1. Nuclear EM Currents in χEFT

2. Parity-Violating Observables in A=3 and 4 Systems

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Nuclear EM Currents in χEFT

Pastore, Schiavilla, and Goity, PRC**78**, 064002 (2008)

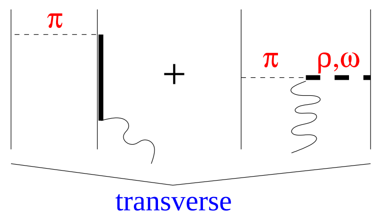
- Currents from nuclear interactions
- χEFT calculation: preliminaries
- Currents up to one loop (or N^3LO)
- Calculation of EM observables at N^2LO (no loops) in A=2 and 3 systems

Conserved Currents from Nuclear Interactions

Marcucci *et al.*, PRC**72**, 014001 (2005)

$$\mathbf{j} = \mathbf{j}^{(1)}$$

$$+\ \mathbf{j}^{(2)}(\mathrm{v}) +$$



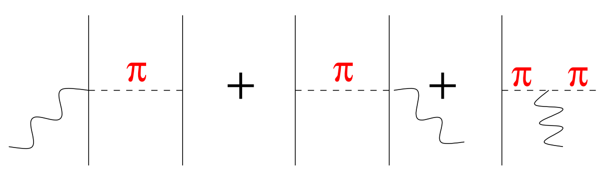
$$+\ \mathbf{j}^{(3)}(\mathrm{V}^{2\pi})$$

- Static part v_0 of v from π-like (PS) and ρ-like (V) exchanges
- Currents from corresponding PS and V exchanges, for example

$$\begin{aligned} \mathbf{j}_{ij}(v_0; PS) &= \mathrm{i}\left(\boldsymbol{\tau}_i \times \boldsymbol{\tau}_j\right)_z \Big[v_{PS}(k_j)\boldsymbol{\sigma}_i \left(\boldsymbol{\sigma}_j \cdot \mathbf{k}_j\right) \\ &+ \frac{\mathbf{k}_i - \mathbf{k}_j}{k_i^2 - k_j^2} v_{PS}(k_i)\left(\boldsymbol{\sigma}_i \cdot \mathbf{k}_i\right)\left(\boldsymbol{\sigma}_j \cdot \mathbf{k}_j\right)\Big] + i \leftrightharpoons j \end{aligned}$$

with $v_{PS}(k) = v^{\sigma\tau}(k) - 2\, v^{t\tau}(k)$ projected out from v_0 components

$$\mathbf{j}^{(2)}(\mathrm{v}) \xrightarrow[\text{long range}]{}$$



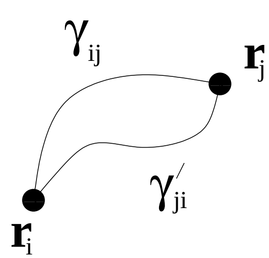
- Currents from v_p via minimal substitution in i) explicit and ii) implicit p-dependence, the latter from

$$\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j = -1 + (1 + \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j)\, \mathrm{e}^{\mathrm{i}(\mathbf{r}_{ji}\cdot\mathbf{p}_i + \mathbf{r}_{ij}\cdot\mathbf{p}_j)}$$

- Currents from v_p are short ranged, and contain both isoscalar and isovector terms

- Incidentally, this method leads to a general and elegant formula for the (conserved) current due to any $v_{ij}\, \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j$:

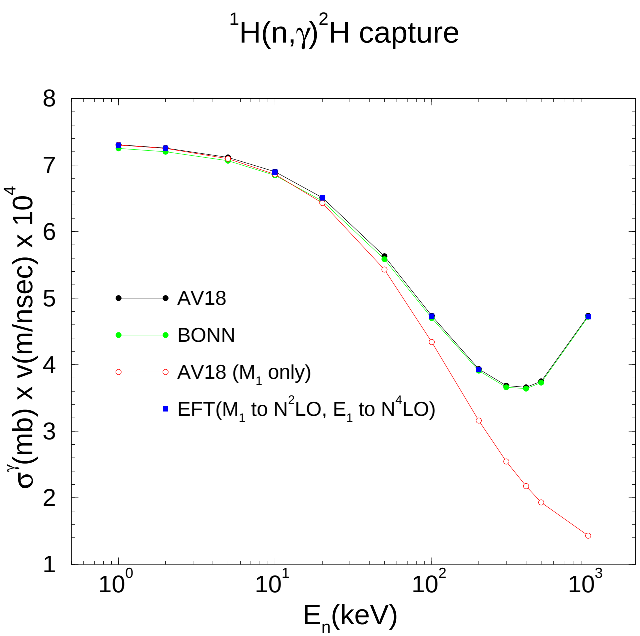
$$\mathbf{j}_{ij}(\mathbf{q}) = \mathrm{i}\, v_{ij} \left(\epsilon_i \int_{\gamma_{ij}} \mathrm{d}\mathbf{s}\, \mathrm{e}^{\mathrm{i}\mathbf{q}\cdot\mathbf{s}} + \epsilon_j \int_{\gamma'_{ji}} \mathrm{d}\mathbf{s}'\, \mathrm{e}^{\mathrm{i}\mathbf{q}\cdot\mathbf{s}'} \right) (1 + \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j)$$

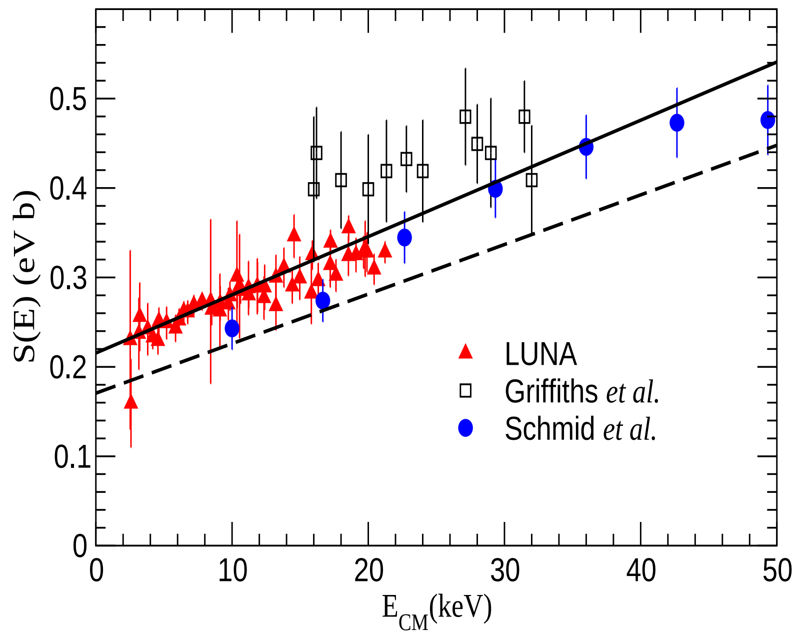


arbitrary paths joining endpoints and back

Satisfactory description of a variety of nuclear EM properties [see Marcucci *et al.* (2005) and (2008)]

