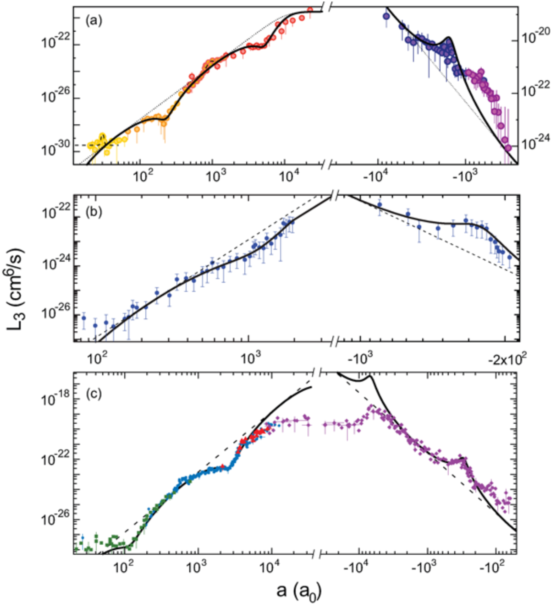


Ferlaino and Grimm, Physics **3**, 9 (2010)

Efimov, Phys. Lett. B **33**, 563 (1970)

Review: Naidon and Endo (2017)

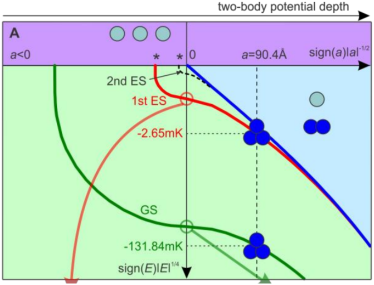
Efimov Physics in Ultracold Atoms

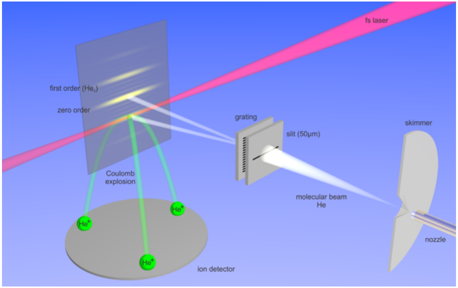


Ferlaino and Grimm, Physics **3**, 9 (2010)

- ^{39}K
  Zaccanti *et al.*,
  Nature Phys. **5**, 586 (2009).
- ^{7}Li
  Gross *et al.*,
  Phys. Rev. Lett. **103**, 163202 (2009).
- ^{7}Li
  Pollack *et al.*,
  Science **326**, 1683 (2009)

- Since a is finite here, only two trimers survive.
- The excited trimer was also observed experimentally.





Theory: Hiyama and Kamimura, Phys Rev A. **85**, 062505 (2012);
Experiment: Kunitski *et al.*, Science **348** 551 (2015).

Efimov Physics in Nuclei

- Triton is an Efimov state: Phillips line.
- Efimov suggested that the Hoyle state in ^{12}C is universal α trimer ...but long-range Coulomb interaction complicated the analysis.
- Maybe ^6He? ...but ^6He binding is based on $n\alpha$ p-wave resonance.
- In other halo nuclei the ground state binding is s-wave. But is there Efimov spectrum?

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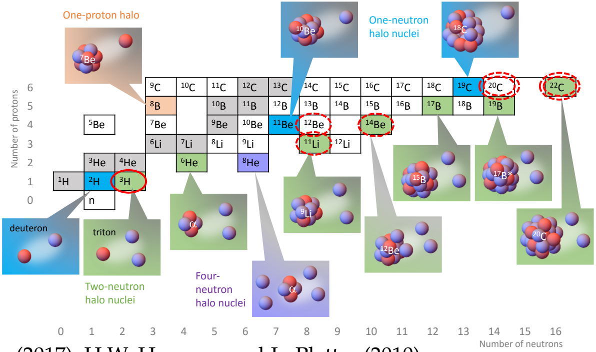

