Nuclear electroweak processes from ChEFT

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Historical perspective

- first considerations of pion-exchange electroweak currents in nuclei were based on PCAC and soft pion theorems in the 1970's [Riska-Brown 19, Chemtob-Rho 1971]

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- after Weinberg's formulation of nuclear ChEFT, nuclear four-current operators were computed in heavy-baryon ChPT at 1-loop [Park-Min-Rho 1993, 1996]

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- after Weinberg's formulation of nuclear ChEFT, nuclear four-current operators were computed in heavy-baryon ChPT at 1-loop [Park-Min-Rho 1993, 1996]
- nuclear electromagnetic operators were reconsidered in "recoil corrected" TOPT [Pastore et al 2009, Piarulli et al. 2011] and with the "unitary transformation method" [Koelling-Epelbaum-Krebs-Meissner 2009, 2011]
- differences were found with the heavy-baryon derivation due to the treatment of "reducible diagrams"

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Chiral symmetry is not exact, but this can be easily incorporated in the chiral Ward identities

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  indeed pions (as Goldstone bosons)
  - are light, $m_\pi \ll \Lambda_{\rm H}$
  - interact weakly at low energies (*soft pion theorems*)

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  perturbative expansion in powers of $\frac{p, m_\pi}{\Lambda_{\rm H}} \ll 1$
- however, there is no warranty about the convergence ...
  expect slower convergence if the mass scales are not well separated

The effective theory

QFT of interacting pions and nucleons

$$Z[v_\mu, a_\mu, s, p, \eta, \bar\eta] = \int \mathcal{D}[N, \bar N, \pi] e^{i \int dx \mathcal{L}_{\rm eff}(N, \bar N, \pi, v_\mu, a_\mu, s, p, \eta, \bar\eta)}$$

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- symmetry restricts the form of $\mathcal{L}_{\rm eff}$, yet there are infinite structures increasingly suppressed by powers of small momenta or quark masses
- dynamical fields are integrated upon
  $\Longrightarrow$ physical scattering amplitudes do not depend on the choice of pions and nucleons interpolating fields
- this gives useful checks for the calculation, and allows to use field equations of motion iteratively

Low-energy expansion

the steps to be taken

- derive $H = H_0 + H_1$ from $\mathcal{L}_{\rm eff}$ in the canonical formalism ($\mathcal{H}_1 \neq -\mathcal{L}_1$)
- higher derivative theory! $\Longrightarrow$ eliminate higher time derivatives using iteratively fields' equations of motion
- compute in TOPT

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

- order by counting small momenta
  N vertices, N_K purely nucleonic intermediate states, L loops:

$$\left[\prod_{i=1}^{N} p^{\nu_i}\right] \left(\frac{1}{p}\right)^{(N-N_K-1)} \left(\frac{1}{p^2}\right)^{N_K} \left(p^3\right)^L$$

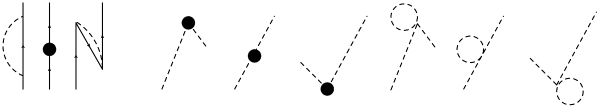
  Also expand recoil corrections

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

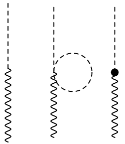
Renormalization

ultraviolet divergences are handled in dimensional regularization, and renormalized in the standard way

$$\pi = \sqrt{Z_\pi}\pi^r, \quad N = \sqrt{Z_N}N^r, \quad {m_\pi^r}^2 = m_\pi^2 + \delta m_\pi^2, \quad m^r = m + \delta m$$

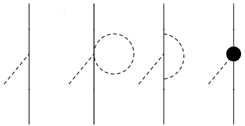


imposing that the nucleon and pion propagators behave as they should inside general time-ordered diagrams pion decay constant and nucleon axial charge are also renormalized



$$f_\pi^r = f_\pi \left(1 + \frac{m_\pi^2}{f_\pi^2} l_4 + \frac{m_\pi^2}{8\pi^2 f_\pi^2 \epsilon} + \ldots \right)$$

$$g_A^r = g_A \left[1 + 2\frac{m_\pi^2}{g_A}(2d_{16} - d_{18}) + \frac{m_\pi^2}{16\pi^2 f_\pi^2 \epsilon}(2 + g_A^2) + \ldots \right]$$



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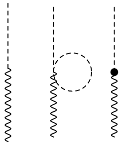

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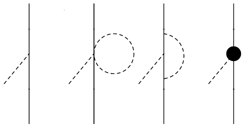

finite scheme dependence may arise, but divergencies are dictated by general properties

Irreducible kernels

as a result we have a well defined low-energy expansion, e.g. for the NN amplitude,

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

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- an infinite resummation is needed to account for nuclear bound states.
- we define an irreducible kernel $v = v^{(0)} + v^{(1)} + \dots$ that, when iterated in the LS equation, generates the on-shell T

$$T = v + vG_0v + vG_0vG_0v + \dots$$

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)} + \mathrm{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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- 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

