Building renormalizable very low-energy theory for few-body nuclear processes and bound states

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Towards high precision in multi-channel reactions of composite nuclei

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Thanks to my collaborators...

Betzalel Bazak, Nir Barnea, Mirko Bagnarol, Johannes Kirscher, Lorenzo Contessi, Ubirajara van Kolck, Rimantas Lazauskas, Jaume Carbonell, Matúš Rojik, Sourav Mondal

Introduction

Analyzing power A_y in low-energy N-d and p-$^3\mathrm{He}$ elastic scattering

(A. Margaryan et al. Phys. Rev. C 93 (2016) 054001; L. Girlanda, Phys. Rev. C 99 (2019) 054003)

Isoscalar monopole resonance of $^4\mathrm{He}$ (the first $^4\mathrm{He}$ excited state)

(S. Bacca et al., Phys. Rev. Lett. 110 (2013) 042503; S. Kegel et al. Phys. Rev. Lett. 130 (2023) 152502)

$\rightarrow$ discrepancy between experimental and theoretically predicted monopole transition form factor

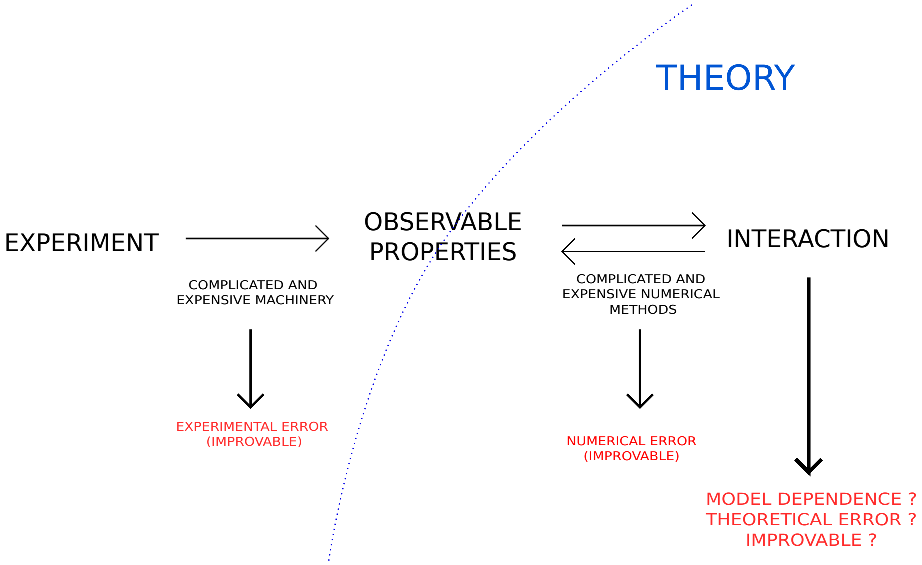
Splitting between $^2P_{3/2}$ and $^2P_{1/2}$ partial waves in $^4\mathrm{He} + \mathrm{n}$

(R. Lazauskas, Phys. Rev C 97 (2018) 044002; A. M. Shirokov et al.,Phys. Rev. C 98 (2018) 044624)

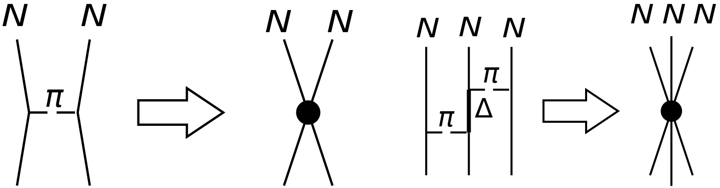
Big Bang Nucleosynthesis reactions

$\rightarrow$ astrophysical S-factors of $d(d,p)^3\mathrm{H}$ and $d(d,n)^3\mathrm{He}$ reactions at very low energies (100 keV)

Introduction



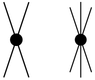
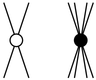
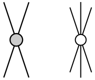
$\not\pi$EFT - basic idea



Baryonic EFT :

$\rightarrow$ no pionic degrees of freedom

$\not\pi$EFT

LO		$\delta(\mathbf{r}_{12}),\ \delta(\mathbf{r}_{12})\delta(\mathbf{r}_{23})$
NLO		$\overleftarrow{\nabla}^2_{\mathbf{r}_{12}}\delta(\mathbf{r}_{12}) + \delta(\mathbf{r}_{12})\overrightarrow{\nabla}^2_{\mathbf{r}_{12}},\ \delta(\mathbf{r}_{12})\delta(\mathbf{r}_{23})\delta(\mathbf{r}_{34})$
N^2LO		$S-D$ tensor ($T=0$), momentum dep. 3-body
N^3LO	...	$(\nabla_{\mathbf{r}_1}\cdot\nabla_{\mathbf{r}_2})\delta(\mathbf{r}_{12})$, LS, tensor ($T=1$), more 4-body ?

(H.-W. Hammer, Sebastian König, and U. van Kolck, Rev. Mod. Phys. 92 (2020) 025004)

$\not\pi$EFT

Where do we stand ?

- NLO $\not\pi$EFT using 6 experimental constraints
  (a, r) of $NN(^1S_0)$ and $NN(^3S_1)$, $B(^3\mathrm{H})$, $B(^4\mathrm{He})$
  $+$ 3 additional at NLO with non-perturbative Coulomb interaction
  (a, r) of $pp(^1S_0)$ and $B(^3\mathrm{He})$
- perturbative treatment of higher-order corrections
  (development of both interaction potentials and numerical few-body techniques)

What do we want to study ?

- behavior of $\not\pi$EFT predictions with increasing Λ
- comparison with experimental results

$\longrightarrow$ techniques developed for $\not\pi$EFT can be also used in other renormalizable EFTs that demand perturbative corrections
(nuclear EFTs with perturbative pions, RG-invariant versions of χEFT, ...)