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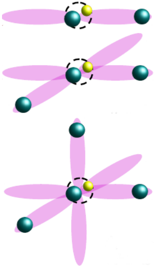
Efimov physics beyond 3 particles

- Heavy fermions can be bound by a light atom, forming Efimov states.

system	L^π	M/m	Ref.
2+1	1^-	13.607	[1]
3+1	1^+	13.384	[2]
4+1	0^-	13.279	[3]
5+1	0^-	—	[4]

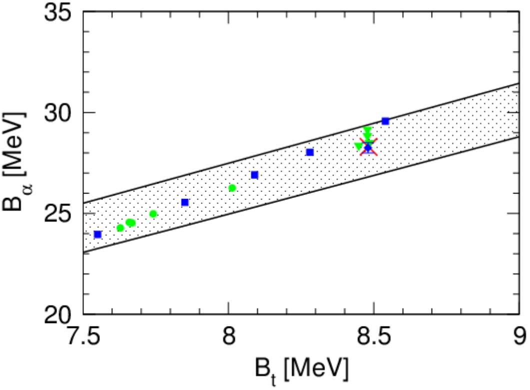


1. Efimov, Nucl. Phys. A **210**, 157 (1973).
2. Castin, Mora, and Pricoupenko, PRL **105**, 223201 (2010).
3. Bazak and Petrov, PRL **118**, 083002 (2017).
4. Bazak, PRA **96**, 022708 (2017).

Tjon line

Are more terms needed to stabilize heavier systems?
No, since the Tjon line exists, i.e. the correlation between the binding energies of the triton and the α-particle.

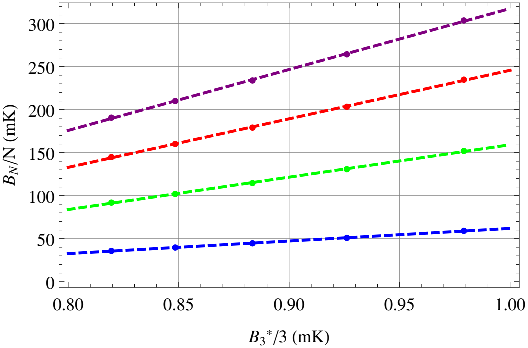
Tjon, Phys. Lett. B **56**, 217 (1975).



Platter, Hammer, and Meissner, Phys. Lett. B **607**, 254 (2005).

Clusters of He atoms in short-range EFT

- Same is true for 4-, 5- and 6- He atoms clusters, attached to an Efinov trimer,

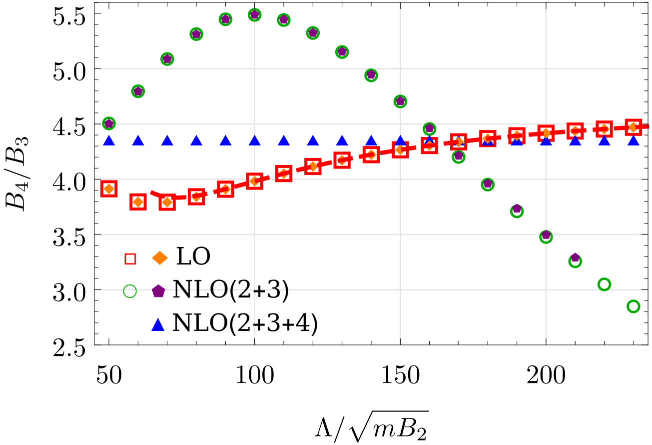


Bazak, Eliyahu and van Kolck, PRA **94**, 052502 (2016)

...therefore, no 4, 5 or 6-body terms are needed at LO.

NLO

The 4-body system at NLO is surprising...

