Dipartimento di Matematica e Fisica "Ennio De Giorgi" — Università del Salento (www.unisalento.it) — INFN Istituto Nazionale di Fisica Nucleare

Nuclear electromagnetic processes in ChEFT

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work with: L.E. Marcucci, S. Pastore, M. Piarulli, R. Schiavilla, M. Viviani

S. Pastore, et al. Phys. Rev. C80 (2009) 034004

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

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

M. Piarulli et al. Phys. Rev. C87 (2013) 014006

Outline

- Noether currents in ChEFT
- Calculational framework: recoil-corrected TOPT
- Anatomy of charge and current operators up to 1-loop
- Strategies to fix the LECs
- Applications: elastic electron scattering on $A = 2, 3$ systems
- Summary and conclusions

External currents in ChEFT

Γ_c generates connected Green functions of quark bilinears

$$e^{\Gamma_c[\mathcal{V}_\mu,\mathcal{A}_\mu,\mathcal{S},\mathcal{P}]} = \int [\mathcal{D}\mu]_{\rm QCD} e^{i\int dx \{\mathcal{L}_{YM} + \bar{q}[i\not{D} + \not{\mathcal{V}} + \gamma_5 \not{\mathcal{A}} - \mathcal{S} + i\gamma_5 \mathcal{P}]q\}}$$

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2. Take the sources to transform as gauge fields

$$\begin{aligned}
\mathcal{V}_\mu + \mathcal{A}_\mu &\to \mathcal{V}'_\mu + \mathcal{A}'_\mu = g_R(x)\,(\mathcal{V}_\mu + \mathcal{A}_\mu)\,g_R^\dagger(x) + i g_R(x)\partial_\mu g_R^\dagger(x) \\
\mathcal{V}_\mu - \mathcal{A}_\mu &\to \mathcal{V}'_\mu - \mathcal{A}'_\mu = g_L(x)\,(\mathcal{V}_\mu - \mathcal{A}_\mu)\,g_L^\dagger(x) + i g_L(x)\partial_\mu g_L^\dagger(x) \\
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\end{aligned}$$

$\Longrightarrow$ it amounts to local transformations of the quark fields, $q_L \to g_L(x) q_L$, $q_R \to g_R(x) q_R$, that leave Γ_c (almost) invariant

The effective theory is a low-energy representation of Γ_c given in terms of the active degrees of freedom

$$e^{\Gamma_c[\mathcal{V}_\mu,\mathcal{A}_\mu,\mathcal{S},\mathcal{P}|\bar\eta]} = \int [\mathcal{D}U\mathcal{D}\psi] e^{i\int dx\{\mathcal{L}_{\rm eff}[U,\psi;\mathcal{V}_\mu,\mathcal{A}_\mu,\mathcal{S},\mathcal{P}]+\bar\eta\psi\}}$$

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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)

History

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(some) related 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)

Power counting

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

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

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

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

order by order in the chiral expansion

From amplitudes to potentials

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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- 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*

Off-shell ambiguity

There exists 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 $v^{(3)}(\nu)$

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

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

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

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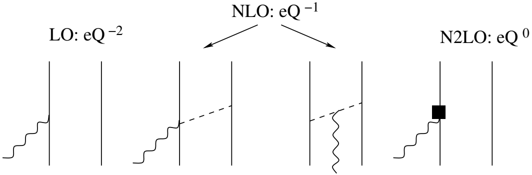
\end{aligned}
$$

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

Current operator to 1 loop



- 1-body operator (convection current and spin-magnetization)
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- Relativistic corrections to the 1-body operator

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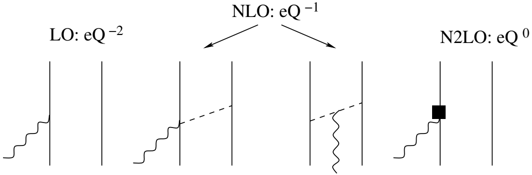

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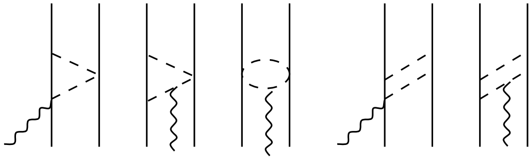
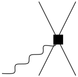
At N3LO, $O(eQ)$