^{2}H$(p,\gamma)^3$He capture





but i) ^{2}H$(n,\gamma)^3$H and ^{3}He$(n,\gamma)^4$He cross-sections too large by $\approx 10\%$ and $\approx 60\%$, ii) isoscalar magnetic moments are a few % off (10% in A=7 nuclei) , ...

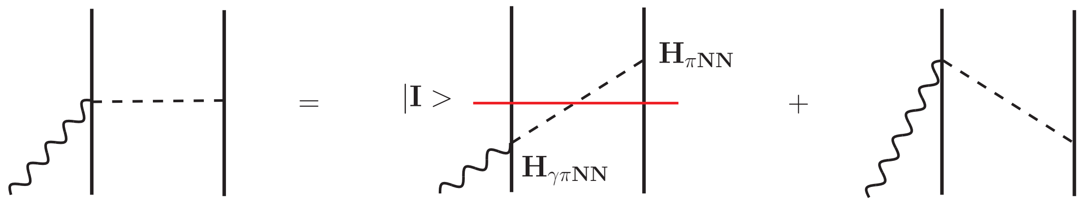
χEFT Calculation: Preliminaries

- Degrees of freedom: pions(π), nucleons (N), and Δ-isobars (Δ)
- Time-ordered perturbation theory (TOPT):

$$-\frac{\hat{\mathbf{e}}_{\mathbf{q}\lambda}}{\sqrt{2\,\omega_q}}\cdot\mathbf{j} \;=\; \langle N'N' \mid T \mid NN;\gamma\rangle$$

$$=\; \langle N'N' \mid H_1 \sum_{n=1}^{\infty}\left(\frac{1}{E_i - H_0 + i\,\eta}H_1\right)^{n-1} \mid NN;\gamma\rangle$$

- H_0 = free π, N, and Δ Hamiltonians; H_1 = interacting π, N, Δ, and γ Hamiltonians
- Term with M H_1's $\rightarrow$ $M!$ time-ordered diagrams; for example



Interaction Hamiltonians from χEFT

Weinberg, PLB**251**, 288 (1990); NPB**363**, 3 (1991); PLB**295**, 114 (1992)

- A quantitative understanding of low-energy nuclear processes from *ab initio* QCD calculations is not (yet) available
- χEFT exploits the χ-symmetry exhibited by QCD to restrict the form of π interactions with other π's, and with N's, Δ's, ...
- The pion couples by powers of its momentum Q, and $\mathcal{L}_{\rm eff}$ can be systematically expanded in powers of Q/M ($M \simeq 1$ GeV)

$$\mathcal{L}_{\rm eff} = \mathcal{L}^{(0)} + \mathcal{L}^{(1)} + \mathcal{L}^{(2)} + \ldots$$

- χEFT allows for a perturbative treatment in terms of a Q–as opposed to a coupling constant–expansion
- The unknown coefficients in this expansion–the LEC's–are fixed by comparison with experimental data

Power Counting

- In the chiral expansion the transition amplitude is expressed as

  $$T = T^{LO} + T^{NLO} + T^{N^2LO} + \ldots\,, \;\; \text{and} \;\; T^{N^nLO} \sim (Q/M)^n \, T^{LO}$$

  and power counting allows one to arrange contributions to T in powers of Q

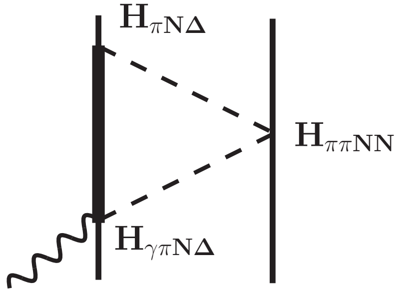
- A contribution with N interaction vertices and L loops scales as

  $$\underbrace{e \left(\prod_{i=1}^{N} Q^{\alpha_i - \beta_i/2} \right)}_{H_1 \text{ scaling}} \times \underbrace{Q^{-(N-1)}}_{\text{denominators}} \times \underbrace{Q^{3L}}_{\text{loop integrations}}$$

  α_i = number of derivatives (momenta) and β_i = number of π's at each vertex

- This power counting also follows from considering Feynman diagrams, where loop integrations are in four dimensions

An Example

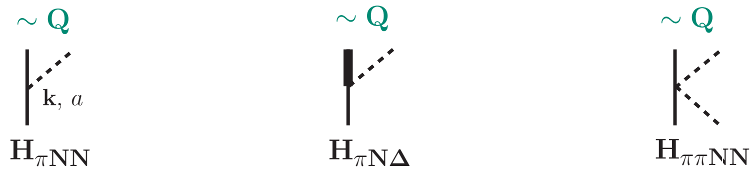


$$\underbrace{e\left(\prod_{i=1}^{N} Q^{\alpha_i-\beta_i/2}\right)}_{e\,Q^0} \times \underbrace{Q^{-(N-1)}}_{Q^{-2}} \times \underbrace{Q^{3L}}_{Q^3} = e\,Q^1$$

- H_1 scaling $\sim \underbrace{Q^1 \times Q^{-1/2}}_{H_{\pi N\Delta}} \times \underbrace{Q^1 \times Q^{-1}}_{H_{\pi\pi NN}} \times \underbrace{e\,Q^0 \times Q^{-1/2}}_{H_{\pi\gamma N\Delta}} \sim e\,Q^0$
- Two energy denominators, each scaling as Q in the static limit