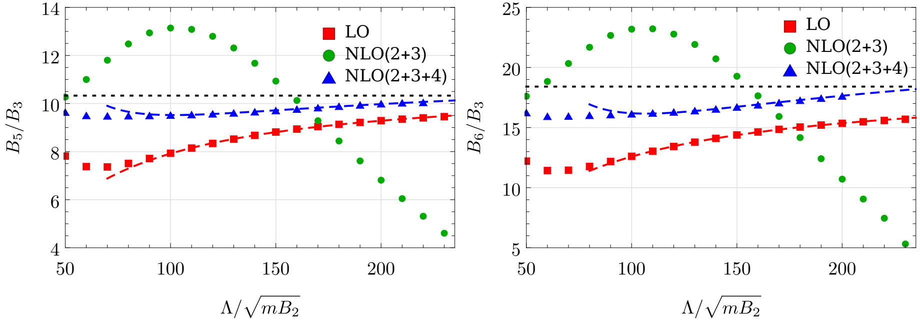


which suggests the need of a new 4-body counter-term!

Bazak, Kirscher, König, Valderrama, Barnea, and van Kolck, PRL **122**, 143001 (2019)

NLO

This counter-term indeed regularizes also the 5- and 6-body systems.



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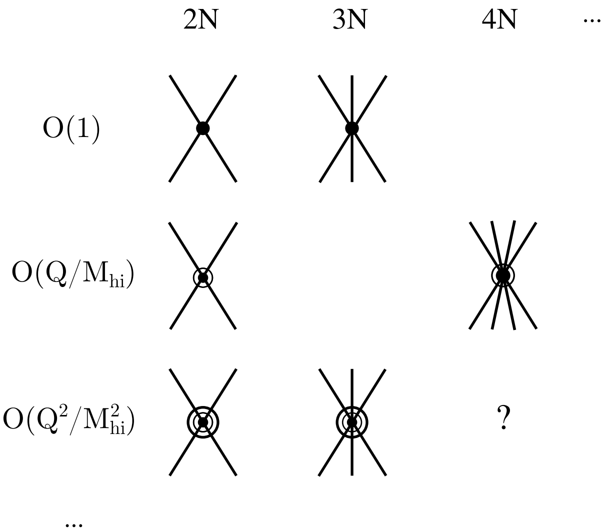
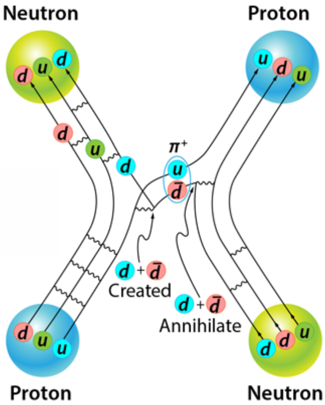
$\not{\pi}$EFT potential

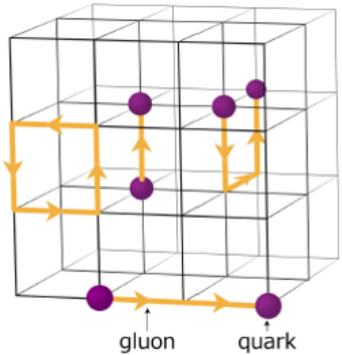


Hammer, König and van Kolck, Rev. Mod. Phys. **92**, 025004 (2020)