$\not\pi$EFT

- breakdown scale $M = m_\pi$
- EFT tailored to describe nuclear processes/properties at very low typical momenta
- simplicity, clearer separation of different EFT orders, theoretical errors

Regularization/Renormalization

$$C\ \delta(\mathbf{r}_{ij}) \rightarrow C(\lambda)\left(\frac{\lambda}{2\sqrt{\pi}}\right)^3 \mathrm{e}^{\frac{-\lambda^2 r_{ij}^2}{4}}$$

$$D\ \delta(\mathbf{r}_{ij})\delta(\mathbf{r}_{jk}) \rightarrow D(\lambda)\left(\frac{\lambda}{2\sqrt{\pi}}\right)^6 \mathrm{e}^{\frac{-\lambda^2 (r_{ij}^2+r_{jk}^2)}{4}}$$

- $C(\lambda), D(\lambda)$ are low energy constants (LECs) tuned to reproduce two-body resp. three-body observables for each λ
- required (RG invariance for $\lambda >> M$)
  $\rightarrow$ all observable will become λ independent when $\lambda \rightarrow \infty$

  $O_\lambda = O_\infty + \frac{\alpha}{\lambda} + \frac{\beta}{\lambda^2} + \frac{\gamma}{\lambda^3} + \ldots$

$\not\pi$EFT potential up to NLO

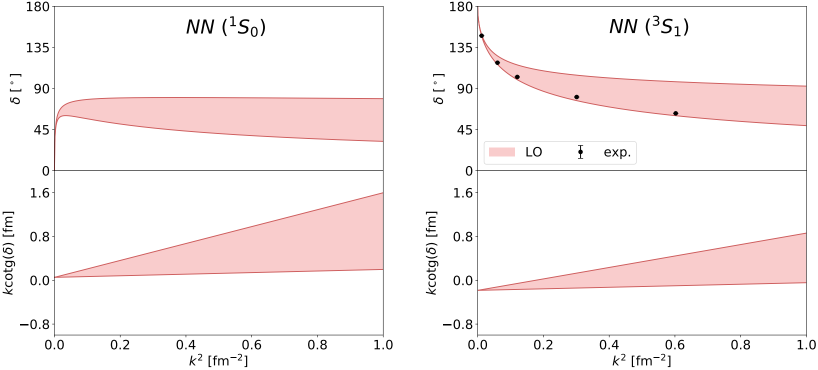
Leading order potential (3 LECs; iterated) :

$$V^{(\mathrm{LO})} = \sum_{i<j} \left[C_0^{(0)}(\lambda) P_{ij}^{T=1,S=0} + C_1^{(0)}(\lambda) P_{ij}^{T=0,S=1} \right] e^{-\frac{\lambda^2}{4}\mathbf{r}_{ij}^2} + D_0^{(0)}(\lambda) \sum_{i<j<k} \mathcal{Q}_{ijk}^{T=1/2,S=1/2} \sum_{\mathrm{cyc}} e^{-\frac{\lambda^2}{4}(\mathbf{r}_{ij}^2+\mathbf{r}_{jk}^2)}$$

Next-to-leading order potential (6 LECs; 1st order PT) :

$$\begin{aligned} V^{(\mathrm{NLO})} = & \sum_{i<j} \left[C_0^{(1)}(\lambda) P_{ij}^{T=1,S=0} + C_1^{(1)}(\lambda) P_{ij}^{T=0,S=1} \right] e^{-\frac{\lambda^2}{4}\mathbf{r}_{ij}^2} \\ & + \sum_{i<j} \left[C_2^{(1)}(\lambda) P_{ij}^{T=1,S=0} + C_3^{(1)}(\lambda) P_{ij}^{T=0,S=1} \right] (\mathbf{k}^2 + \mathbf{q}^2) e^{-\frac{\lambda^2}{4}\mathbf{r}_{ij}^2} \\ & + D_0^{(1)}(\lambda) \sum_{i<j<k} \mathcal{Q}_{ijk}^{T=1/2,S=1/2} \sum_{\mathrm{cyc}} e^{-\frac{\lambda^2}{4}(\mathbf{r}_{ij}^2+.\mathbf{r}_{jk}^2)} \\ & + E_0^{(1)}(\lambda) \sum_{i<j<k<l} \mathcal{Q}_{ijkl}^{T=0,S=0} e^{-\frac{\lambda^2}{4}(\mathbf{r}_{ij}^2+\mathbf{r}_{ik}^2+\mathbf{r}_{il}^2+\mathbf{r}_{jk}^2+\mathbf{r}_{jl}^2+\mathbf{r}_{kl}^2)} \end{aligned}$$

LO $\not\pi$EFT



Leading order (LO) :

(exp. constraints)

a^0_{NN} (a^0_{nn}) $=$ $-18.95(40)$ fm

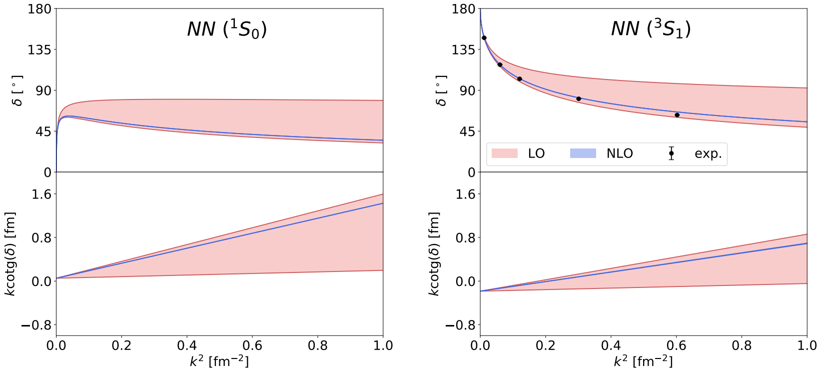
a^1_{NN} (a^1_{np}) $=$ $5.419(7)$ fm

$B(^3\mathrm{H}) = 8.482$ MeV

Effective range expansion :

$$k\mathrm{cotg}(\delta) = -\frac{1}{a} + \frac{1}{2} r k^2 + \ldots$$

NLO $\not\pi$EFT



Leading order (LO) :

