Nuclear electromagnetic charge and current operators in ChEFT

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S. Pastore, J. Goity, R. Schiavilla Phys. Rev. C78 (2008) 064002

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L. Girlanda et al. Phys. Rev. Lett. 105 (2010) 232502

S. Pastore et al. Phys. Rev. C84 (2011) 024001

Outline

Chiral symmetry and nuclear physics

QCD chiral symmetry $\longleftarrow$ pions $\longrightarrow$ nuclear physics

- pions are the consequence of spontaneous chiral symmetry breaking
- pions mediate the nuclear interaction

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the connection can be made more precise in the context of a low-energy effective field theory with pions and nucleons.
Power counting is the organizing principle
-it works because of chiral symmetry: Goldstone bosons have derivative interactions
-it explains the hierarchy of nuclear forces and gives rise to realistic potentials (Entem-Machleidt, Epelbaum-Gloeckle-Meissner)

External currents can be naturally incorporated: their couplings are strongly constrained, because they are coupled to the Noether currents of chiral symmetry

this idea goes back to the original Weinberg proposal, on the hybrid approach.

work on electromagnetic processes:

- Park, Min, Rho, 1996
  application to hybrid calculations in A=2-4 systems (Song, Lazauskas, Park, 2009-2011)
- Meissner, Walzl, 2001; D. Phillips 2003
  isoscalar component, applied to deuteron static properties and form factors
- Koelling, Epelbaum, Krebs, Meissner, 2009-2011
  within the unitary transformation formalisms;
  hybrid application to d and ^{3}He photodisintegration (Rozpedzik et al, 2011)

Consider the NN amplitude

$$\langle f|T|i\rangle = \langle f|H_I \sum_n \left(\frac{1}{E_i - H_0 + i\epsilon} H_I\right)^{n-1} |i\rangle$$

a generic (reducible or irreducible) contribution with N vertices will scale like

$$\left[\prod_{i=1}^{N} p^{\nu_i}\right] p^{-(N-N_K-1)} p^{-2N_K}$$

out of the $N-1$ energy denominators, N_K are purely nucleonic (small) the remaining (large) energy denominators can be further expanded in E/ω_π

$$\frac{1}{E_i - E_I - \omega_\pi} \sim -\frac{1}{\omega_\pi}\left[1 + \frac{E_i - E_I}{\omega_\pi} + \ldots\right]$$

at the end

$$T = T^{(0)} + T^{(1)} + T^{(2)} + \ldots, \quad T^{(n)} \sim O(p^n)$$

We can define $v = v^{(0)} + v^{(1)} + \ldots$ such that

$$T = v + vG_0 v + vG_0 vG_0 v + \ldots$$

order by order in the chiral expansion

Solving for $v^{(n)}$ we have

$$
\begin{aligned}
v^{(0)} &= T^{(0)} , \\
v^{(1)} &= T^{(1)} - \left[v^{(0)} G_0 v^{(0)} \right] , \\
v^{(2)} &= T^{(2)} - \left[v^{(0)} G_0 v^{(0)} G_0 v^{(0)} \right] \\
&\quad - \left[v^{(1)} G_0 v^{(0)} + v^{(0)} G_0 v^{(1)} \right] , \\
v^{(3)} &= T^{(3)} - \left[v^{(0)} G_0 v^{(0)} G_0 v^{(0)} G_0 v^{(0)} \right] \\
&\quad - \left[v^{(1)} G_0 v^{(0)} G_0 v^{(0)} + \text{permutations} \right] \\
&\quad - \left[v^{(2)} G_0 v^{(0)} + v^{(0)} G_0 v^{(2)} \right] - \left[v^{(1)} G_0 v^{(1)} \right] .
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where $G_0 \sim p^{-2} d^3 p \sim O(p)$

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where $G_0 \sim p^{-2} d^3 p \sim O(p)$

- this procedure allows to systematically subtract the terms due to the iteration of the dynamical equation
- nevertheless it is ambiguous, because we need the $v^{(n)}$ *off shell*

There exist a whole class of 2nd order recoil corrections to OPE which are equivalent on shell, parametrized by a parameter ν (Friar 1980)

$$v_{RC}^{(2)}(\nu=0) = v_\pi^{(0)}(\mathbf{k})\,\frac{(E_1'-E_1)^2+(E_2'-E_2)^2}{2\omega_k^2}$$

$$v_{RC}^{(2)}(\nu=1) = -v_\pi^{(0)}(\mathbf{k})\,\frac{(E_1'-E_1)(E_2'-E_2)}{\omega_k^2}$$