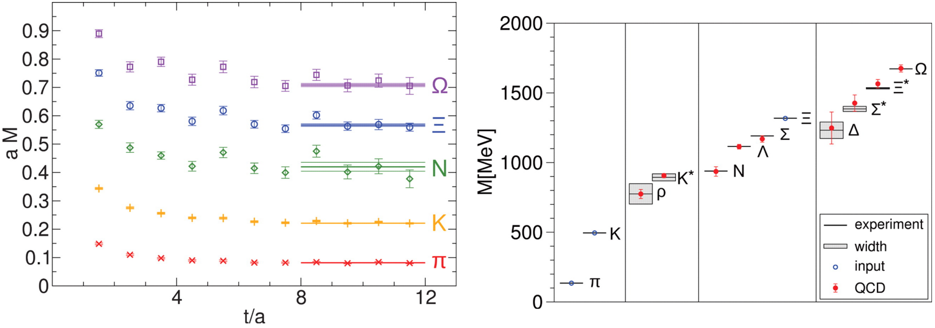
Lattice QCD



APS/Alan Stonebraker

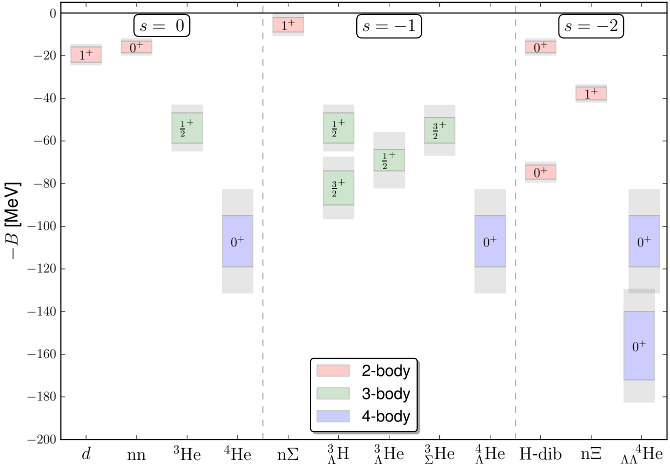


The light hadron spectrum from Lattice QCD



Dürr et al., Science **322**, 1224 (2008)

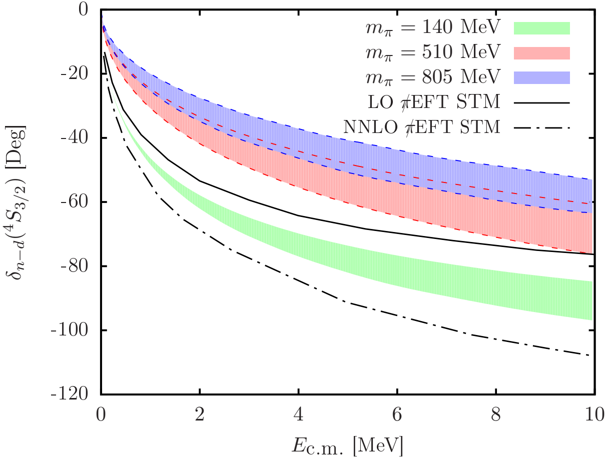
NPLQCD calculations for SU(3) flavor symmetry



NPLQCD Collaboration, Phys. Rev. D **87**, 034506 (2013).

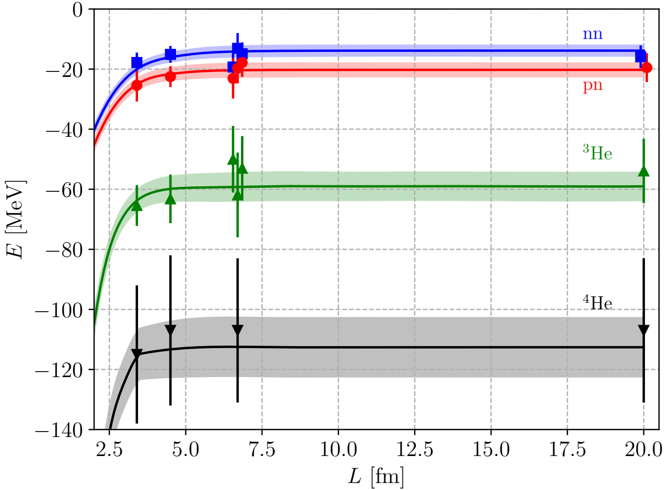
- In nature,
  $m_u \approx m_d \ll m_s$
  $m_\pi \approx 140$ MeV
  $m_N \approx 939$ MeV.
- SU(3) flavor symmetry:
  $m_u = m_d = m_s$
  $m_\pi \approx 806$ MeV
  $m_N \approx 1634$ MeV.

EFT for LQCD: observables



Kirscher, Barnea, Gazit, Pederiva, and van Kolck, Phys. Rev. C **92**, 054002 (2015).