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$$a^1_{NN}\ (a^1_{np}) = \ 5.419(7)\ \mathrm{fm}$$

$$B(^3\mathrm{H}) = 8.482\ \mathrm{MeV}$$

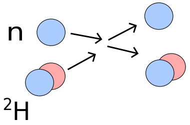
Next-to-leading order (NLO) :

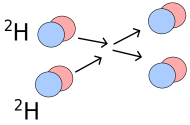
(exp. constraints)

$$r^0_{NN}\ (r^0_{nn}) = \ 2.75(11)\ \mathrm{fm}$$

$$r^1_{NN}\ (r^1_{np}) = \ 1.753(8)\ \mathrm{fm}$$

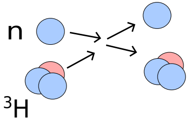
$$B(^4\mathrm{He}) = 28.296\ \mathrm{MeV}$$

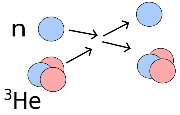




Few-Body scattering

(elastic; no Coulomb interaction)





Correlated Gaussian basis

(K. Varga et al., NPA571 (1994) 447, K. Varga, Y. Suzuki, PRC52 (1995) 2885)

$$H\psi = E\psi, \qquad \psi = \sum_{i=0}^{N} c_i \varphi^i$$

Basis states

- antisymmetrized correlated Gaussians
- here shown for $L = 0$; Global Vector representation for higher Ls (Y. Suzuki *et al.*, Few Body Syst 42 (2008) 33)

$$\varphi^i_{SM_S TM_T}(\mathbf{x}, A_i) = \mathcal{A}\{G_{A_i}(\mathbf{x})\chi_{SM_S}\eta_{TM_T}\}, \quad G_{A_i}(\mathbf{x}) = e^{-\frac{1}{2}\mathbf{x}A_i\mathbf{x}}$$

- Jacobi coordinates $\mathbf{x}$, A_i symmetric positive definite matrix of $\frac{N(N-1)}{2}$ real parameters, spin χ_{SM_S} and isospin η_{TM_T} parts

optimization of variational basis in a **random trial and error procedure**

Few-body scattering: BERW formula

$\rightarrow$ assumption of short-range potential with range $R << b_{\mathrm{HO}} = \sqrt{\frac{1}{\mu\omega}}$

Quantization condition (BERW formula)

$$(-)^{l+1}\left(\sqrt{4\mu\omega}\right)^{2l+1}\frac{\Gamma\left(3/4+l/2-\epsilon_n/2\omega\right)}{\Gamma\left(1/4+l/2-\epsilon_n/2\omega\right)} = k^{2l+1}\,\mathrm{cotg}(\delta),\;\; k=\sqrt{2\mu\epsilon_n}$$

(A. Suzuki, Phys. Rev. A 80 (2009) 033601, T. Bush Found. of Phys. 28 (1998) 4)

LO :

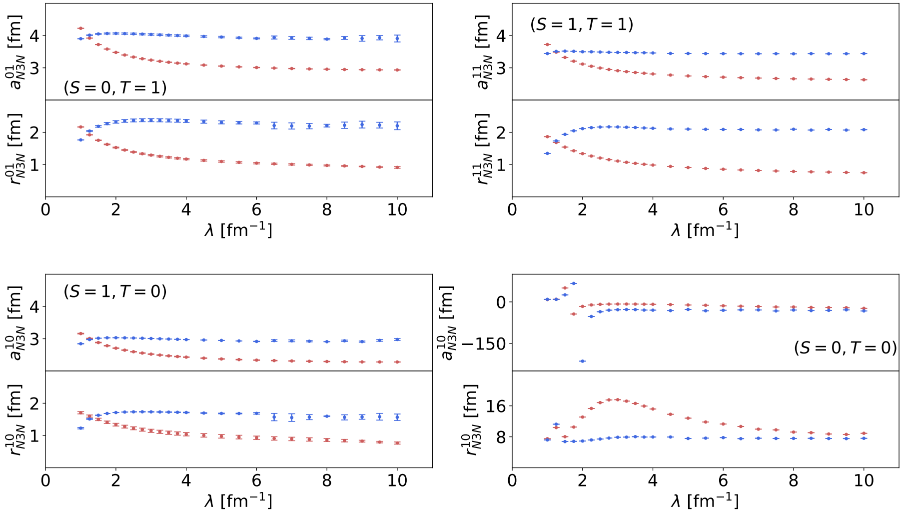
$$H(\omega) = T_k + V_\lambda^{(\mathrm{LO})} + V_{\mathrm{HO}}(\omega) \;\longrightarrow\; H(\omega)\psi_n = \epsilon_n\psi_n \;\overbrace{\longrightarrow}^{\mathrm{BERW}}\; k\,\mathrm{cotg}(\delta)$$

NLO :

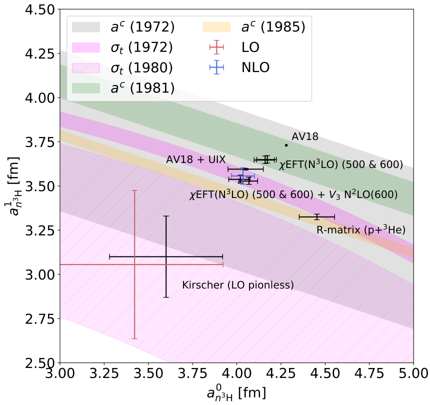
$$\epsilon_n^{(\mathrm{NLO})} = \epsilon_n + \langle\psi_n|\, V_\lambda^{(\mathrm{NLO})}\,|\psi_n\rangle \;\overbrace{\longrightarrow}^{\mathrm{BERW}}\; k\;\mathrm{cotg}(\delta^{(\mathrm{NLO})})$$