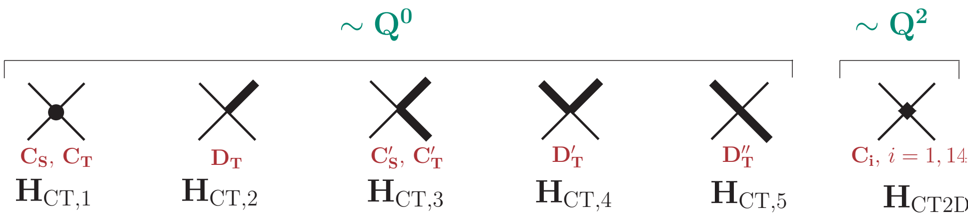
$$\frac{1}{E_i - H_0}|I\rangle \sim \frac{1}{2\,m_N - (m_\Delta + m_N + \omega_\pi)}|I\rangle \sim \frac{1}{Q}|I\rangle$$

Strong Interaction Vertices



$$V_{\pi NN} = -i \frac{g_A}{F_\pi} \frac{\boldsymbol{\sigma} \cdot \mathbf{k}}{\sqrt{2\,\omega_k}} \tau_a \qquad V_{\pi N\Delta} = -i \frac{h_A}{F_\pi} \frac{\mathbf{S} \cdot \mathbf{k}}{\sqrt{2\,\omega_k}} T_a$$

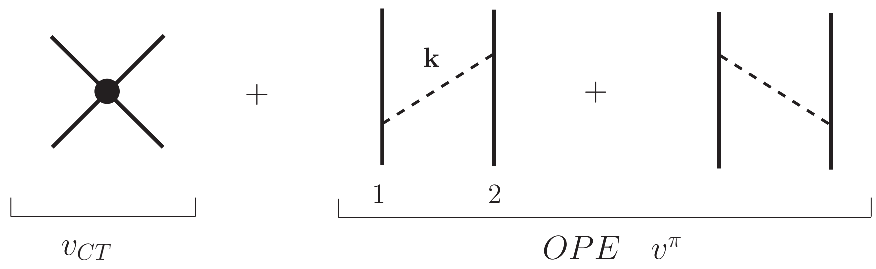
- $(m_\pi\, g_A/F_\pi)^2/(4\,\pi) = 0.075$ from Nijmegen analysis of NN data
- $h_A = 2.77$ from width of Δ resonance



- $H_{\rm CT,1}$: 4-nucleon contact terms, 2 LEC's
- $H_{\rm CT,2-5}$: contact terms involving one or two Δ's, 5 LEC's
- $H_{\rm CT2D}$: 4-nucleon contact terms with two gradients, 14 LEC's

χEFT NN Potential at LO

$$v_{NN}^{LO} \quad = \quad$$



$$\sim Q^0$$

$$\begin{aligned} T_{f\,i}^{LO} &= \langle N'N' \mid H_{\mathrm{CT},1} \mid NN \rangle \\ &+ \sum_I \langle N'N' \mid H_{\pi NN} \mid I \rangle \frac{1}{E_i - E_I} \langle I \mid H_{\pi NN} \mid NN \rangle \end{aligned}$$

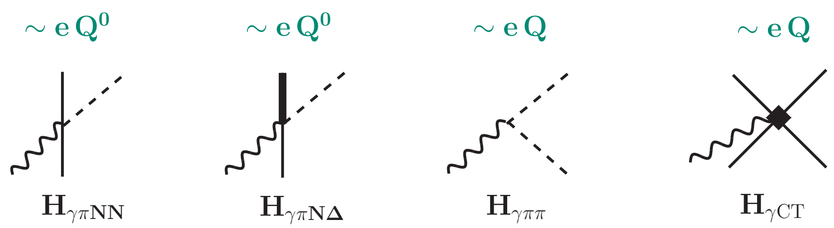
LO potential

$$v_{NN}^{L0} = C_S + C_T\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 - \frac{g_A^2}{F_\pi^2} \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{k}\, \boldsymbol{\sigma}_2 \cdot \mathbf{k}}{\omega_k^2} \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$$

Electromagnetic Interaction Vertices

- Minimal substitution in the π- and N-derivative couplings

$$\nabla \pi_{\mp}(\mathbf{x}) \rightarrow [\nabla \mp i\, e\mathbf{A}(\mathbf{x})]\, \pi_{\mp}(\mathbf{x}) \quad \nabla N(\mathbf{x}) \rightarrow [\nabla - i\, e\, e_N\, \mathbf{A}(\mathbf{x})]\, N(\mathbf{x})$$



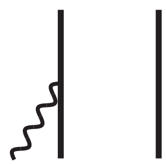
- $H_{\gamma NN}$ and $H_{\gamma N\Delta}$ include non-minimal couplings

with $\mu_p = 2.793\, \mu_N$ and $\mu_n = -1.913\, \mu_N$, and $\mu^* \simeq 3\, \mu_N$ from $\gamma N \Delta$ data