- Two-pion exchange diagrams - only isovector

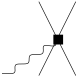


Contact terms from the subleading Lagrangian

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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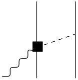
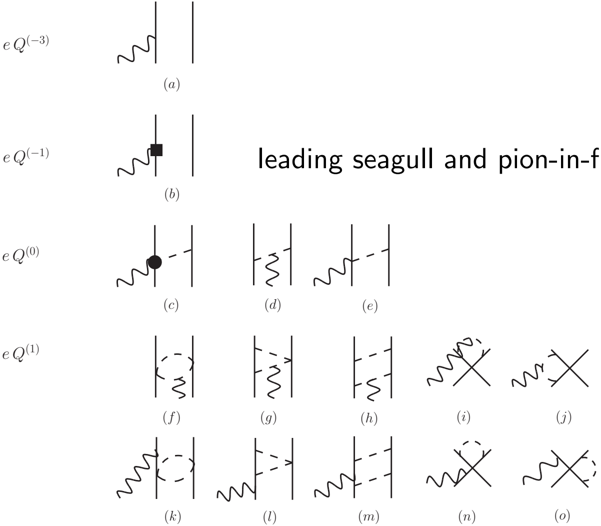

Subleading corrections to one pion exchange

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

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

Charge operator to 1 loop



leading seagull and pion-in-flight vanish

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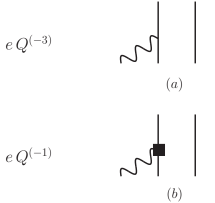

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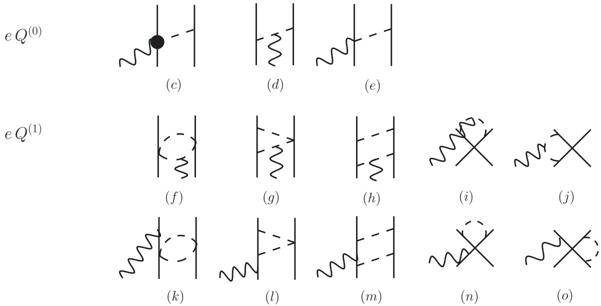


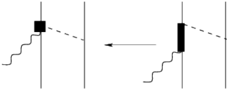
All divergences cancel, since there are no LECs contributing.
Renormalization of OPE and relativity corrections not included yet.

Fixing the LECs

- in the minimal coupling current we take the C_i from N3LO potentials
- 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



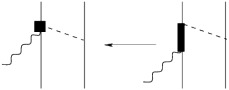
with $d_8' = 4 d_{21}' = 4\mu^* h_A/(9 m_N \Delta)$

Fixing the LECs

- in the minimal coupling current we take the C_i from N3LO potentials
- 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



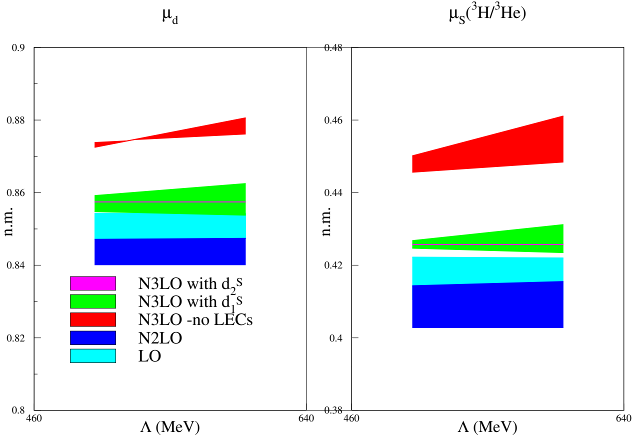
with $d_8' = 4 d_{21}' = 4\mu^* h_A/(9 m_N \Delta)$