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The off-shell ambiguities will affect successive terms $v^{(n)}$: for each $v^{(2)}(\nu)$ there is a corresponding $v^{(3)}$

However, the different choices are related by a unitary transformation,

$$H(\nu) = \mathrm{e}^{-iU(\nu)}H(\nu=0)\mathrm{e}^{iU(\nu)}$$

with $U = U^{(0)} + U^{(1)} + \ldots$ explicitly

$$i\,U^{(0)}(\nu) = -\nu\,\frac{v_\pi^{(0)}(\mathbf{p}'-\mathbf{p})}{(\mathbf{p}'-\mathbf{p})^2+m_\pi^2}\,\frac{p'^{\,2}-p^{\,2}}{2\,m_N}, \qquad i\,U^{(1)}(\nu) = -\frac{\nu}{2}\int_{\mathbf{s}}\frac{v_\pi^{(0)}(\mathbf{p}'-\mathbf{s})v_\pi^{(0)}(\mathbf{s}-\mathbf{p})}{(\mathbf{p}'-\mathbf{s})^2+m_\pi^2}$$

thus extending the unitary equivalence to the TPEP

Analogously for the electromagnetic transition operator $v_\gamma = A^0\rho - \mathbf{A}\cdot\mathbf{j}$ we start by expanding the amplitude $T_\gamma = T_\gamma^{(-3)} + T_\gamma^{(-2)} + \ldots$ and then match order by order

$$
\begin{aligned}
v_\gamma^{(-3)} &= T_\gamma^{(-3)} \\
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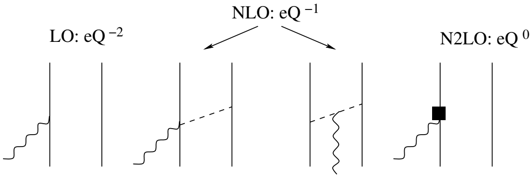
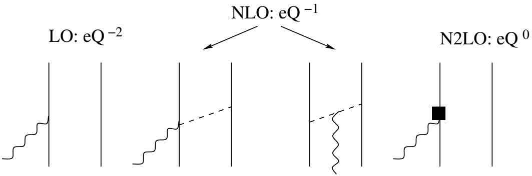
\end{aligned}
$$

At this order, the offshell ambiguity in v affects only the charge operator However, $\rho(\nu) = \mathrm{e}^{-iU(\nu)}\rho(\nu=0)\mathrm{e}^{iU(\nu)}$ with the same $U(\nu)$ as before



- 1-body operator (convection current and spin-magnetization)
- Two-body currents (seagull and pion-in-flight) - only isovector
- Relativistic corrections to the 1-body operator



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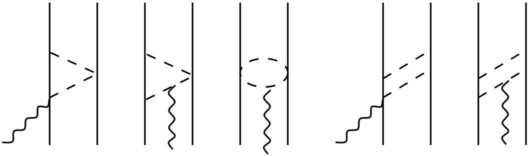
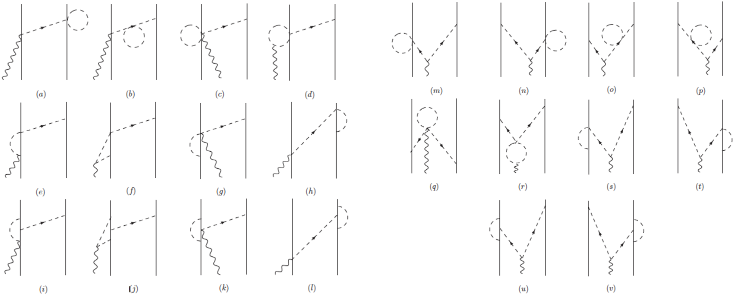
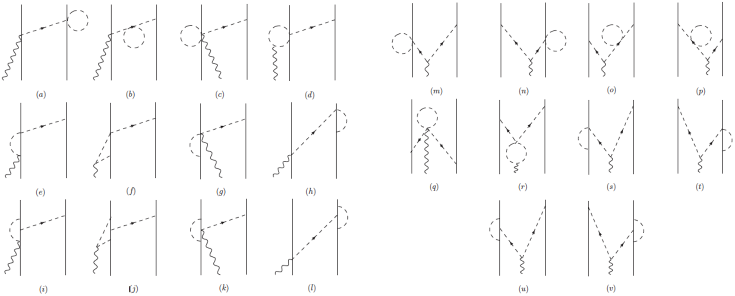
At N3LO, $O(eQ)$