Currents up to $\mathrm{N^2LO}$

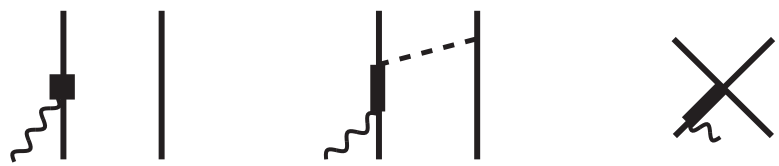
- Up to $\mathrm{N^2LO}$

LO : eQ^{-2}



NLO : eQ^{-1}

$\mathbf{N^2LO}$: eQ^{0}

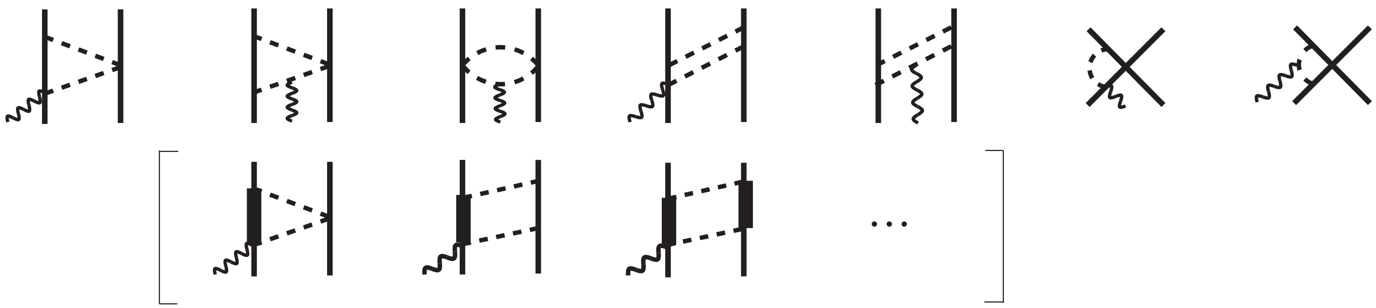


$\mathrm{N^2LO-RC}$ $\mathrm{N^2LO-\Delta}$ $\mathrm{N^2LO-\Delta_c}$

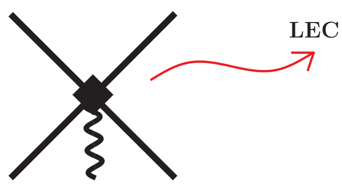
- One-loop corrections to the one-body current, absorbed into μ_N and $\langle r_N^2 \rangle$

Currents at $\mathrm{N^3LO}$ $(e\,Q)$

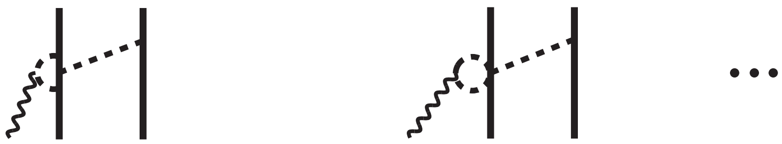
- One-loop corrections



- Currents from $(NN)(NN)$ contact interactions with two gradients involving a number of LEC's

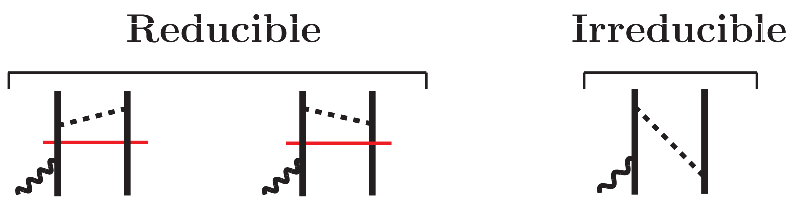


- One-loop renormalization of tree-level currents



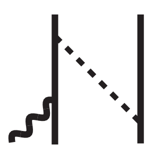
Technical Issues I: Recoil Corrections at N^2LO

- N^2LO reducible and irreducible contributions in TOPT

$\mathbf{j}^{N^2LO} =$ 

- Recoil corrections to the reducible contributions obtained by expanding in powers of $(E_i - E_I)/\omega_\pi$ the energy denominators

$$= v^\pi \left(1 + \frac{E_i - E_I}{2\,\omega_\pi}\right) \frac{1}{E_i - E_I}\, \mathbf{j}^{\rm LO}$$

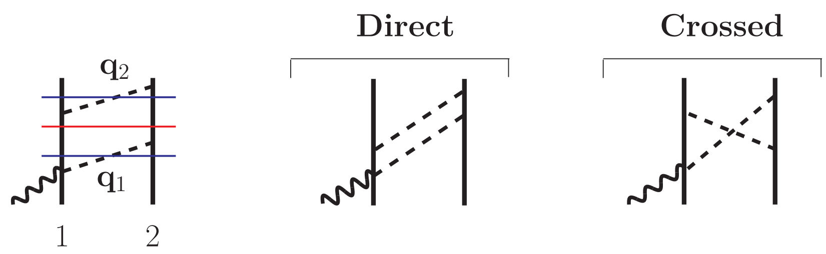


$$= \; -\frac{v^\pi}{2\,\omega_\pi}\, \mathbf{j}^{\rm LO}$$

- Recoil corrections to reducible diagrams cancel irreducible contribution

Technical Issues II: Recoil Corrections at N^{3}LO

$\mathbf{j}^{\mathbf{N^3LO}} \quad =$



- Reducible contributions

$$\mathbf{j}_{\rm red} \;=\; \int v^\pi(\mathbf{q}_2)\, \frac{1}{E_i - E_I}\, \mathbf{j}^{\rm NLO}(\mathbf{q}_1)$$
$$-2\int \frac{\omega_1+\omega_2}{\omega_1\,\omega_2}\, V_{\pi NN}(2,\mathbf{q}_2)\, V_{\pi NN}(2,\mathbf{q}_1)\, V_{\pi NN}(1,\mathbf{q}_2)\, V_{\gamma\pi NN}(1,\mathbf{q}_1)$$

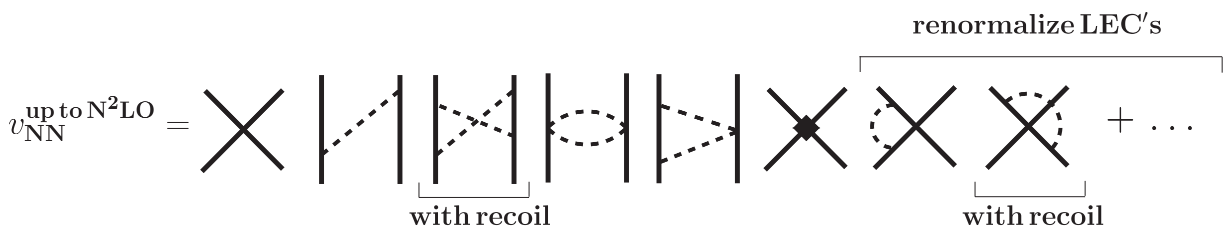
- Irreducible contributions

$$\mathbf{j}_{\rm irr} \;=\; 2\int \frac{\omega_1+\omega_2}{\omega_1\,\omega_2}\, V_{\pi NN}(2,\mathbf{q}_2)\, V_{\pi NN}(2,\mathbf{q}_1)\, V_{\pi NN}(1,\mathbf{q}_2)\, V_{\gamma\pi NN}(1,\mathbf{q}_1)$$
$$+\; 2\int \frac{\omega_1^2+\omega_2^2+\omega_1\,\omega_2}{\omega_1\,\omega_2(\omega_1+\omega_2)}\, [V_{\pi NN}(2,\mathbf{q}_1), V_{\pi NN}(2,\mathbf{q}_2)]_-\; V_{\pi NN}(1,\mathbf{q}_2) V_{\gamma\pi NN}(1,\mathbf{q}_1)$$

- Partial cancellations between recoil corrections to reducible diagrams and irreducible contributions (valid to all orders?)