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

thus extending the unitary equivalence to the TPEP

Analogously for the axial transition operator $v_5 = A^0 \rho_5 - \mathbf{A} \cdot \mathbf{j}_5$ we start by expanding the amplitude $T_5 = T_5^{(-3)} + T_5^{(-2)} + \ldots$ and then match order by order to the iteration of $v + v_5$

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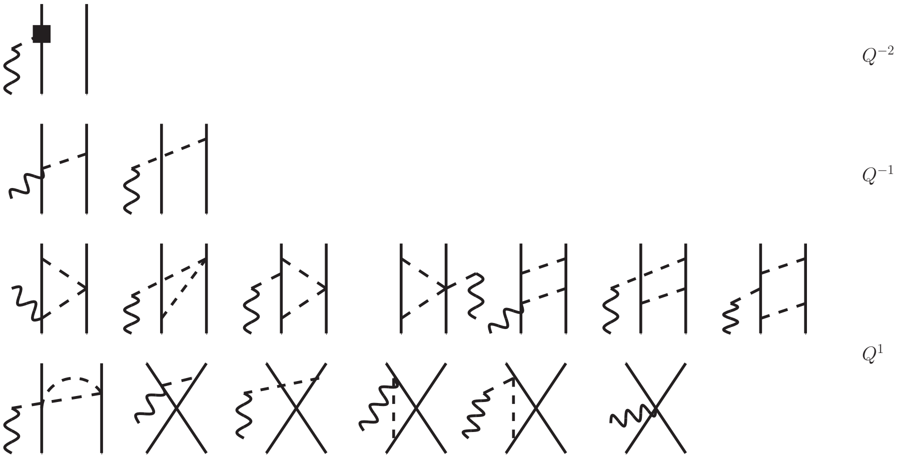
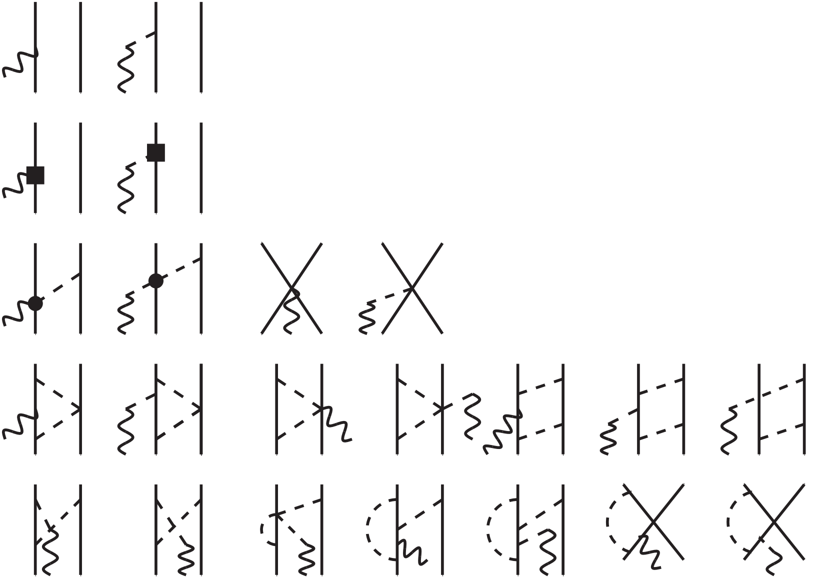
- at this order, the offshell ambiguity in v only affects $\mathbf{j}_5$
- we expect unitary equivalence of different choices

Axial charge diagrams



Axial current diagrams



Q^{-3}

Q^{-1}

Q^{0}

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- checks of calculation
  - independence of the pion field choice
  - after renormalization, results are finite, *with the known anomalous dimensions of LECs*
  - current conservation in the chiral limit is satisfied order by order in the power counting

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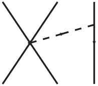
- axial current depends only on 1 LEC, z_0, related to c_D entering TNI



[Gardestig-Phillips 2006 PRL]

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- axial charge depends on 3 independent short-distance LECs $z_{1,2,3}$, yet to be determined

  a further combination is a $1/m$ correction induced by z_0

Fitting of z_0 from ^{3}H β-decay

- we evaluate the individual orders contribution to the Gamow-Teller matrix element with Montecarlo techniques
- accurate trinucleon wavefunction from HH method AV18/UIX and chiral N3LO/N2LO ($\Lambda = 500, 600$ MeV)
- GT matrix element extracted from

$$(1+\delta_R)tf_V = \frac{K/G_V^2}{\langle \mathbf{F}\rangle^2 + f_A/f_V g_A^2 \langle \mathbf{GT}\rangle^2}, \quad GT_{\mathrm{EXP}} = 0.9511 \pm 0.0013$$

