Progress in the quest for a realistic 3N force

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joint project with

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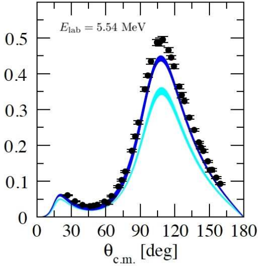

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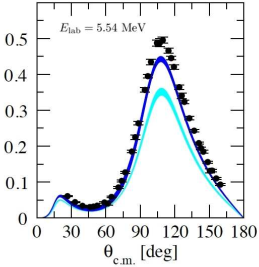
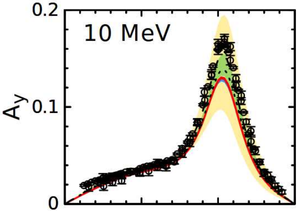
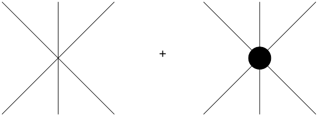




- For Nd, possibly affected by large uncertainty [LENPIC, 1505.07218]

Subleading 3N LECs

- next genuine $3N$ LECs appear at N4LO



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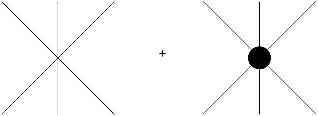

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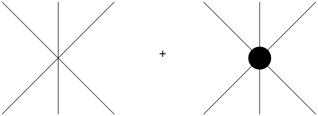

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- a local $3N$ potential

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\begin{aligned}
V \;=\; & \sum_{i\neq j\neq k} (E_1 + E_2 \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j + E_3 \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j + E_4 \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) \left[Z_0''(r_{ij}) + 2 \frac{Z_0'(r_{ij})}{r_{ij}} \right] Z_0(r_{ik}) \\
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& + (E_7 + E_8 \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_k)(\mathbf{L} \cdot \mathbf{S})_{ij} \frac{Z_0'(r_{ij})}{r_{ij}} Z_0(r_{ik}) \\
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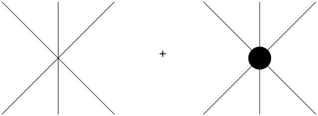

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- is this possible? it depends on the flexibility of the subleading contact potential to fill existing discrepancies
- to check the flexibility, we start with AV18 *NN* potential and no 3NF whatsoever
- we then fit the relevant LECs to reproduce the bound state b.e., the doublet and quartet $n-d$ scattering lengths and accurate experimental data on $p-d$ differential cross section and polarization observables at 3 MeV proton energy [Shimizu et al. PRC52 (1995) 1193]
- for so doing we use the HH method

Numerical implementation

The N-d scattering wave function is written as

$$\Psi_{LSJJ_z} = \Psi_C + \Psi_A$$

with Ψ_C expanded in the HH basis

$$|\Psi_C\rangle = \sum_\mu c_\mu |\Phi_\mu\rangle$$

and Ψ_A describing the asymptotic relative motion

$$\Psi_A \sim \Omega^R_{LS}(k,r) + \sum_{L'S'} R_{LS,L'S'}(k)\Omega^I_{L'S'}(k,r)$$

with the unknown c_μ and R-matrix elements (related to the S-matrix) to be determined so that the Kohn functional is stationary

$$[R_{LS,L'S'}] = R_{LS,L'S'} - \langle \Psi_C + \Psi_A | H - E | \Psi_C + \Psi_A \rangle$$

imposing the Kohn functional to be stationary leads to a *linear* system

$$\sum_{L''S''} R_{LS,L''S''} X_{L'S',L''S''} = Y_{LS,L'S'}$$

with the matrices

$$X_{LS,L'S'} = \langle \Omega^I_{LS} + \Psi^I_C | H - E | \Omega^I_{L'S'} \rangle \quad Y_{LS,L'S'} = -\langle \Omega^R_{LS} + \Psi^R_C | H - E | \Omega^I_{L'S'} \rangle$$

and the $\Psi^{R/I}_C$ solutions of

$$\sum_{\mu'} c_\mu \langle \Phi_\mu | H - E | \Phi_{\mu'} \rangle = -D^{R/I}_{LS}(\mu)$$