Current Conservation

- Potential at N^2LO in χEFT (ignoring Δ's)



- It is in agreement with that obtained with the method of unitary transformations [Epelbaum *et al.*, NPA**637**, 107 (1998)]

- Retaining recoil corrections in both v_{NN} and $\mathbf{j}$ ensures current conservation up to N^3LO included

$$\mathbf{q}\cdot\mathbf{j} = \left[\frac{p_1^2}{2\,m_N} + \frac{p_2^2}{2\,m_N} + v_{NN}\ ,\ e(e_1+e_2)\right]_- \qquad e_i \equiv (1+\tau_{i,z})/2$$

- In hybrid calculations, the continuity equation is not strictly satisfied . . .

Calculation

- To remove divergencies in matrix elements of two-body currents, a simple Gaussian cutoff is adopted

$$C_\Lambda(p) = \mathrm{e}^{-(p/\Lambda)^2} \qquad \Lambda \leq 1 \text{ GeV}$$

- It is expected that predictions should be independent of Λ (or only weakly dependent on Λ, see later)
- In the present study, Λ in the range (500–800) MeV has been considered
- Hybrid approach: matrix elements of EM currents from χEFT between A=2 (3) w.f.'s from realistic $2N$ ($2N$+$3N$) interactions
- No loops (for the time being)

Isoscalar EM Observables at N^{2}LO

Isoscalar currents :

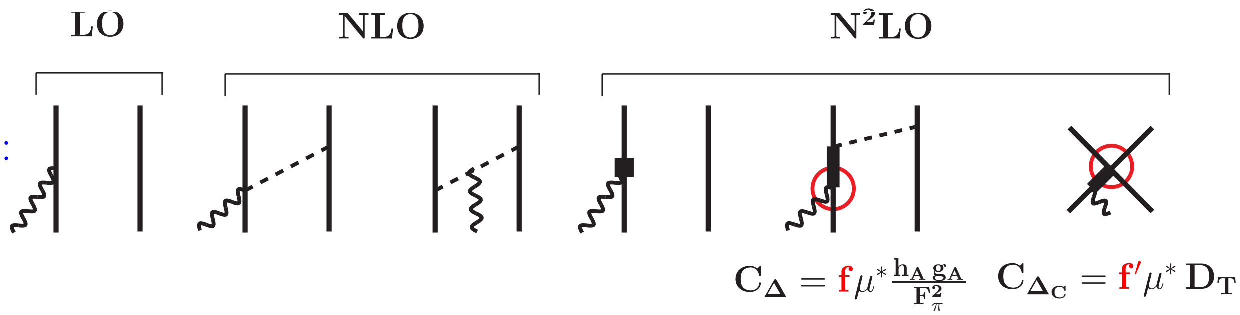
- d magnetic moment (μ_d) and isoscalar combination (μ_S) of ^{3}H/^{3}He magnetic moments

	μ_d (μ_N)		μ_S (μ_N)	
	AV18	CDB	AV18/UIX	CDB/UIX*
LO	+ 0.8469	+ 0.8521	+ 0.4104	+ 0.4183
N^{2}LO-RC	− 0.0082	− 0.0080	− 0.0045	− 0.0052
EXP	+0.8574		+0.426	

- N^{2}LO contribution (Λ-independent) is $\simeq$ 1% of LO, but of opposite sign

Isovector EM Observables at N^{2}LO: $np \to d\gamma$

Isovector currents :

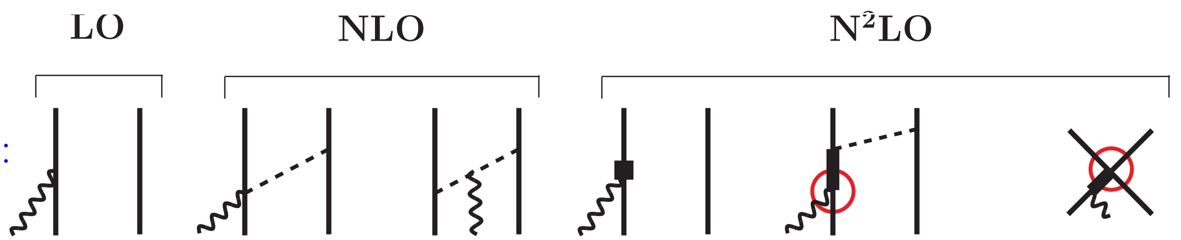


	$m.e. \equiv \sqrt{\sigma}$ (mb$^{1/2}$)
	AV18
Λ (MeV)	600
LO	17.45
NLO	0.42
N^{2}LO-RC	$-$ 0.05
N^{2}LO-Δ	0.16
Sum	17.99
EXP	18.24

- N^{2}LO-Δ_c contribution vanishes, as $\mu_{\Delta_c}^{N^2LO}|\Psi_{NN};\, L = \text{even}\rangle\ = 0$
- If h_A (μ^*) from Δ width (γN data), (EXP–TH)/EXP $\simeq 2.5\%$

Isovector EM Observables at N^{2}LO: μ_V (^{3}He/^{3}H)

Isovector currents :



$C_\Delta = f \mu^* \frac{h_A g_A}{F_\pi^2}$ $C_{\Delta_C} = f' \mu^* D_T$

- $C_\Delta(\Lambda)$ fixed to reproduce $\sigma^{\rm EXP}(np \rightarrow d\gamma)$

	μ_V (μ_N)	
	AV18/UIX	CDB/UIX*
LO	− 2.159	−2.180
NLO	− 0.197	− 0.156
N^{2}LO-RC	+ 0.029	+0.024
N^{2}LO-Δ	− 0.253	−0.202
Sum	− 2.580	−2.514
EXP	−2.553	