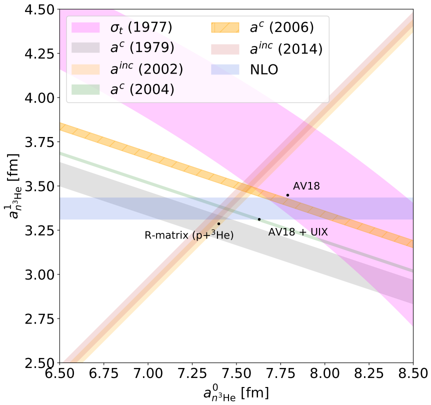
$n + {}^3\mathrm{H}$ and $n + {}^3\mathrm{He}$ scattering

(M. Schäfer, B. Bazak, Phys. Rev. C 107, 2023, 064001)



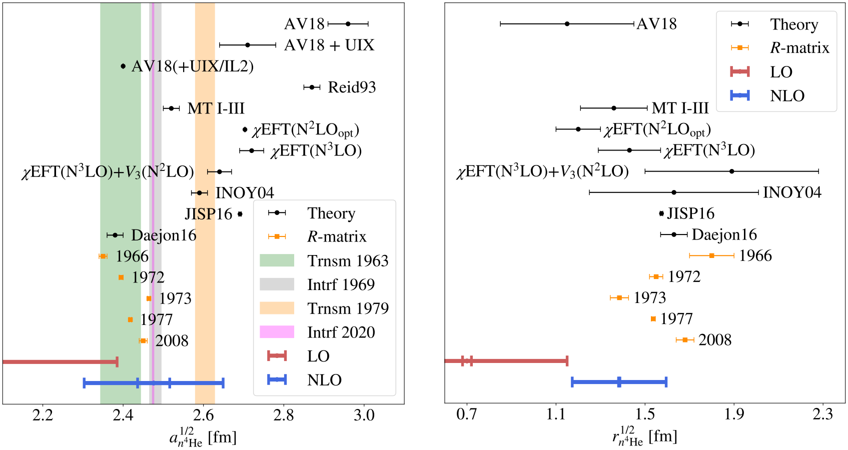
Experiment & Theory : $n + {}^3\mathrm{H}$ and $n + {}^3\mathrm{He}$ scattering lengths (M. Schäfer, B. Bazak, Phys. Rev. C 107, 2023, 064001)



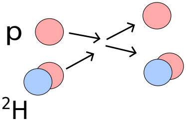


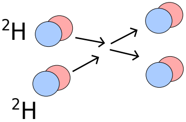
(Phys. Rev. C 42 (1990) 438; Phys. Rev. C 102 (2020) 034007; Few-Body Syst. 34 (2004) 105; Phys. Lett B 721 (2013) 355; Phys. Rev. C 68(R) (2003) 021002)

$n + {}^4\mathrm{He}$ scattering (M. Bagnarol et al., Phys. Lett. B 844, 2023, 138078)

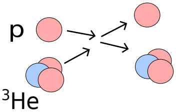


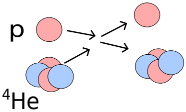
For references to all theoretical results, see (Phys. Lett. B 844 (2023) 138078).





Few-Body scattering with nonperturbative Coulomb interaction





$\not\pi$EFT potential with nonperturbative Coulomb interaction

- new *pp* 2-body cnt. force at LO
  (Kong, Ravndal, Nucl. Phys. A 665 (2000) 137; Rupak, Kong, Nucl. Phys. A 717 (2003) 73)
- new *ppn* 3-body cnt. force at NLO
  (J. Vanasse *et al.*, Phys. Rev. C 89 (2014) 064003; S. König *et al.*, J. Phys. G 42 (2015) 045101)

Additional leading order potential terms (1 LECs; iterated) :

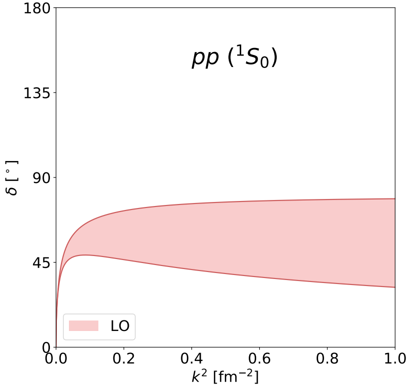
$$V_C^{(\mathrm{LO})} = \sum_{i<j} C_2^{(0)}(\lambda) P_{ij}^{T=1,S=0;pp} e^{-\frac{\lambda^2}{4}\mathbf{r}_{ij}^2} + \frac{e^2}{r}$$

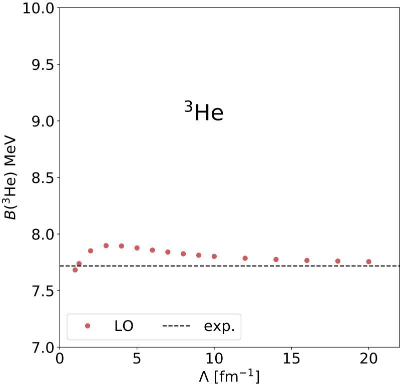
Additional next-to-leading order potential terms (3 LECs; 1st order PT) :

$$V_C^{(\mathrm{NLO})} = \sum_{i<j} P_{ij}^{T=1,S=0;pp} \left[C_4^{(1)}(\lambda) + C_5^{(1)}(\lambda)(\mathbf{k}^2 + \mathbf{q}^2) \right] e^{-\frac{\lambda^2}{4}\mathbf{r}_{ij}^2}$$

$$+ D_0^{(1)}(\lambda) \sum_{i<j<k} \mathcal{Q}_{ijk}^{T=1/2,S=1/2;ppn} \sum_{\mathrm{cyc}} e^{-\frac{\lambda^2}{4}(\mathbf{r}_{ij}^2 + .\mathbf{r}_{jk}^2)}$$