- Two-pion exchange diagrams - only isovector



- one loop corrections to the one pion exchange. From comparison with Koelling et al. these contributions need revision



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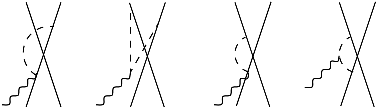
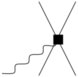


- loop corrections to contact operators. We have revised these by considering recoil corrections in the one-body sector, in order to properly identify the irreducible contribution. As a result all these contributions cancel, in agreement with Koelling et al.

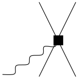


Contact terms from the subleading Lagrangian

There are two classes of contributions:

- terms from the gauging of the subleading two nucleon contact Lagrangian (minimal substitution)
  these can be expressed in terms of the same LECs entering the *NN* potential
- terms involving the electromagnetic field strenght tensor - 1 isoscalar and 1 isovector

$$\mathbf{j}^{(1)} = -i\, e \left[C'_{15}\, \boldsymbol{\sigma}_1 + C'_{16}\, (\tau_{1,z} - \tau_{2,z})\, \boldsymbol{\sigma}_1 \right] \times \mathbf{q} + 1 \rightleftharpoons 2 \;,$$



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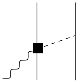


Subleading corrections to one pion exchange

$$\mathbf{j}^{(1)} = i\, e\, \frac{g_A}{F_\pi^2} \frac{\boldsymbol{\sigma}_2 \cdot \mathbf{k}_2}{\omega_{k_2}^2} \left[\Big(d'_8 \tau_{2,z} + d'_9\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \Big) \mathbf{k}_2 - d'_{21} (\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2)_z\, \boldsymbol{\sigma}_1 \times \mathbf{k}_2 \right] \times \mathbf{q} + 1 \rightleftharpoons 2 \,,$$

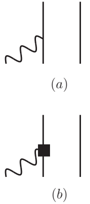
two isovector and one isoscalar. One additional contribution vanishes for real photons

Magnetic moment operator

- comparison with Koelling (2009-2011)
  - LO, NLO, N2LO, N3LO TPE, N3LO CT, N3LO tree agree
  - loop corrections to OPE related to the renormalization missing. Renormalization is accomplished by Koelling et al.
- comparison with Park (1996)
  - Sachs' magnetic moment, depending on the center of mass position, was not considered
  - TPE box contribution at N3LO is different, because of the absence of recoil corrections

$e\,Q^{(-3)}$

$e\,Q^{(-1)}$



leading seagull and pion-in-flight vanish

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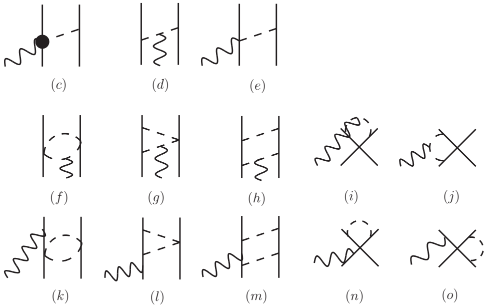

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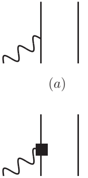

(a) (b)

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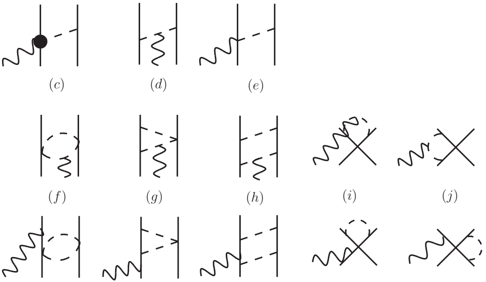

(c) (d) (e)

(f) (g) (h) (i) (j)

(k) (l) (m) (n) (o)

All divergences cancel, since there are no LECs contributing. Pion loop correction to one pion exchange need revision. Relativity corrections not included yet.