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11 set of matrices are calculated once for all, and only linear systems are solved for each choice of E_i's

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- we exclude 1 LEC from the fits (e.g. E_8) and absorb its effect in the remaining LECS

Fit strategy

- we first rescale the LECs using naïve dimensional analysis

$$E_0 = \frac{c_E}{F_\pi^4 \Lambda} \ \text{(LO)}, \quad E_{i=1,\ldots,10} = \frac{e_i^{NN}}{F_\pi^4 \Lambda^3} \ \text{(NLO)}$$

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- we study the sensitivity of the 6 observables to the 10 LECs by performing 2-parameter fits for each one
- we find that E_3 can be used with c_E to reproduce $B(^3\text{H})$ and *nd* scattering lengths; moreover

$$T_{20} \to E_5, \quad A_y, T_{11} \to E_7, \quad T_{21} \to E_{10}, \quad T_{22} \to E_9$$

- this allows to establish starting points for the minimization procedure

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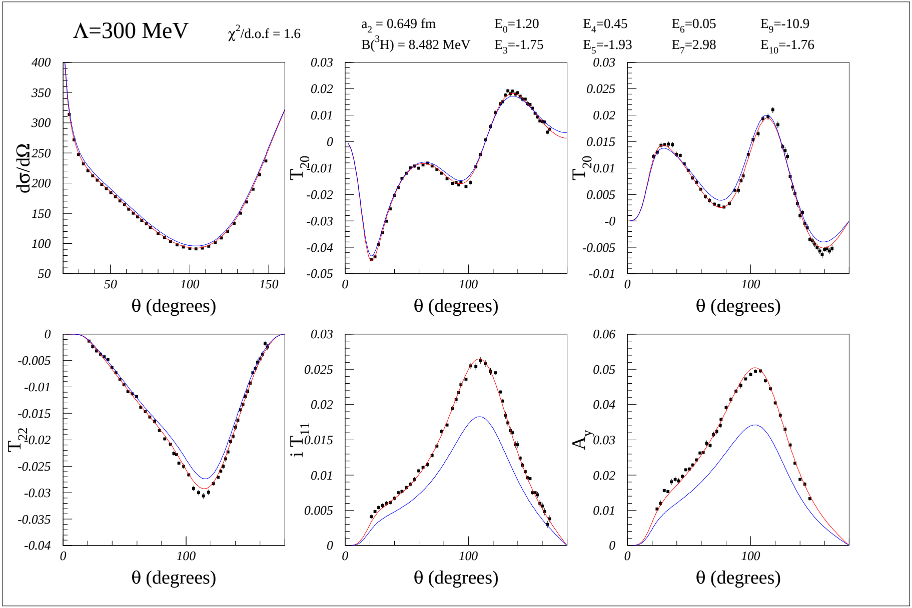
- e.g. for $\Lambda = 300$ MeV we obtain $\chi^2/\mathrm{d.o.f.} = 1.6$


Λ=300 MeV
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a₂ = 0.649 fm
B(³H) = 8.482 MeV
E₀=1.20
E₃=-1.75
E₄=0.45
E₅=-1.93
E₆=0.05
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E₁₀=-1.76
dσ/dΩ
T₂₀
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- needed theoretical uncertainty to make $\chi^2 \sim 1$: 1 %
- experimental errors given with 1 significant digit: a 10% larger error would imply $\chi^2 \sim 1.6 \to 1.3$, in line with realistic NN potentials

Insight from the large-N_c limit

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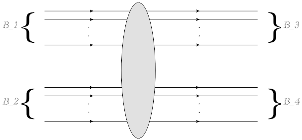

$$T \sim N_c \sum \left(\frac{S}{N_c}\right)^n_S \left(\frac{I}{N_c}\right)^n_I \left(\frac{G}{N_c}\right)^n_G \qquad S \sim \sigma, I \sim \tau, G \sim \sigma\tau$$

[Kaplan, Savage, Dashen, Jenkins, Manohar,...]