LO $\not\pi$EFT with nonperturbative Coulomb interaction



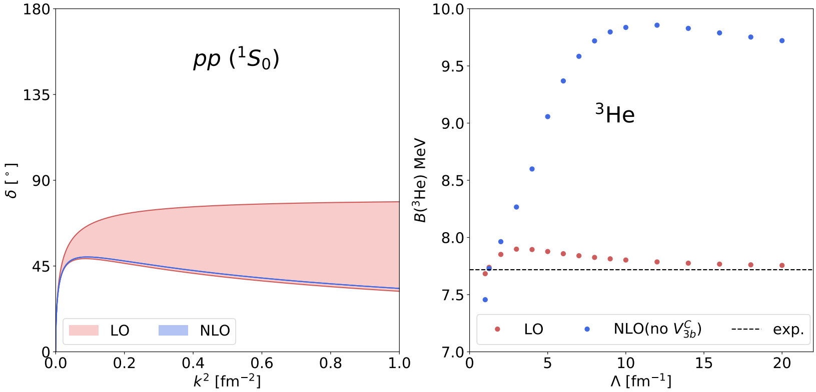


Additional LO parameters :

$a_{pp}(^1S_0) = \ -7.8063(26)$ fm

$e^2/(\hbar c)^2 = 1.44$ MeV.fm

NLO $\not\pi$EFT with nonperturbative Coulomb interaction



Additional NLO parameters :

$r_{pp}(^1S_0) = 2.794(14)$ fm

$B(^3\mathrm{He}) = 7.718$ MeV

BERW formula for charged projectile and target

(M. Bagnarol et al., Phys. Lett. B 861 (2025) 139230)

Quantization condition for the HO trap energy spectrum

$$\det\left[\cot\left(\delta(E)\right) - \mathcal{F}^{\mathrm{HO}}(E)\right] = 0$$

$$\mathcal{F}^{\mathrm{HO}}(E) = \left(2\mu k^{2l+1} C_l^2(\eta)\right)^{-1} \lim_{r,r'\to 0} \frac{\Re\left[G_l^C(r,r';E)\right] - G_l^{C,\,\omega}(r,r';E)}{(rr')^l}$$

(P. Guo, Phys. Rev. C 103 (2021) 064611; H. Zhang *et al.* Phys. Lett. B 850 (2024) 138490)

[20pt] $C_l(\eta) = \frac{2^l}{(2l+1)!}\left|\Gamma\left(l+1+i\eta\right)\right| e^{-\frac{\pi}{2}\eta}$; $\eta = q_1 q_2 \mu / k$

$G_l^C(r,r';E)$ ... Coulomb Green function
$G_l^{C,\,\omega}(r,r';E)$ ... Coulomb + HO potential Green function

BERW formula for charged projectile and target

(M. Bagnarol et al., Phys. Lett. B 861 (2025) 139230)

$\rightarrow$ developed new code to which connects $(E, \omega) \leftrightarrow (\delta, \omega)$

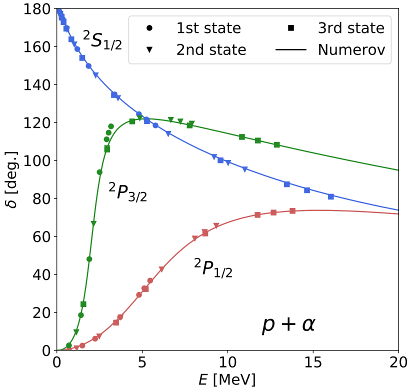
Limit approximation:

$$\frac{\Re\left[G_l^C(r_{\min}, r_{\min}, E)\right] - G_l^{C,\omega}(r_{\min}, r_{\min}, E)}{(r_{\min})^{2l}}$$

Numerical solution of Dyson equations:

$$G_l^C(r, r') = G_l^{\text{free}}(r, r') +$$
$$+ \int_0^{+\infty} \mathrm{d}r'' \; G_l^{\text{free}}(r, r'') \; r''^2 V_C(r'') \; G_l^C(r'', r')$$

$$G_l^{C,\,\omega}(r, r') = G_l^{\omega}(r, r') +$$
$$+ \int_0^{+\infty} \mathrm{d}r'' \; G_l^{\omega}(r, r'') \; r''^2 V_C(r'') \; G_l^{C,\,\omega}(r'', r')$$



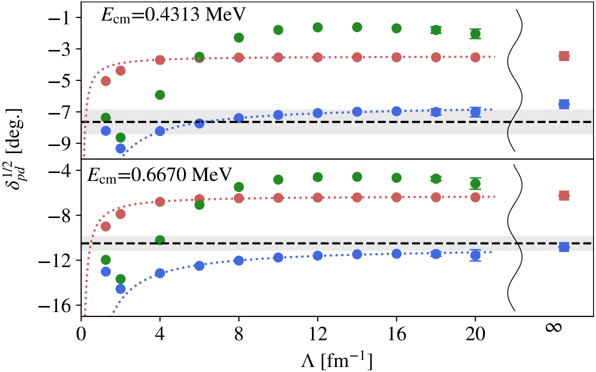
$\rightarrow$ code tested on s- and p-wave $p + \alpha$ scattering

s-wave $p + d$ scattering

(M. Rojik et al., arXiv:2507.16250 [nucl-th] 2025)

- experimental phase shifts from *pd* PSA

(M. H. Wood *et al.*, Phys. Rev. C 65 (2002) 0334002)