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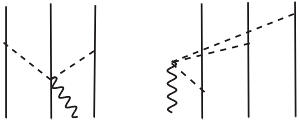
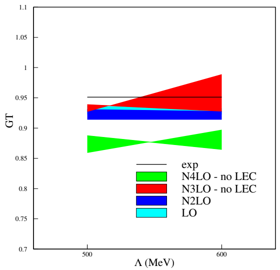
- also 3-body currents enter at the same order $O(p^4)$

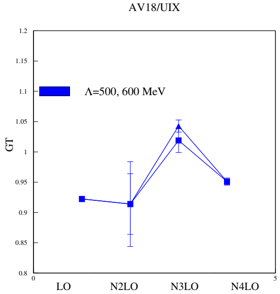


[Park et al. 2003 PRC]

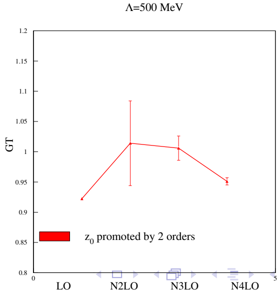
Convergence study

- cumulative contributions

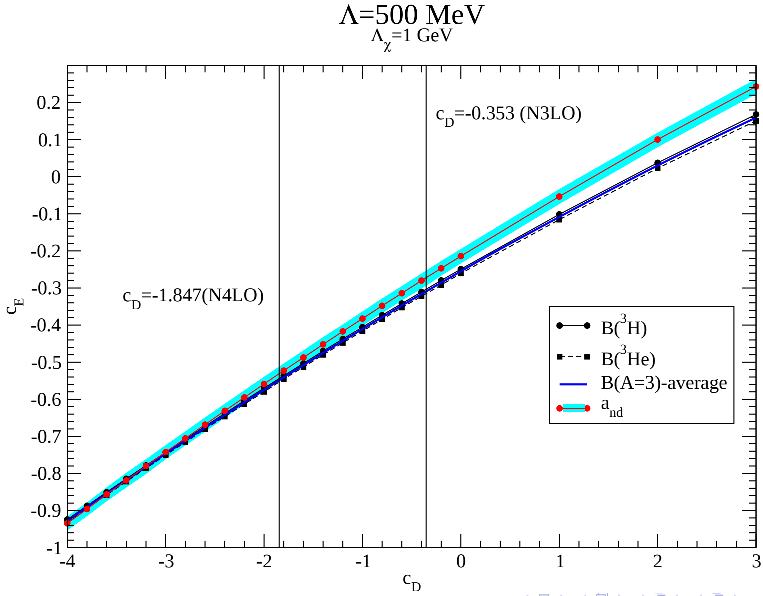




- promoting contact interaction?



Fitting with the chiral TNI



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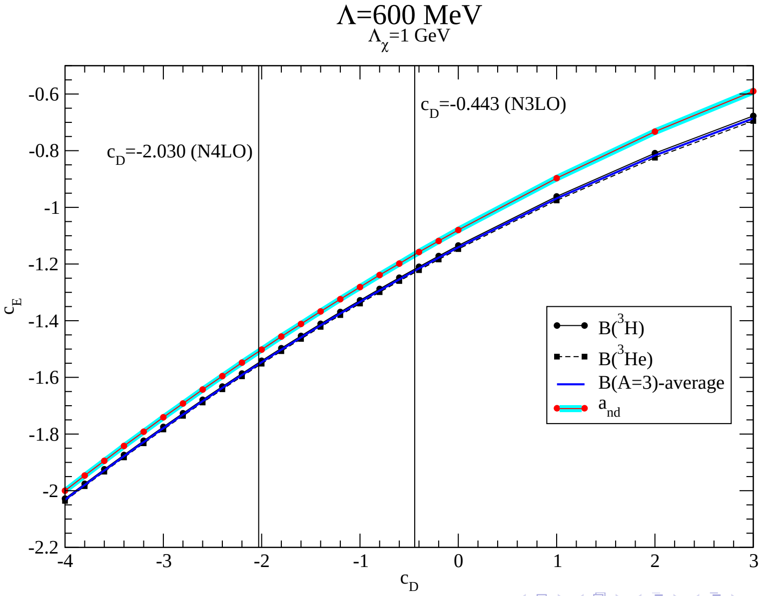

Concluding remarks

- nuclear axial operators derived in TOPT open the way to fully consistent calculation of electroweak observables of few-nucleon systems in ChEFT
- our formalism allows to control the off-shell ambiguities by addressing simultaneously the transition operator and the interaction potential
- finiteness upon renormalization, current conservation in the chiral limit, independence on the pion field choice, give us confidence on the formalism
- convergence looks problematic for hybrid calculations
- strict consistency not achieved yet in the chiral calculations
  need to include the N3LO TNI and to match different off-shell behaviours
- open issues: are contact interaction to be "promoted"? will the inclusion of Δ improve convergence?