The UT method

Epelbaum, Gloeckle, Meissner, Krebs, Koelling

- a formalism to integrate out the pions from the theory, decoupling the purely nucleonic subspace from pions (Okubo, 1957)

$$\tilde{H} = U^\dagger H U = \begin{pmatrix} \eta \tilde{H} \eta & 0 \\ 0 & \lambda \tilde{H} \lambda \end{pmatrix}, \quad U = \begin{pmatrix} (1 + A^\dagger A)^{-1/2} & -A^\dagger (1 + AA^\dagger)^{-1/2} \\ A(1 + A^\dagger A)^{-1/2} & (1 + AA^\dagger)^{-1/2} \end{pmatrix}$$

  where $A = \lambda A \eta$ and $\eta = 1 - \lambda$ projects on the purely nucleonic subspace
- in effective theories, with a power counting, one must enforce

$$\lambda (H - [A, H] - AHA) \eta = 0$$

  order by order in the power counting to find the chiral expansion of A.

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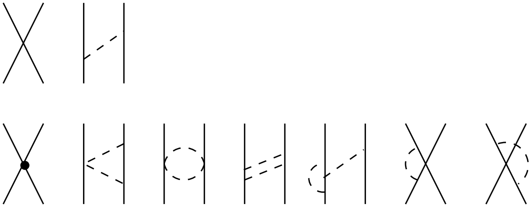
  order by order in the power counting to find the chiral expansion of A.
- additional unitary transformation are needed to renormalize the $3N$ potential
- one must transform also the current operator, and additional A_μ-dependent unitary transformations are needed to renormalize it

- the renormalizability requirement for the current strongly constrain the unitary transformation
- once this is done, all divergences disappear when renormalizing the LECs with the known β-function. [Koelling et al. PRC 80 (2009) 045502, PRC 84 (2011) 054008]
- non hybrid "fully consistent" ChEFT calculations are therefore now possible
- first calculations of this type will become available soon (cfr. Koelling's talk - Few-body tuesday session - for charge form factors in $e-d$ and $e-^3$He scattering)

Among the LECs appearing in our model there are the ones coming from the minimal substitution.

They also appear in the N2LO NN potential $\Longrightarrow$ fit the NN potential as derived within the same formalism



At this order, our results agree with those in the UT approach, modulo differences in the renormalization of the LECs

Current continuity equation of the current is fulfilled

$$\mathbf{q} \cdot \mathbf{j} = [H, \rho]$$

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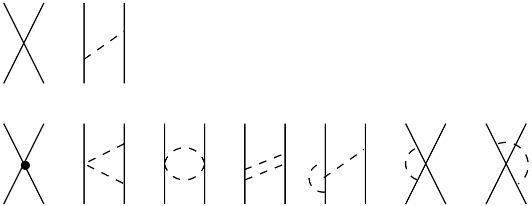

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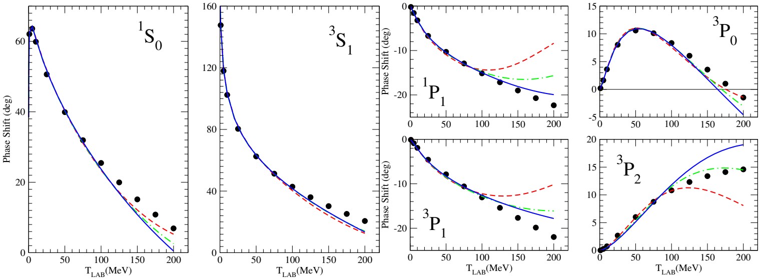
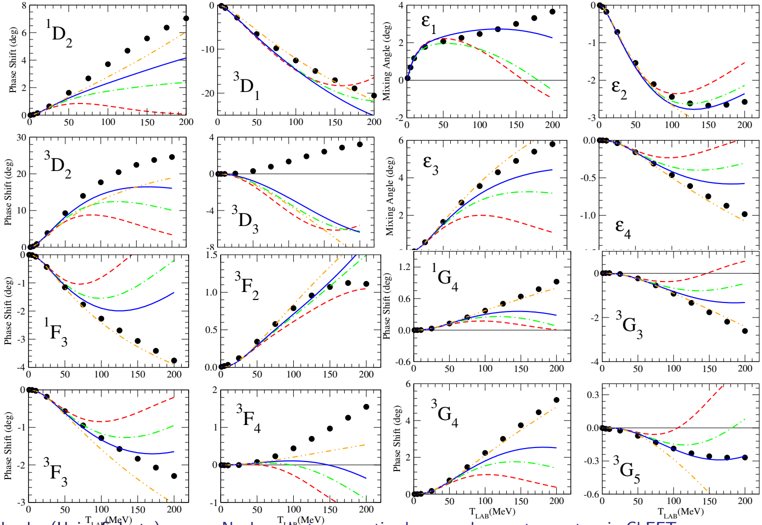
The (regularized) potential depends on 9 contact LECs, that we fitted to B_d and *np* S- and P-wave phaseshifts from the analysis of Gross and Stadler (2008). We did this for $\Lambda = 500, 600, 700$ MeV, up to 100 MeV kinetic energy in the laboratory frame.