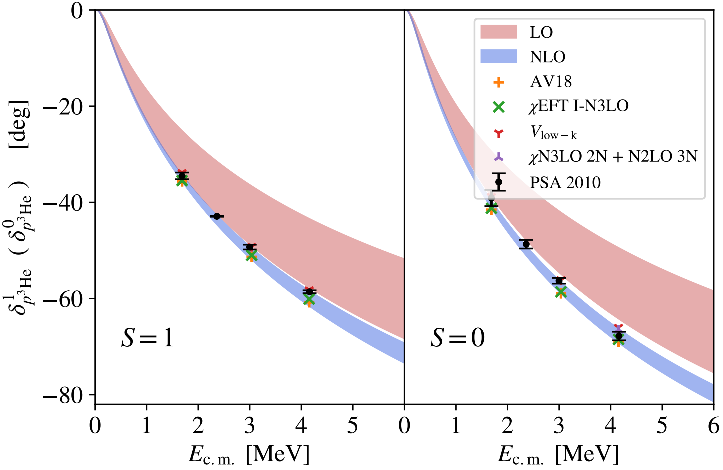
Inclusion of the NLO ppn force leads to a larger cutoff dependence in this channel.(J. Vanasse *et al.*, Phys. Rev. C 89 (2014) 064003

s-wave $p+{}^3$He scattering

(M. Rojik et al., arXiv:2507.16250 [nucl-th] 2025)

- experimental data from p^3He phase-shift analysis

(T. V. Daniels *et al.*, Phys. Rev. C 82 (2010) 034002)



Perturbative corrections to few-body observables

(S. Mondal et al., arXiv:2509.17366 [nucl-th] 2025)

Numerically feasible methods to calculate perturbative corrections to few-body observables

$$< \hat{O} >= O^{(0)} + \delta O^{(1)} + \delta O^{(2)} + \dots$$

Introducing multipliers:

$$\hat{H}[\alpha, \beta] \, |\psi\rangle = (\, \hat{T} + \hat{V}^{(0)} + \alpha \cdot \hat{V}^{(1)} + \beta \cdot \hat{O}) \, |\psi\rangle = E \, |\psi\rangle$$

$\rightarrow$ solving Schrödinger equation on the (α, β) grid
$\rightarrow$ energies and wave functions are functions of α and β

One-multiplier method:

$$< \hat{O} > \overset{(I)}{\equiv} O_n(\alpha; \beta = 0) \overset{(II)}{=} O_n^{(0)} + \sum_{i=1} \alpha^i \; \delta O_n^{(i)}$$

Perturbative corrections to few-body observables

(S. Mondal et al., arXiv:2509.17366 [nucl-th] 2025)

Introducing multipliers:

$$\hat{H}[\alpha,\beta]\,|\psi\rangle = (\hat{T} + \hat{V}^{(0)} + \alpha\cdot\hat{V}^{(1)} + \beta\cdot\hat{O})\,|\psi\rangle = E\,|\psi\rangle$$

Two-multiplier method:

$$E_n \overset{(I)}{\equiv} E_n(\alpha,\beta) \overset{(II)}{=} E_n^{(0,0)} + \sum_{\substack{i,j=0\\ i\neq j=0}}^{N} \alpha^i \beta^j \;\delta E_n^{(i,j)}$$

$\rightarrow$ applying Feynman-Hellmann theorem

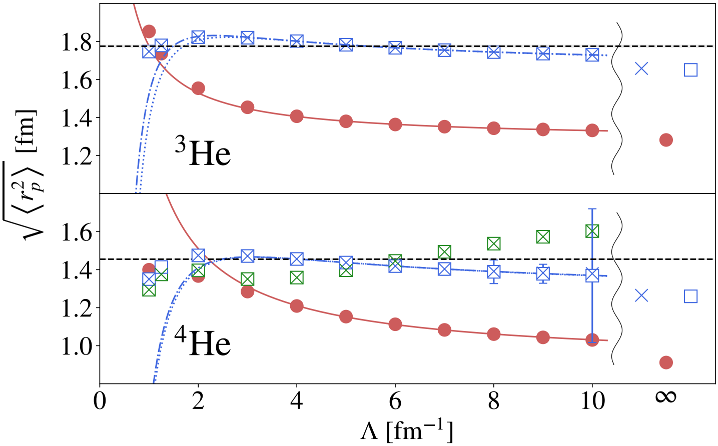
$$\frac{\partial E_n(\alpha,\beta)}{\partial\beta} = \left\langle \frac{\partial \hat{H}[\alpha,\beta]}{\partial\beta} \right\rangle = \hat{O}$$

relates the expansion coefficients linear in β, $\delta E(i,1)$, to the ith perturbation order of the observable

$$O_n^{(0)} + \sum_{i=1}^{N} \alpha^i \;\delta O_n^{(i)} = \delta E_n^{(0,1)} + \sum_{i=1}^{N} \alpha^i \;\delta E_n^{(i,1)}$$

Perturbative corrections to few-body observables

(S. Mondal et al., arXiv:2509.17366 [nucl-th] 2025)

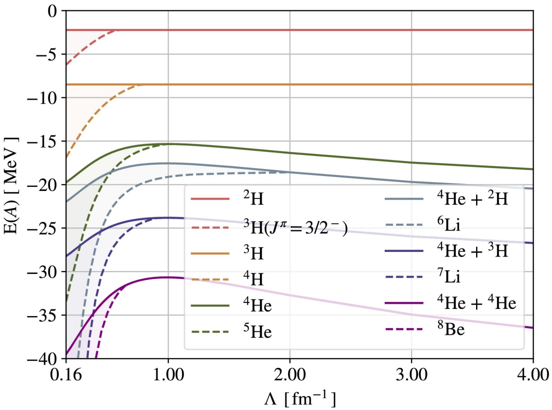


crosses - one-multiplier method

squares - two-multipliers method

LO $\not\pi$EFT calculations of several p-shell nuclei up to ^{8}Be

(M. Schäfer, L. Contessi, J. Kirscher, and J. Mareš, Phys. Lett. B 816 (2021) 136194)