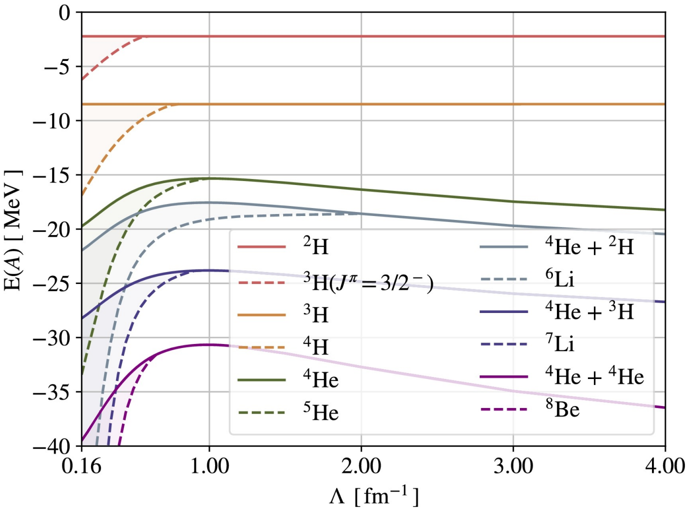
EFT for LQCD: extrapolation



Eliyahu, Bazak, and Barnea, Phys. Rev. C **102**, 044003 (2020).

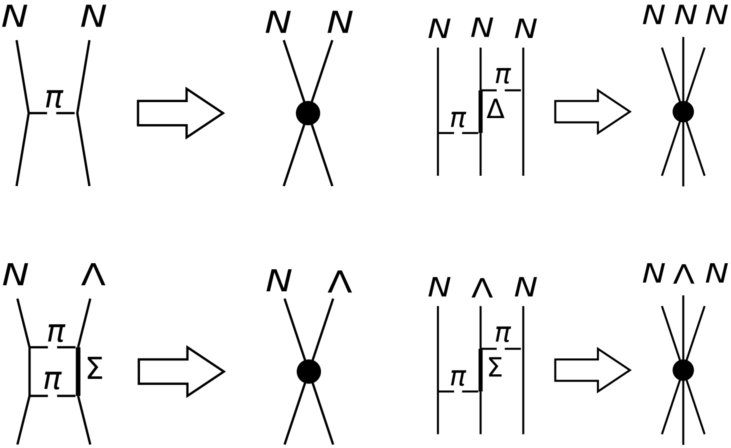
p-shell nuclei puzzle

p-shell nuclei are not bound in LO $\not\pi$EFT !



Schäfer, Contessi, Kirscher and Mares, Phys.Lett. B **816**, 136194 (2021).

Single Λ pionless EFT



Single Λ pionless EFT

	A=2	A=3	A=4	A=5
$\mathcal{S}=0$	$a_{NN}(^1S_0)$ $^2\mathrm{H}(1^+)$	$^3\mathrm{H}(\frac{1}{2}^+)$	$^4\mathrm{He}(0^+)$	
$\mathcal{S}=-1$	$a_{N\Lambda}(^1S_0)$ $a_{N\Lambda}(^3S_1)$	$^3_\Lambda\mathrm{H}(\frac{1}{2}^+)$ $^3_\Lambda\mathrm{H}(\frac{3}{2}^+)$ $^3_\Lambda\mathrm{n}(\frac{1}{2}^+)$	$^4_\Lambda\mathrm{H}(0^+)$ $^4_\Lambda\mathrm{H}(1^+)$	$^5_\Lambda\mathrm{He}(\frac{1}{2}^+)$

. . . fitted (scattering lengths, bound state energies)

. . . prediction (bound states, resonances, ..)