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

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

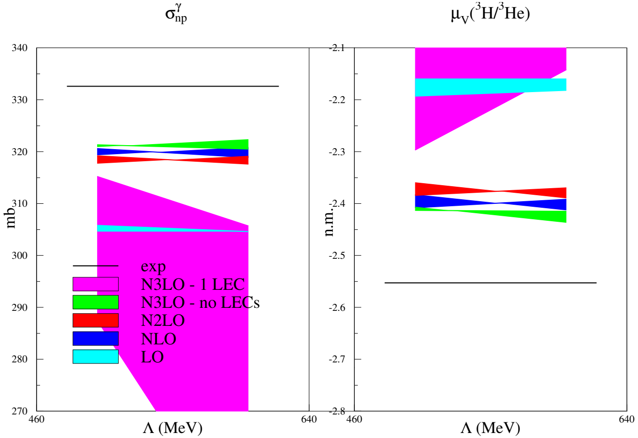
Isoscalar LECs

For each Λ, we fixed isoscalar LECs to reproduce μ_d and μ_S
Accurate nuclear wave functions from HH method with AV18+UIX and N3LO+N2LO



Isovector LECs

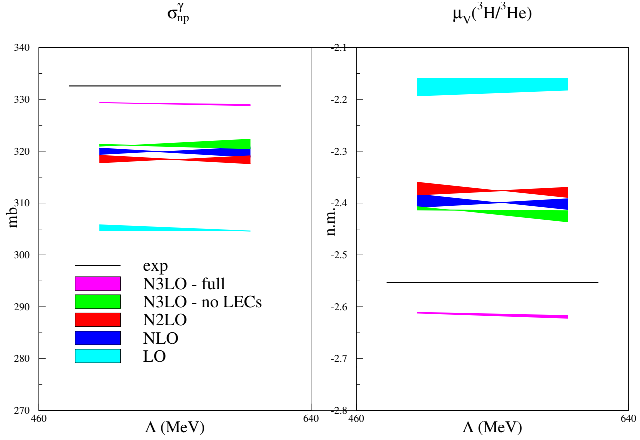
Set I: fix the LECs to reproduce μ_V and σ_{np}^{γ}



unnatural convergence pattern, huge model and cutoff dependence

Isovector LECs

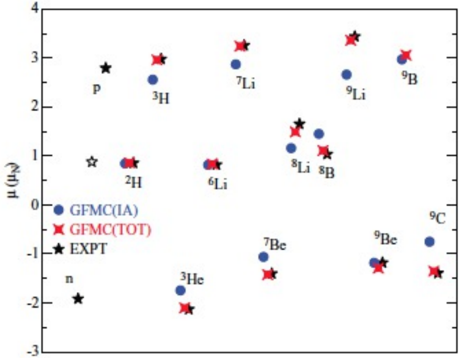
Set II-III: fix d_2^V from Δ saturation and d_1^V from either μ_V or σ_{np}^γ