I. Stetcu, B. R. Barrett, and U. van Kolck, Phys. Lett. B 653 (2007) 358

L. Contessi *et al.*, Phys. Lett. B 772 (2017) 839

W. G. Dawkins, J. Carlson, U. van Kolck, and A. Gezerlis, Phys. Rev. Lett. 124 (2020) 143402

Intermezzo

Conjecture based on the numerical evidence :

Beyond *s*-shell nuclear systems break in the zero-range limit into *p*, *n*, $^2\mathrm{H}$, $^3\mathrm{H}/^3\mathrm{He}$, and $^4\mathrm{He}$. (free nucleon(s) + spherically-symmetric fragments)

Option 1 :
LO shallow continuum pole; RG invariant; can be mutated into a bound state with perturbative insertions of sub-leading operators.

Option 2 :
Identical as above; nonperturbative mechanism required to move the pole into a bound-state region.

Option 3 :
No LO RG invariant continuum pole in the EFT's convergence radius; must be created nonperturbatively by modifying the LO.

^{4}H resonances

Experimental evidence :

→ n^3H elastic cross-sections

(Ann. Phys. 74 (1972) 250;Phys. Rev. C 22 (1980) 384)

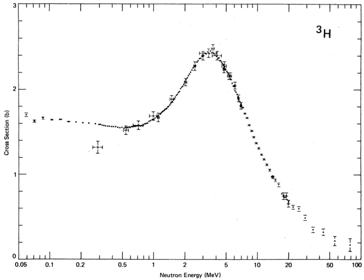
→ π^- absorption experiments

(Phys. Lett. B 103 (1981) 409; Nucl. Phys. A 531 (1991) 613)

→ transfer reactions

(Phys. Rev. C 33 (1986) 2204; Nucl. Phys. A 719 (2003) C229)

→ extracted resonance positions significantly differ



Theory :

→ RGM with complex scaling

(Phys. Rev. C 68 (2003) 034303)

→ Spin-dipole strength functions

(Phys. Rev C 87 (2013) 034001)

→ Faddeev-Yakubovsky equations

(Phys. Lett. B 791 (2019) 335)

→ No-core Gamov Shell Model

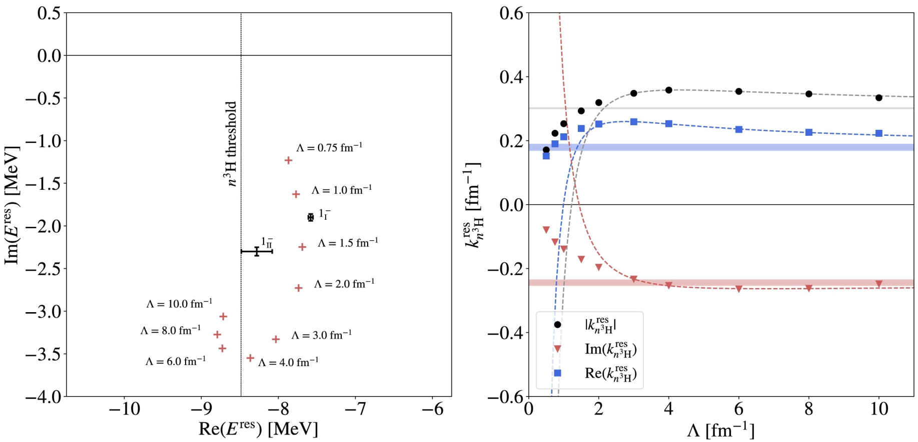
(Phys. Rev. C 104 (2021) 024319)

J^π	E_r [MeV]	Γ [MeV]
2^-	1.15(5)	3.97(7)
1^-_I	0.90(3)	3.80(8)
0^-	0.78(15)	7.7(7)
1^-_{II}	0.2(2)	4.6(1)

INOY; (Phys. Lett. B 791 (2019) 335)

Emergence of $^4\mathrm{H}$ $J^\pi = 1^-$ resonance in LO $\not\pi$EFT

(L. Contessi, M. Schäfer, J. Kirscher, R. Lazauskas, J. Carbonell, Phys. Lett. B 840 (2023) 137840)



$$k_{\mathrm{res}} = \sqrt{2\mu \tilde{E}_{\mathrm{res}}}, \qquad \tilde{E}_{\mathrm{res}} = E_{\mathrm{res}} - E_t$$

Summary

- Beyond *s*-shell nuclear systems break in the zero-range limit into *p*, *n*, $^{2}\mathrm{H}$, $^{3}\mathrm{H}/^{3}\mathrm{He}$, and $^{4}\mathrm{He}$ (conjecture based on the numerical evidence)
- Suprisingly, the same type of instability for $^{6}\mathrm{Li}$ and $^{16}\mathrm{O}$ found using RG-invariant power-counting scheme at LO in χEFT (Phys. Rev. C 103 (2021) 054304)
- Numerical evidence of stabilization of $^{4}\mathrm{H}$ $J^{\pi}=1^{-}$ resonance pole with increasing momentum cutoff

→ We can speculate that in heavier systems:

$^{6}\mathrm{Li}\rightarrow\alpha+\mathrm{d}$	(likely 4+2 virtual(antibound) state)
$^{6}\mathrm{He}\rightarrow\alpha+\mathrm{n}+\mathrm{n}$	(likely 4+1+1 resonance)
$^{7}\mathrm{Li}\rightarrow\alpha+\mathrm{t}$	(likely 4+3 resonance)
$^{8}\mathrm{Be}\rightarrow\alpha+\alpha$	(likely 4+4 virtual(antibound) state)
$^{16}\mathrm{O}\rightarrow\alpha+\alpha+\alpha+\alpha$	(likely 4+4+4+4 resonance)