	Λ (MeV)			
	500	600	700	Expt.
a_s (fm)	−23.729	−23.736	−23.736	−23.749(8)
r_s (fm)	2.528	2.558	2.567	2.81(5)
a_t (fm)	5.360	5.371	5.376	5.424(3)
r_t (fm)	1.665	1.680	1.687	1.760(5)
B_d (MeV)	2.2244	2.2246	2.2245	2.224575(9)
η_d	0.0267	0.0260	0.0264	0.0256(4)
r_d (fm)	1.943	1.947	1.951	1.9734(44)
μ_d (μ_N)	0.860	0.858	0.853	0.8574382329(92)
Q_d (fm^2)	0.275	0.272	0.279	0.2859(3)
P_D (%)	3.44	3.87	4.77	

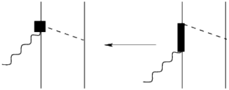

$^1D_2$
$^3D_1$
ε_1
ε_2
$^3D_2$
$^3D_3$
ε_3
ε_4
$^1F_3$
$^3F_2$
$^1G_4$
$^3G_3$
$^3F_3$
$^3F_4$
$^3G_4$
$^3G_5$
Phase Shift (deg)
Mixing Angle (deg)
T_{LAB}(MeV)

Fixing the other LECs

- in the subleading OPE current

$$\mathbf{j}^{(1)} = i\, e\, \frac{g_A}{F_\pi^2} \frac{\boldsymbol{\sigma}_2 \cdot \mathbf{k}_2}{\omega_{k_2}^2} \left[\left(d_8' \tau_{2,z} + d_9' \, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \right) \mathbf{k}_2 - d_{21}' (\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2)_z \, \boldsymbol{\sigma}_1 \times \mathbf{k}_2 \right] \times \mathbf{q} + 1 \rightleftharpoons 2 \,,$$

the LECs could in principle be taken from πN observables. Instead, we fix them from nuclear data. However, isovector contributions can be saturated by Δ-excitation diagrams



with $d_8' = 4 d_{21}' = 4\mu^* h_A/(9 m_N \Delta)$

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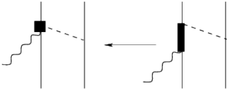

with $d_8' = 4 d_{21}' = 4\mu^* h_A / (9 m_N \Delta)$

We fix $d_{21}' = d_8'/4 \Longrightarrow$ 4 adjustable LECs

$$d_1^S = \Lambda^4 C_{15}', \quad d_1^V = \Lambda^4 C_{16}', \quad d_2^S = \Lambda^2 d_9', \quad d_2^V = \Lambda^2 d_8'$$

We fixed, for the different Λ,

- isoscalar LECs to reproduce μ_d and μ_S
- isovector LECs to μ_V and σ_{np}^{γ}

Accurate nuclear wave functions from HH method with AV18+UIX and N3LO+N2LO

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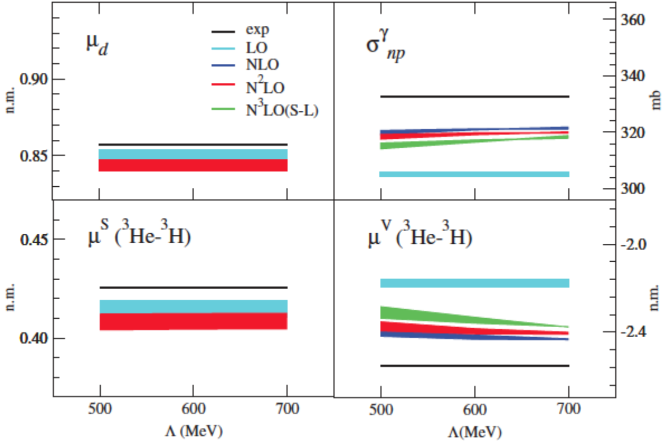
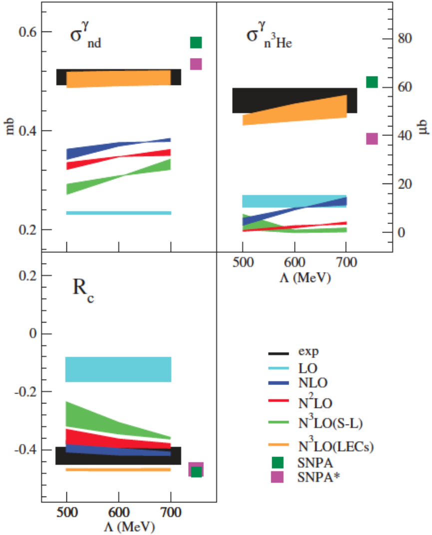
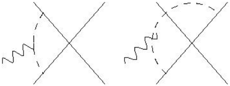