- AV18/UIX (CDB/UIX*) $|\mu_V|$ too large (small) by $\simeq 1$ %; N^{2}LO contribution larger than NLO

N^2LO Predictions for nd (and $\vec{n}d$) Capture

- N^2LO currents constrained to reproduce $\sigma_\gamma^{\rm EXP}(np)$ and $\mu_V^{\rm EXP}$
- γ circular polarization, $P_\gamma = R_c\, \mathbf{P}_n \cdot \hat{\mathbf{q}}$, has also been measured

	σ_T (mb)			R_c		
Λ (MeV)	500	600	800	500	600	800
LO	0.229	0.229	0.229	– 0.060	– 0.060	– 0.060
LO+NLO	0.272	0.260	0.243	– 0.218	– 0.182	– 0.123
LO+NLO+N^2LO	0.450	0.382	0.315	– 0.437	– 0.398	– 0.331
EXP	0.508 ± 0.015			-0.42 ± 0.03		

- $\sigma^{\rm LO} \simeq 45\%\ \sigma^{\rm EXP}$: suppressed M1 transition (well known)
- NLO π-seagull and π-in-flight contributions nearly cancel out: at LO+π-seagull, $\sigma = 0.425$ mb and R_c=–0.425 (Λ=500 MeV)
- Up to N^2LO, theory is $\simeq 25\%$ smaller than EXP: strong Λ dependence partly due to NLO accidental cancellations

Summary and Outlook

- Currents up to N^{3}LO have been derived in χEFT with explicit N, Δ, and π d.o.f. in a TOPT framework
- Currents up to N^{2}LO constrained to reproduce experimental values for $\sigma_\gamma(np)$ and $\mu_V(^3\text{He}/^3\text{H})$
- N^{2}LO predictions for $\sigma_\gamma(nd)$ and R_c are NOT in satisfactory agreement with experiment and exhibit strong Λ-dependence
- Next stage (a major program!):
  1. Fix LEC's occurring in $\mathbf{j}^{\text{N}^3\text{LO}}$ by fitting $v_{NN}^{\text{N}^2\text{LO}}$ (in progress)
  2. Include N^{3}LO currents in A=3–7 calculations
  3. Derive three-body currents (also entering at N^{3}LO)

Parity-Violating Observables in A=3 and 4 Systems

- Theoretical framework: the DDH and EFT PV potentials
- PV observables in few-nucleon systems:
  1. Neutron spin rotation in $\vec{n}$-d scattering[a]
  2. Longitudinal asymmetry in the $\vec{n}\,{}^3\text{He} \rightarrow p\,{}^3\text{H}$ reaction[b]
- Summary and outlook

[a] Schiavilla, Viviani, Girlanda, Kievsky, and Marcucci, PRC**78**, 014002 (2008)

[b] Viviani and Schiavilla, in preparation (2009)

Theoretical Framework

- Weak interactions in the Standard Model

$$H_{\rm W} = \frac{G_F}{\sqrt{2}} \left(J_\mu^{\rm CC} J^{\mu\,{\rm CC}} + \frac{1}{2} J_\mu^{\rm NC} J^{\mu\,{\rm NC}} \right)$$

- $H_{\rm W}$ has I=0, 1, and 2 components
- Meson-exchange and EFT approaches to hadronic weak interactions: $H_{\rm W} \rightarrow H_{\rm W}(N, \pi, \ldots)$

The standard meson exchange formulation, *i.e* the DDH model, involves π-, ρ-, and ω-exchanges, and seven independent couplings (h_π^1, $h_\rho^{0,1,2}$, $h_\rho^{1\,\prime}$, and $h_\omega^{0,1}$)

EFT Formulation

- Pionless EFT:

$$v_{ij}^{\mathrm{EFT-SR}} = \frac{2\mu^2}{\Lambda_\chi^3}\Bigg[\left[C_1 + (C_2 + C_4)\left(\frac{\tau_i + \tau_j}{2}\right)_z + C_5\, \mathcal{I}_{ab}\tau_i^a\tau_j^b\right]\left(\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j\right)\cdot\left[\mathbf{p}_{ij}\,,\, f_\mu(r)\right]_+$$

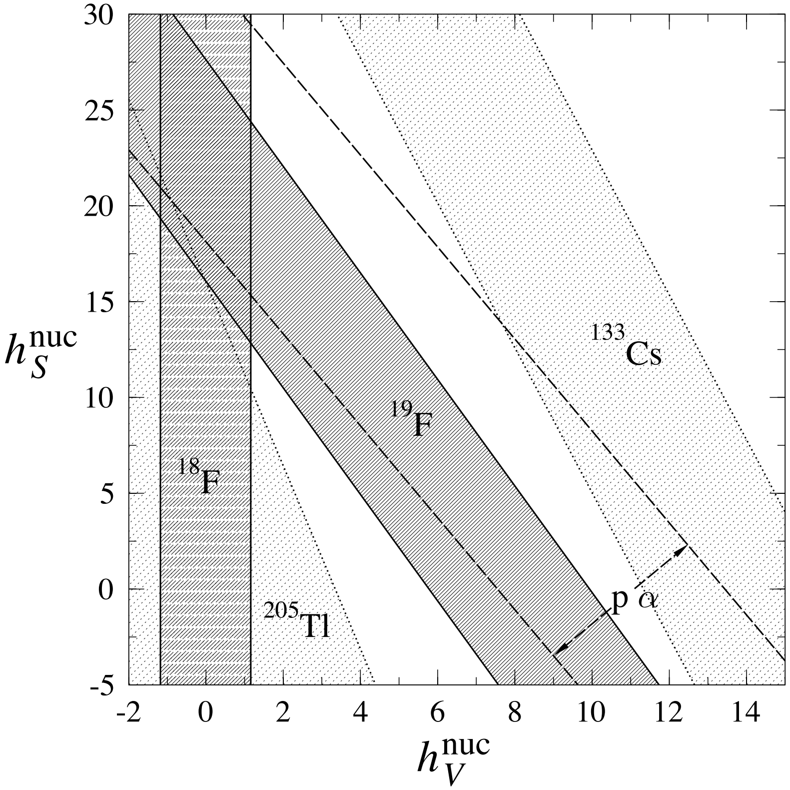
$$+ \quad i\,\tilde{C}_1\left(\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j\right)\cdot\left[\mathbf{p}_{ij}\,,\, f_\mu(r)\right]_- + i\, C_6\,\epsilon^{ab3}\tau_i^a\tau_j^b\left(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j\right)\cdot\left[\mathbf{p}_{ij}\,,\, f_\mu(r)\right]_-\Bigg]$$

determined by five LEC's [Girlanda (2008), Zhu *et al.*(2005)]

