$\not\pi$EFT in $A \leq 3$ systems: status, long-term plan, and challenges

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Nuclear interaction behind the looking glass

Nuclear interaction :

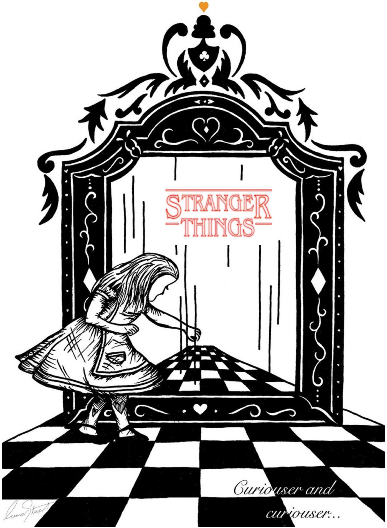
Two-body
(*NN* scattering, $^{2}\mathrm{H}$)

Three-body
(*Nd* scattering, $^{3}\mathrm{H}$, $^{3}\mathrm{He}$, ...)

Bound state properties
($^{4}\mathrm{He}$, ...)

$\longrightarrow$
Precise few-body methods
$\longrightarrow$

Few-body $A > 3$ continuum
(scattering, reactions, ...)



Nuclear few-body continuum

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

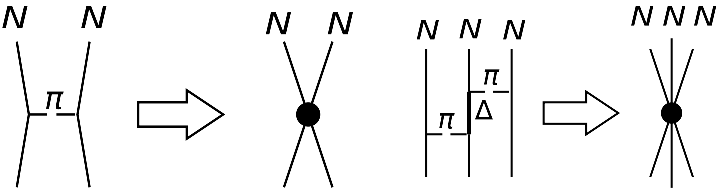
Splitting between $^2P_{3/2}$ and $^2P_{1/2}$ partial waves in $^4\mathrm{He} + \mathrm{n}$

(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)

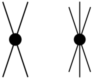
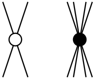
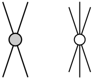
$\not\pi$EFT - basic idea



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

- 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 $\Lambda \rightarrow \infty$

  $$O_\Lambda = O_\infty + \frac{\alpha}{\Lambda} + \frac{\beta}{\Lambda^2} + \frac{\gamma}{\Lambda^3} + \dots$$

$\not\pi$EFT potential at LO and NLO

Leading order potential (3 LECs) :

$$V_\Lambda^{(\mathrm{LO})} = \sum_{i<j} \left[C_0^{(0)}(\Lambda) P_{ij}^{T=1,S=0} + C_1^{(0)}(\Lambda) P_{ij}^{T=0,S=1} \right] e^{-\frac{\Lambda^2}{4}\mathbf{r}_{ij}^2}$$

$$+ D_0^{(0)}(\Lambda) \sum_{i<j<k} \mathcal{Q}_{ijk}^{T=1/2,S=1/2} \sum_{\mathrm{cyc}} e^{-\frac{\Lambda^2}{4}(\mathbf{r}_{ij}^2+\mathbf{r}_{jk}^2)}$$

Next-to-leading order potential (6 LECs) :

$$V_\Lambda^{(\mathrm{NLO})} = \sum_{i<j} \left[C_0^{(1)}(\Lambda) P_{ij}^{T=1,S=0} + C_1^{(1)}(\Lambda) P_{ij}^{T=0,S=1} \right] e^{-\frac{\Lambda^2}{4}\mathbf{r}_{ij}^2}$$

$$+ \sum_{i<j} \left[C_2^{(1)}(\Lambda) P_{ij}^{T=1,S=0} + C_3^{(1)}(\Lambda) P_{ij}^{T=0,S=1} \right] (\mathbf{k}^2 + \mathbf{q}^2) e^{-\frac{\Lambda^2}{4}\mathbf{r}_{ij}^2}$$

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

$$+ E_0^{(1)}(\Lambda) \sum_{i<j<k<l} \mathcal{Q}_{ijkl}^{T=0,S=0} e^{-\frac{\Lambda^2}{4}(\mathbf{r}_{ij}^2+\mathbf{r}_{ik}^2+\mathbf{r}_{il}^2+\mathbf{r}_{jk}^2+\mathbf{r}_{jl}^2+\mathbf{r}_{kl}^2)}$$

Various applications ...