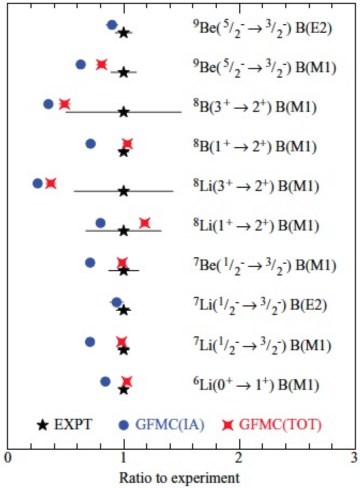


stable, model-independent prediction to 1% and 2% respectively

Predictions for $A \leq 9$

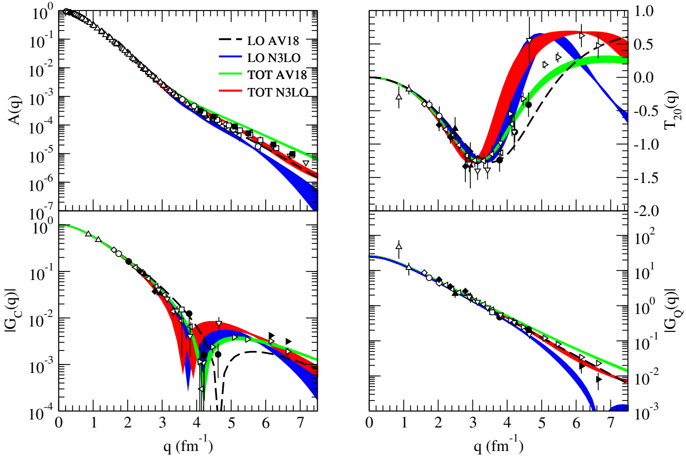
using Set III





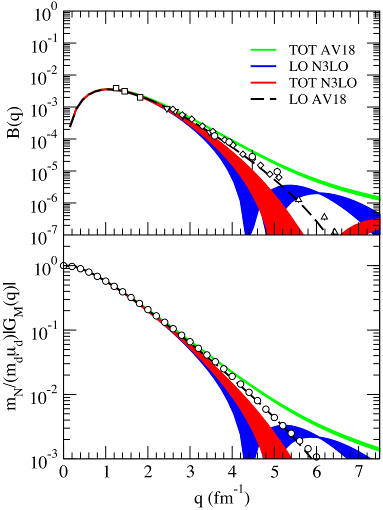
S. Pastore, S. Pieper, R. Schiavilla, R. Wiringa, PRC87 (2013) 035503

Deuteron charge and quadrupole form factors



agreement with data extends to $q \sim 3 - 4\ \text{fm}^{-1}$ or beyond

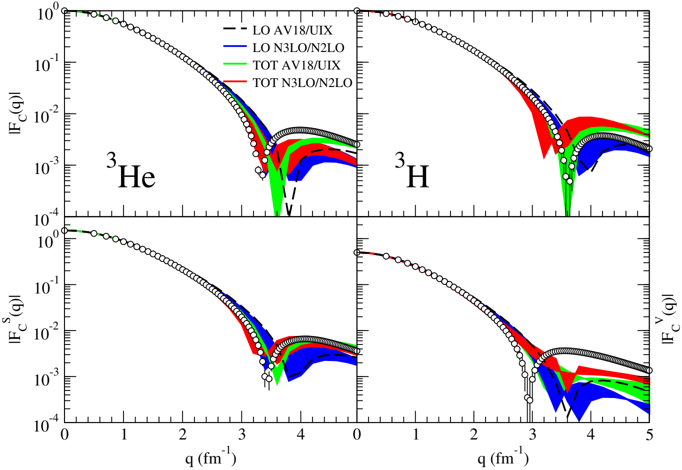
Deuteron magnetic form factor



good agreement up to $q < 3$ fm^{-1}

large cutoff dependence with the chiral potentials, presumably due to scheme dependence

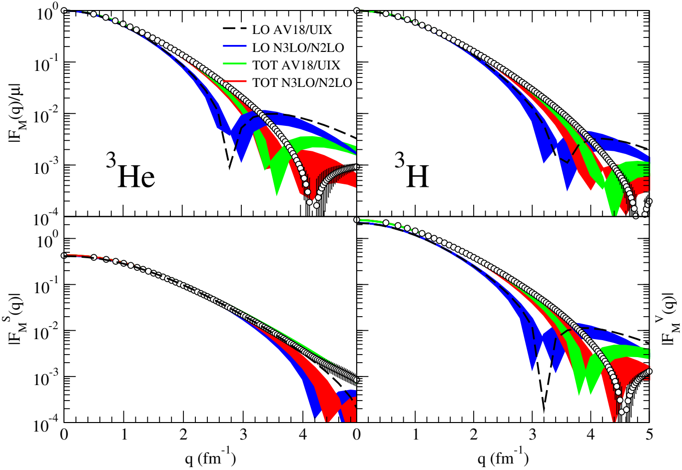
Trinucleon charge form factors



chiral loops bring theory closer to experiment in the diffraction region
good agreement below 2.5 fm^{-1}

Trinucleon magnetic form factors

Set III: magnetic moments are fitted



large effect of two-body currents

Summary and outlook

- electroweak currents are naturally embedded in the ChEFT machinery
- special care is required to properly isolate the truly irreducible contribution, accounting systematically for the nucleon recoil
- we encountered ambiguities due to the off-shell behaviour of the potential. However, they don't affect observables, since different choices are unitarily equivalent, both at the level of OPE (Friar, '77) and TPE
- we have applied our charge and current operators to compute static properties and elastic form factors of the deuteron and trinucleons, finding good agreement up to $q \sim 2 - 3$ fm^{-1}
- large cutoff dependence and convergence pattern not yet satisfactory, pointing to the necessity including the Δ in the effective theory.