- predictions for σ^{γ}_{nd}, $\sigma^{\gamma}_{n^3\mathrm{He}}$ and photon circular polarization parameter R_c in $\vec{n}d \to^3 \mathrm{H}\gamma$



- in all observables, the LO (1-body) is much suppressed
- in n^3He the (small) LO and NLO intefere destructively
- LECs are dominant $\Longrightarrow$ bad convergence (role of the Δ?)
- SNPA: currents constructed consistently with the interaction (L. Marcucci et al. 2005): no free parameters
- SNPA* include relativistic corrections to the 1-body current; they are significant

triggered by the work of Koelling et al. we have revised our model for the current

- we now consider the recoil corrections in the single nucleon sector, in order to properly subtract them from the 2-nucleon diagram
   $\longrightarrow$ these diagrams add to zero
- we use a different parametrization of the contact current, and now rely on the C_i from N3LO NN potential (Machleidt, Entem 2011) for $\Lambda = 500, 600$ MeV

- Set I: d_1^V and d_2^V are fitted to μ_V and σ_{np}^γ
- Set II, III: use Δ resonance saturation completely to fix $d_2^V = 4\frac{\mu^* h_A}{9 m_N \Delta}\Lambda^2$ and fix d_1^V either to σ_{np}^γ (II) or to μ_V (III)

Λ	d_1^V(I)	d_2^V(I)	d_1^V(II)	d_2^V(II)	d_1^V(III)	d_2^V(III)
500	10.36 (45.10)	17.42 (35.57)	−13.30 (−9.339)	3.458	−7.981 (−5.187)	3.458
600	41.84 (257.5)	33.14 (75.00)	−22.31 (−11.57)	4.980	−11.69 (−1.025)	4.980

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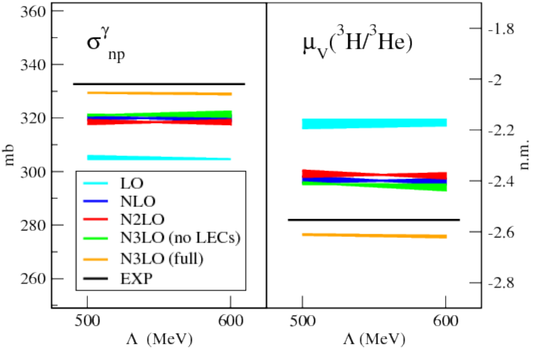

stable, model-independent prediction to 1% and 2% respectively

Outlook

- I described our effort in constructing a ChEFT nuclear electromagnetic current operator in TOPT beyond the static approximation, taking into account the recoil corrections systematically in the chiral expansion
- we encountered ambiguities due to the off-shell behaviour of the potential. They affect the charge operator, but we have shown that different choices are unitarily equivalent, both at the level of OPE (Friar, '77) and TPE
- the results in our framework agree, with the ones of Koelling et al. who performed a complete calculation in UT approach, except for loop corrections to the OPE. This has to do with renormalization, but we believe, that such differences are not crucial for hybrid calculations. The inconsistency should be absorbed in the fitting of the LECs to observables.

- we have applied our currents in hybrid calculation of thermal neutron captures on d and ^{3}He. For these observables the leading order amplitude is very suppressed, and thus they are sensitive to the nuclear structure and exchange currents. For these reactions ChEFT performs better than SNPA, although this is achieved at the price of a large role of LECs. This could imply the failure of the perturbative expansion, and the need to include the Δ.

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thank you!