- When π's are included, three new couplings enter:

$$v_{ij}^{\mathrm{EFT}-\pi} = v_{ij}^{\mathrm{EFT-SR}} + \left[i\,\frac{g_A\, h_\pi^1}{\sqrt{2}\,F_\pi}\,\epsilon^{ab3}\tau_i^a\tau_j^b\left(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j\right)\cdot\left[\mathbf{p}_{ij}\,,\, f_\pi(r)\right]_- + \ldots\right]$$

Present Constraints on Weak Meson-Nucleon Couplings

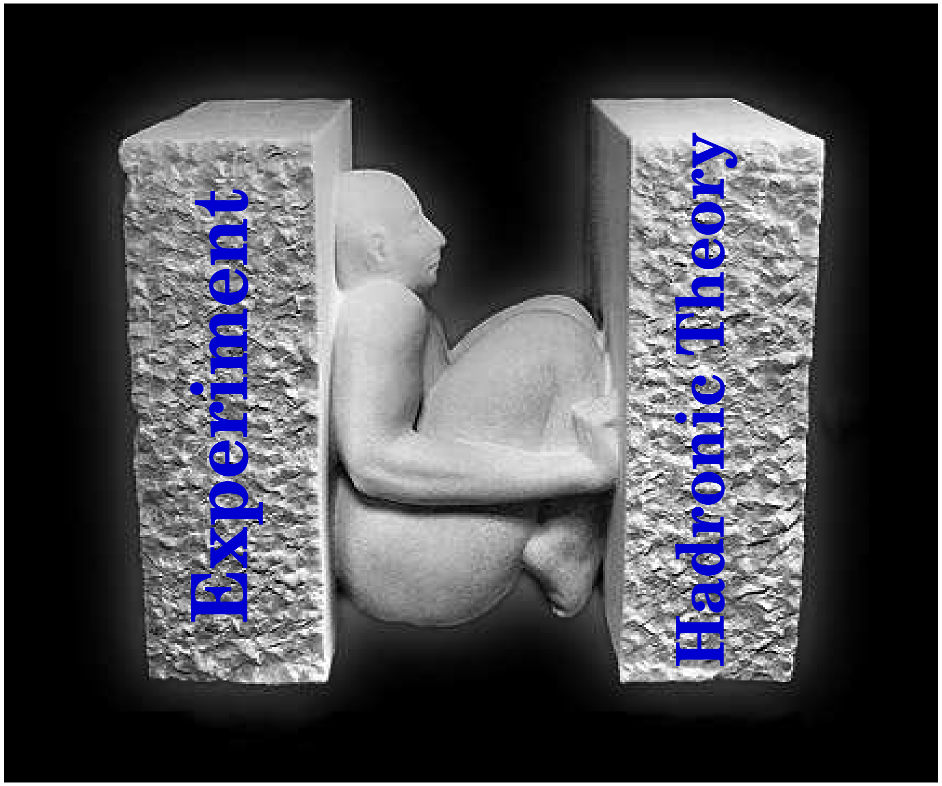


From Haxton via Page and Ramsey-Musolf (2006)

$$h_S^{\rm nuc} = -(h_\rho^0 + 0.7\, h_\omega^0) \qquad h_V^{\rm nuc} = h_\pi^1 - 0.12\, h_\rho^1 - 0.18\, h_\omega^1$$

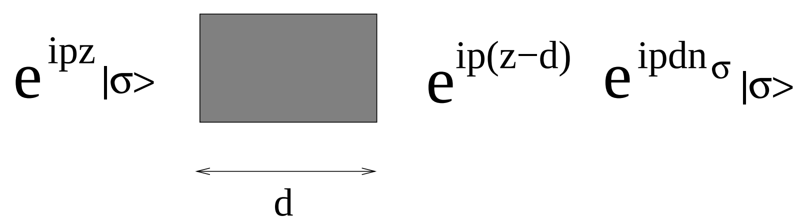
Constraining PV Interactions in Few-Body Nuclei

- A_z in $\vec{p}p$ scattering, A^γ in $\vec{n}p$ capture, and P^γ in $d(\vec{\gamma}, n)p$
- Neutron spin rotation in $\vec{n}p$ and $\vec{n}d$ scattering
- Longitudinal asymmetry in the $\vec{n}\,^3\mathrm{He} \rightarrow p\,^3\mathrm{H}$ reaction



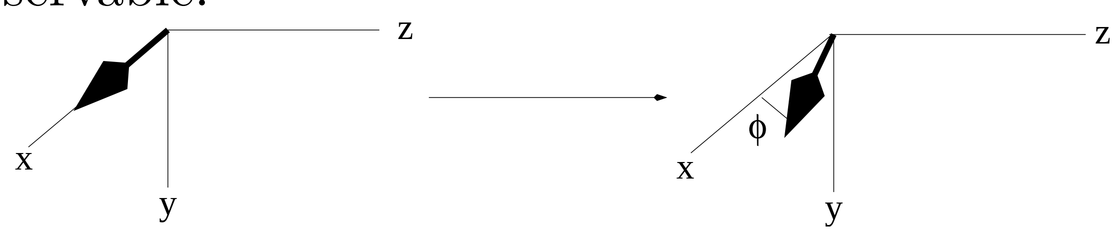
Neutron Spin Rotation

- Transmission of a low energy neutron through matter:



$$n_\sigma = 1 + \frac{2\pi\,\rho}{p^2} M_\sigma(\theta = 0)$$

- PV observable:



$$\frac{\mathrm{d}\phi}{\mathrm{d}d} = -\frac{2\pi\,\rho}{p} Re\left[M_+(\theta = 0) - M_-(\theta = 0)\right]$$