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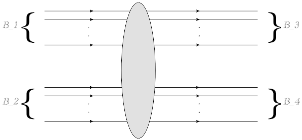

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- as a result, one finds e.g.

$$\mathbf{1} \sim \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \sim O(N_c)$$

while

$$\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \sim \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \sim O(1/N_c)$$

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$$\mathcal{L} = c_1 N^\dagger N N^\dagger N + c_2 N^\dagger \sigma_i N N^\dagger \sigma_i N + c_3 N^\dagger \tau^a N N^\dagger \tau^a N + c_4 N^\dagger \sigma_i \tau^a N N^\dagger \sigma_i \tau^a N \equiv \sum_i c_i o_i$$

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- observable quantities will depend on two combinations of LECs,

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$$\mathcal{L} = (c_1 - 2c_3 - 3c_4) N^\dagger N N^\dagger N + (c_2 - c_3) N^\dagger \sigma_i N N^\dagger \sigma_i N$$

reobtaining the well-established fact that $C_S >> C_T$

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- but since the 6 operators are all proportional, the LEC associated to any choice will be $\sim O(N_c)$

3NF and large-N_c

the generalization to 3 nucleon forces has been given recently [D.R.Phillips and C.Schat, PRC88 (2013) 034002] at the leading order one finds

$$\begin{aligned}\mathcal{L} \equiv & -\sum_i^6 E_i O_i = -E_1 N^\dagger N N^\dagger N N^\dagger N - E_2 N^\dagger \sigma^i N N^\dagger \sigma^i N N^\dagger N \\ & -E_3 N^\dagger \tau^a N N^\dagger \tau^a N N^\dagger N - E_4 N^\dagger \sigma^i \tau^a N N^\dagger \sigma^i \tau^a N N^\dagger N \\ & -E_5 N^\dagger \sigma^i N N^\dagger \sigma^i \tau^a N N^\dagger \tau^a N - E_6 \epsilon^{ijk} \epsilon^{abc} N^\dagger \sigma^i \tau^a N N^\dagger \sigma^j \tau^b N N^\dagger \sigma^k \tau^c N\end{aligned}$$

- only E_1, E_4 and E_6 are $O(N_c)$
- but since the 6 operators are all proportional, the LEC associated to any choice will be $\sim O(N_c)$
- operators with different scaling properties in $1/N_c$ get mixed

large-N_c constraints on subleading 3N contact interaction

- applying Phillips and Schat counting to our redundant operators we get 13 leading structures
- using Fierz identities we find 7 leading operators, out of 10
- we thus have predictions for some of the E_i

$$E_2 = 0 + O(1/N_c)$$
$$E_3 = E_5 + O(1/N_c)$$
$$E_9 = 3E_3 + O(1/N_c)$$

- after isospin $1/2$ projection, working with $E_8 = 0$, large-N_c constraints become

$$\tilde{E}_2 = \frac{2}{3}(\tilde{E}_3 - \tilde{E}_5) + O(1/N_c), \qquad \tilde{E}_9 = 3E_5 + O(1/N_c)$$

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not too far from the fits' outcome

Summary and outlook

- We advocate a pragmatic approach, in which the subleading $3N$ contact interaction is treated as a sort of remainder, to fine-tune existing realistic models
- we tested the feasability of this approach by adopting the AV18 NN interaction. The χ^2 is drastically reduced, until 1.6 per d.o.f.
- 3 MeV data are very well described, *within a theoretical uncertainty of 1%*
- we have identified the constraints from the large-N_c limit, which are qualitatively satisfied

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It will be interesting,

- to repeat the analysis using a realistic pionless NN potential;
- to extend the analysis to other energies, and to include the breakup channel