Improved action on (no only) nuclear EFTs

L. Contessi, M. Schäfer, A. Gnech, A. Lovato, U. van Kolck, arXiv:2505.09299 [nucl-th]

L. Contessi, M. Schäfer, U. Van Kolck, Phys.Rev.A 109 (2024) 022814
L. Contessi, M. P. Valderrama, U. Van Kolck, Phys Lett B 856 (2024) 138903

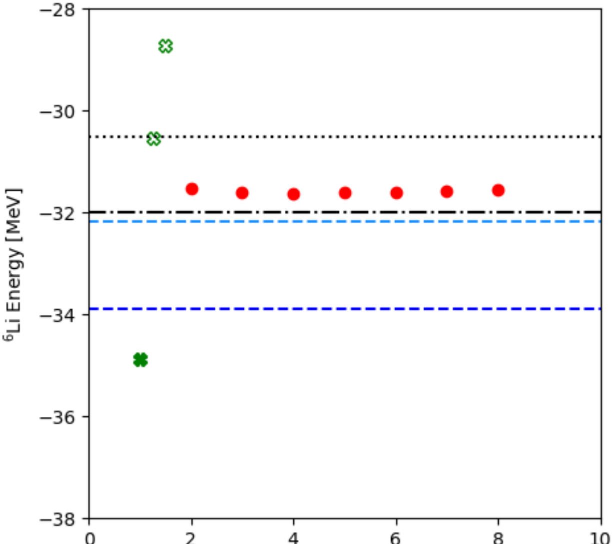
Starting at LO with a certain "fake" finite range to sustain the bound states

$$\begin{aligned}
\tilde{V}^{(0)}_{2\mathrm{B}}(x) &= \tilde{C}^{(0)}_{0,s} \sum_{i<j} \mathcal{P}_{ij,s} \delta_{(xR_s)^{-1}}(\vec{r}_{ij}) \\
&+ \tilde{C}^{(0)}_{0,t} \sum_{i<j} \mathcal{P}_{ij,t} \delta_{(xR_t)^{-1}}(\vec{r}_{ij}), \\
\tilde{V}^{(0)}_{3\mathrm{B}}(x) &= \tilde{D}^{(0)} \sum_{i<j<k} \sum_{\mathrm{cyc}} \delta_{(xR_3)^{-1}}(\vec{r}_{ij})\, \delta_{(xR_3)^{-1}}(\vec{r}_{jk}).
\end{aligned}$$

- higher-order perturbative corrections remain unchanged
- "fake" range must be sufficiently small so that it is reabsorbed at higher-orders
- power-counting remains unchanged

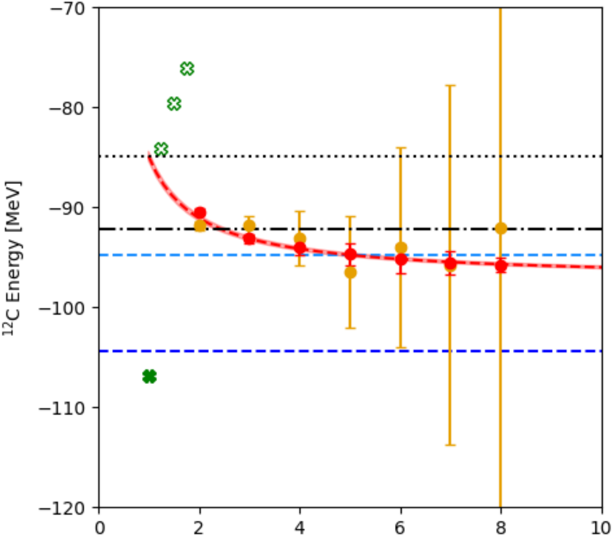
Improved action: ^{6}Li

L. Contessi, M. Schäfer, A. Gnech, A. Lovato, U. van Kolck, arXiv:2505.09299 [nucl-th]



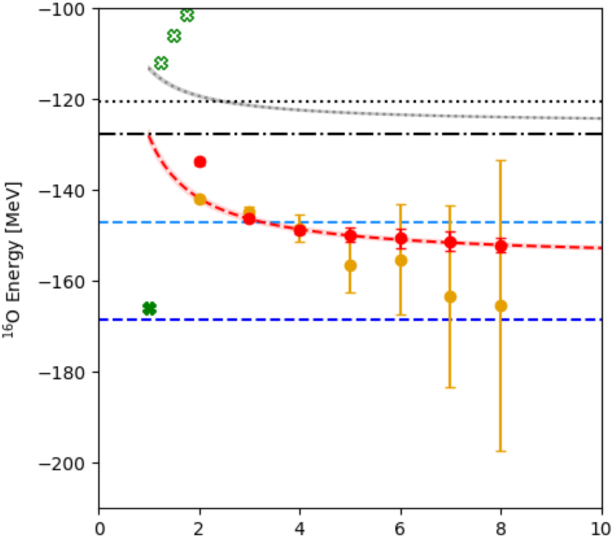
Improved action: ^{12}C

L. Contessi, M. Schäfer, A. Gnech, A. Lovato, U. van Kolck, arXiv:2505.09299 [nucl-th]



Improved action: ^{16}O

L. Contessi, M. Schäfer, A. Gnech, A. Lovato, U. van Kolck, arXiv:2505.09299 [nucl-th]



Questions

How to asses *a priori* typical momenta in nuclear reactions ? (too high for EFT to converge with increasing order)

Which experimental data one should choose to fit parameters (LECs) of the EFT?

On the few-body level the cutoff can not be always varied up to arbitrary high value due to numerical reasons. How we should then asses renormalizability of higher-order EFT corrections to establish the power-counting?

How to accurately evaluate higher-order perturbative corrections in few-body nuclear reactions? Which reaction technique is the most convenient to use?