Analysis of LQCD data (LO; A $\leq$ 16)

(N. Barnea et al., Phys. Rev. Lett. 114 (2015) 052501)
(M. Eliyahu, Phys. Rev. C 102 (2020) 044003)
(W. Detmold et al., Phys. Rev. D 103 (2021) 074503)
(R. Yaron et al., Phys. Rev. D 106 (2022) 014511)

(T. Attia-Weiss et al., Phys. Rev. D 109 (2024) 114515)

Hypernuclei (LO; A $\leq$ 6)

(L. Contessi et al., Phys. Rev. Lett. 121 (2018) 102502)
(L. Contessi et al., Phys. Lett. B 797 (2019) 134893)
(F. Hildenbrand et al., Phys. Rev. C 102 (2020) 064002)
(M. Schäfer et al. Phys. Lett. B 808 (2020) 135614)
M. Schäfer et al., Phys. Rev. C 103 (2021) 025204)
(M. Schäfer et al., Phys. Rev. C 105 (2022) 015202)

(M. Schäfer et al., Phys. Rev. C 106 (2022) L031001)

Atomic systems (LO & NLO; A $\leq$ 6)

(B. Bazak et al., Phys. Rev. A 94 (2016) 052502)

(B. Bazak et al. Phys. Rev. Lett. 122 (2019) 143001)

η-nuclei (LO)

(N. Barnea et al., Phys. Lett. B 771 (2017) 297)

$\rightarrow$ here, I will show selected results of few-body nuclear systems

$\not\pi$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)

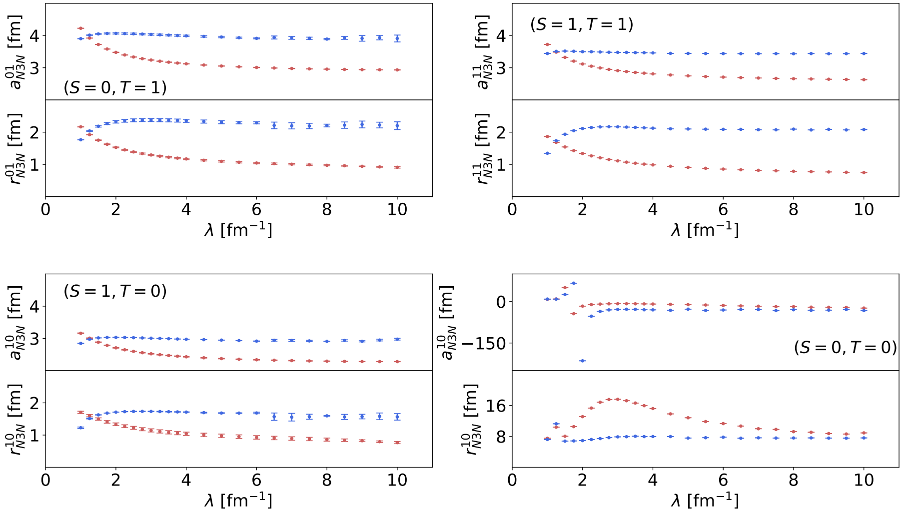
What do we want to study ?

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

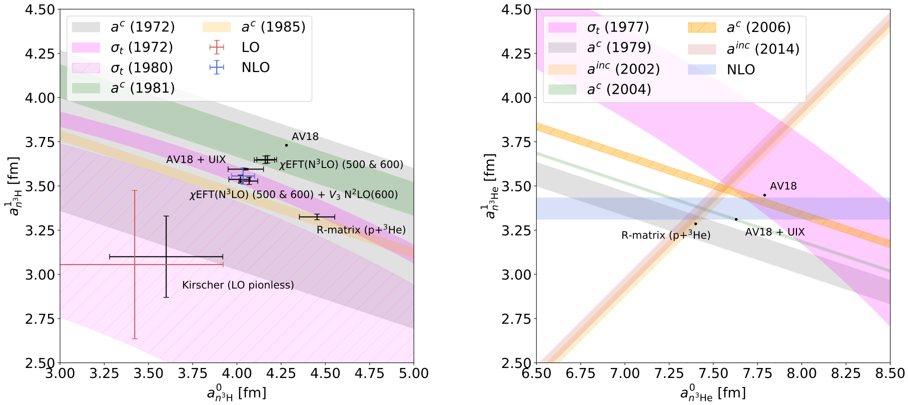
$\longrightarrow$ techniques developed for $\not\pi$EFT can be also used in other renormalizable EFTs that demand perturbative corrections
(nuclear EFTs with perturbative pions, RG-invariant versions of χEFT, ...)