ΛN scattering data

Experimental data

- Alexander et al. (PR173, 1452, 1968)
  $a_{\Lambda N}(^1S_0)$=-1.8 fm
  $a_{\Lambda N}(^3S_1)$=-1.6 fm
- Sechi-Zorn et al. (PR175, 1735, 1968)
  $0 > a_{\Lambda N}(^1S_0) > -9.0$ fm
  $-0.8 > a_{\Lambda N}(^3S_1) > -3.2$ fm

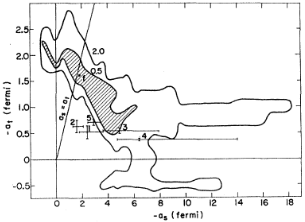


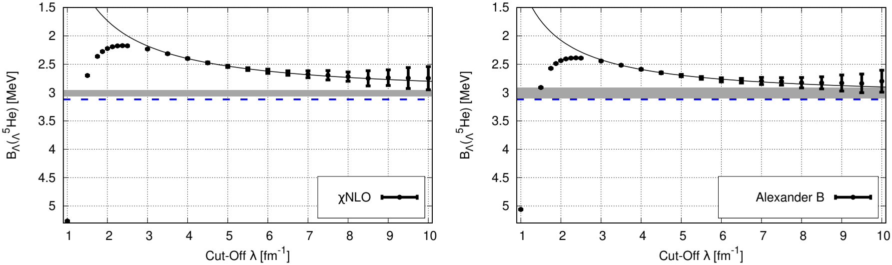
FIG. 9. Mapping of the likelihood function L in the a_s-a_t plane for the four-parameter fit. The shaded area includes all points with likelihood values above $L_{max}/\exp 0.5$, where L_{max} is the value of the best fit (point f). The external smooth curve encloses likelihood values lying above $L_{max}/\exp 2.0$. Points 1–5 represent scattering lengths derived from early hypernuclei calculations.

ΛN interaction models (Gal et al., Rev. Mod. Phys.88, 035004, 2016)

Model	$a_{\Lambda N}(^1S_0)$	$r^{eff}_{\Lambda N}(^1S_0)$	$a_{\Lambda N}(^3S_1)$	$r^{eff}_{\Lambda N}(^3S_1)$
NSC89	-2.79	2.89	-1.36	3.18
NSC97e	-2.17	3.22	-1.84	3.17
NSC97f	-2.60	3.05	-1.71	3.33
ESC08c	-2.54	3.15	-1.72	3.52
Jülich '04	-2.56	2.75	-1.66	2.93
EFT (LO)	-1.91	1.40	-1.23	2.20
EFT (NLO)	-2.91	2.78	-1.54	2.27

Λ Hypernuclear Overbinding Problem

- Most few-body calculations that reproduce ground-state Λ separation energies, overbind ${}^{5}_{\Lambda}$He by 1-3 MeV.
- $\not\pi$EFT interaction reproduces the reported value $B_{\Lambda}^{exp}({}^{5}_{\Lambda}\text{He}) = 3.12 \pm 0.02$ MeV.



Contessi, Barnea, and Gal, Phys. Rev. Lett. **121**, 102502 (2018)

$nn\Lambda$ and ${}^{3}_{\Lambda}\mathrm{H}^{*}$ - physical motivation

${}^{3}_{\Lambda}H(1/2^{+})$

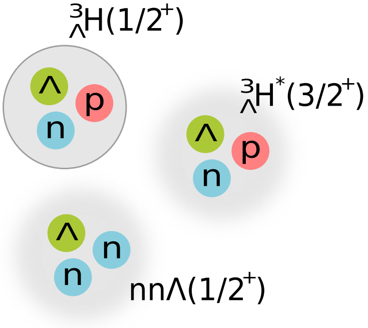
- lightest bound hypernucleus $B_{\Lambda} = 0.13(5)$ MeV
- constraints on ΛN interaction models