$\vec{n}$-p and $\vec{n}$-d Scattering with Cold Neutrons

Relevant m.e.'s: ${}^3S_1 \rightarrow {}^3P_1$ in n-p ; ${}^{2,4}S_{1/2} \rightarrow {}^2P_{1/2}$ and ${}^4P_{1/2}$ in n-d

- Dominated by π-exchange, and weakly dependent on input v^{PC}
- Spin-rotation is an order of magnitude larger in $\vec{n}$-d than in $\vec{n}$-p
- For a (realistic) 10 cm long target, PV effect in $\vec{n}$-d is an order of magnitude larger than in ${}^1H(\vec{n},\gamma){}^2H$

	$\vec{n}$-p		$\vec{n}$-d
	AV18	CDB	AV18/UIX
DDH	5.09	4.63	48.5
DDH-π	5.21	5.18	56.0

$d\phi/dd$ in units of 10^{-9} rad/cm

Longitudinal Asymmetry in $\vec{n}\,^3\text{He} \to p\,^3\text{H}$

- Cold neutrons, two open channels: $p\,^3\text{H}$ (c=1) and $n\,^3\text{He}$ (c=2)

$$\psi_{2,m_3m_1} \simeq \frac{1}{\sqrt{4}} \sum_{p=1}^{4} \sum_{LSJ} \langle \text{CB} \rangle \Big[\Omega^{JJ_z}_{2,LSp}\, j_L(q_2 y_p) + \sum_{L'S'} T^J_{LS,L'S'}\, \Omega^{JJ_z}_{2,L'S'p} \frac{\mathrm{e}^{i(q_2 y_p - L'\pi/2)}}{y_p}$$

$$+ \sum_{L'S'} T^J_{LS,L'S'}\, \Omega^{JJ_z}_{1,L'S'p} \frac{\mathrm{e}^{i(q_1 y_p - L'\pi/2 - \eta_1 \ln(2q_1 y_p) + \sigma_{L'})}}{y_p} \Big]$$

- Relevant amplitude for charge exchange process:

$$M^{m_3' m_1'}_{m_3 m_1} = \sum_{LSL'S'J} \langle \text{CB} \rangle\, i^{L-L'}\, \mathrm{e}^{i\sigma_{L'}}\, T^J_{LS,L'S'}\, Y_{L'M'}(\hat{\mathbf{q}}_1)$$

- PV asymmetry A_z:

$$A_z \propto \sum_{m_3 m_3' m_1'} \left[|M^{m_3' m_1'}_{m_3 +}| - |M^{m_3' m_1'}_{m_3 -}| \right] = \cos(\theta) \sum_n c_n\, \mathcal{R} \left[T^{\text{PV}} (T^{\text{PC}})^* \right]_n$$

and at zero energy 3 PC and 3 PV T-matrix elements enter:

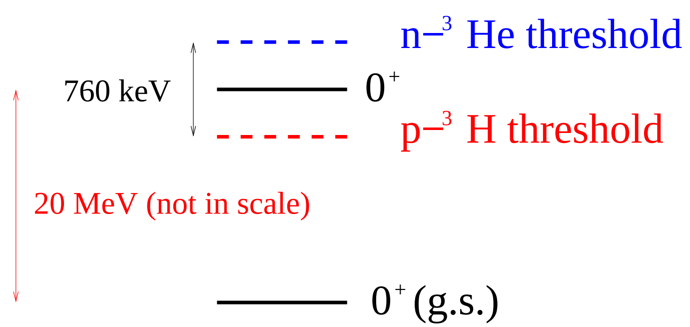
$$\left(T^{J=0}_{00,00} \;\; T^{J=1}_{01,01} \;\; T^{J=1}_{01,21} \right)^{\text{PC}} \qquad \left(T^{J=0}_{00,11} \;\; T^{J=1}_{01,10} \;\; T^{J=1}_{01,11} \right)^{\text{PV}}$$

- Express T-matrix in terms of (real) R-matrix
- Kohn variational principle:

$$\left[R^{cc';J}_{LS,L'S'}\right] = R^{c'c;J}_{L'S',LS} - \langle\psi^J_{c,LS}|H-E|\psi^J_{c',L'S'}\rangle$$

- HH calculation, major effort by Viviani:

$$\psi^J_{c,LS} = \psi^J_{c,LS}(\mathrm{HH}) + \psi^J_{c,LS}(\mathrm{F}) + \sum_{c',L'S'} R^{cc';J}_{LS,L'S'}\psi^J_{c',L'S'}(\mathrm{G})$$



- Scattering lengths close to exprimental values (preliminary)
- PV R-matrix in PT: $(R^{cc';J}_{LS,L'S'})^{\mathrm{PV}} = -\langle\psi^J_{c,LS}|v^{\mathrm{PV}}|\psi^J_{c',L'S'}\rangle$

A_z in $\vec{n}\,{}^3\text{He} \rightarrow p\,{}^3\text{H}$

Viviani and Schiavilla, to be published (2009)

- Preliminary results with χEFT N^{3}LO PC potential [Entem and Machleidt, PRC**68**, 041001 (2003)]

	N^{3}LO
DDH	–0.3971
DDH-π	+0.0079

A_z in units of 10^{-7}

- Contribution of π-component is suppressed: model dependence?
- HH calculation with AV18/UIX Hamilltonian not yet fully converged in $J^\pi = 0^+$ channel

Summary and Outlook

- $A_z(\vec{p}p)$ is weakly dependent on input $v^{\rm PC}$, but sensitive to short-range modeling of $v^{\rm PV}$
- $A^\gamma(\vec{n}p)$ and neutron spin rotation in $\vec{n}d$ scattering provide the "cleanest" determination of h_π
- $P^\gamma(d\vec{\gamma})$ is strongly affected by short-range modeling of both $v^{\rm PC}$ and $v^{\rm PV}$
- A_z in the n-^{3}He charge-exchange process seems to be dominated by the short-range part of $v^{\rm PV}$ (preliminary)
- Outlook:
  1. VMC/GFMC studies of $\vec{n}$-α scattering in progress, and of the $\vec{p}$-α asymmetry feasible
  2. Possibly, HH studies of $\vec{n}\,^2$H and $\vec{n}\,^3$He radiative captures