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

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

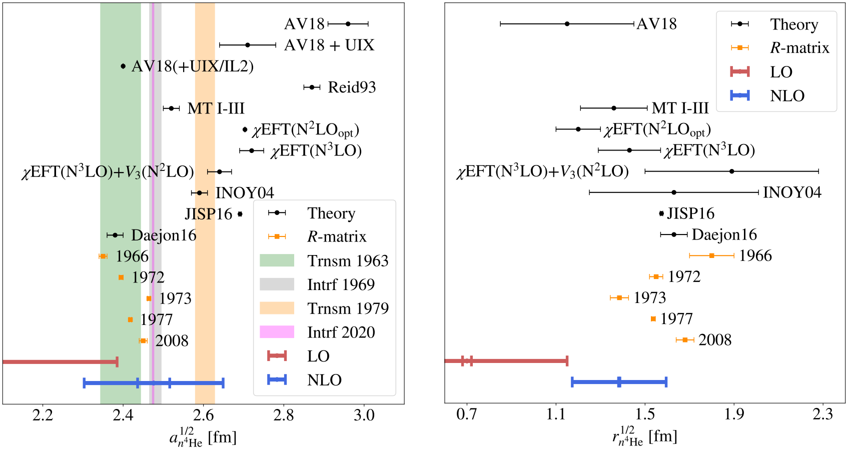


Experiment & Theory : $n + {}^3\mathrm{H}$ and $n + {}^3\mathrm{He}$ scattering lengths (M. Schäfer, B. Bazak, Phys. Rev. C 107, 2023, 064001)



(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)

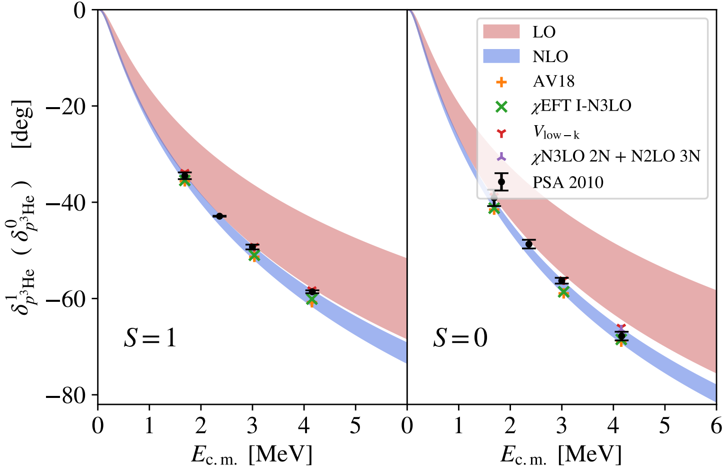
$n + {}^4\mathrm{He}$ scattering (M. Bagnarol et al., Phys. Lett. B 844, 2023, 138078)



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

Adding non-perturbative Coulomb: $p + {}^3\mathrm{He}$ scattering

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

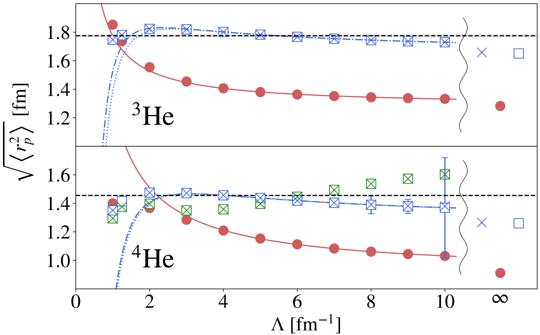


Point-proton rms charge radii of light nuclei

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

One- and two-multipliers methods:

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



→ paths the way to numerically feasible calculations of higher-order perturbative corrections of few-body observables

Summary & Outlook

- constructed $\not{\pi}$EFT potential with nonperturbative Coulomb interaction up to NLO
- tests on calculation of bound states, rms radii, scattering processes of $A \leq 5$ nuclear systems

Next steps :

- ongoing work on higher $\not{\pi}$EFT corrections $(\mathrm{N^2LO},\ \mathrm{N^3LO},...)$
- scattering in higher partial waves
- accurate calculations of nuclear rms charge radii
- inelastic scattering, nuclear reactions