${}^{3}_{\Lambda}H^{*}(3/2^{+})$

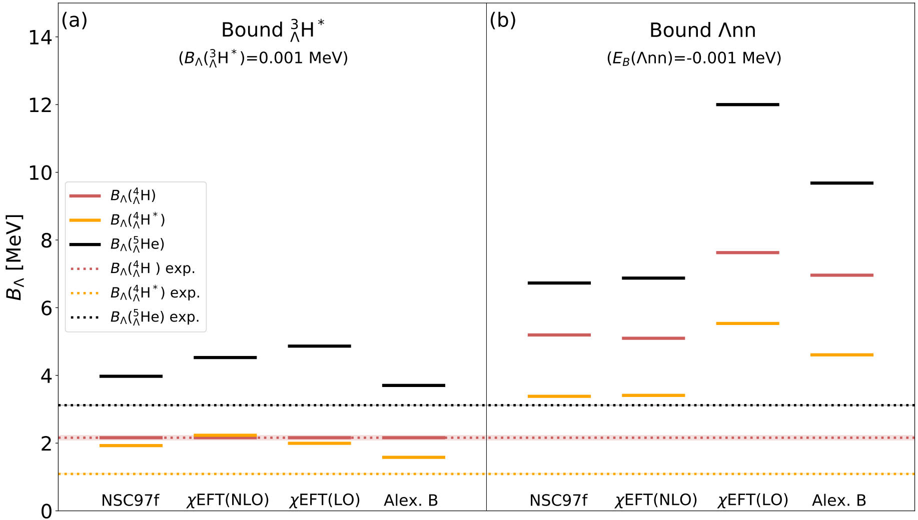
- no experimental evidence
- strict constraint on ΛN $S = 1$ interaction
- JLab C12-19-002 proposal

$nn\Lambda(1/2^{+})$

- experiment (HypHI) vs. theory
- JLab E12-17-003 experiment
- valuable source of $n\Lambda$ interaction
- structure of neutron-rich Λ-hypernuclei



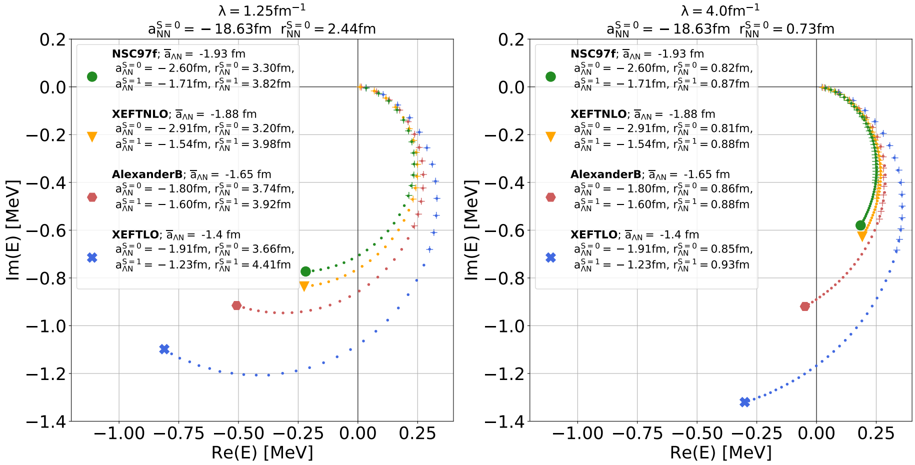
Implications of just bound $nn\Lambda$ and ${}^{3}_{\Lambda}H^*$



- $B_\Lambda({}^{3}_{\Lambda}H)$ is used to fix three-body force in $I,S = 0, 1/2$ channel and remains unaffected

Schäfer, Bazak, Barnea, and Mares, Phys. Rev. C **103**, 025204 (2021).

Resonance in $nn\Lambda$ system



check of the methods : + CSM • IACCC

Schäfer, Bazak, Barnea, and Mares, Phys. Rev. C **103**, 025204 (2021).

Conclusion

- $\not\pi$EFT and its power counting were introduced.
- 3-body term comes at LO, 4-body term comes at NLO.
- We show implementaions for several physical systems, including ^{4}He atoms, light s-shell nuclei and hypernuclei.
- p-shell nuclei binding is still a puzzle.
- $\not\pi$EFT can bridge the gap between LQCD and nuclear physics.
- $nn\Lambda$ and ${}^3_\Lambda H^*$ are unbound in LO $\not\pi$EFT .
- Question of experimentally observable $nn\Lambda$ resonance.