Effective Field Theories for Physics Beyond the Standard Model. Backup Material

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Nuclear Physics Summer School

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Some backup material

More details on χPT power counting

χPT in the two-nucleon sector: chiral EFT

Examples of power counting of two-body currents

The CPV potential

More details on χPT power counting in the 1- and 2-nucleon sectors

The 1-nucleon sector: (Heavy) Baryon Chiral Perturbation Theory

1. degrees of freedom: pions (Goldstone bosons) and nucleons
2. symmetries: global $SU(2)_L \times SU(2)_R \to SU(2)_V$
4. power counting: chiral symmetry & spontaneous breaking allow for an expansion in Q/Λ_χ

$$Q \in \{p, m_\pi\}, \qquad \Lambda_\chi \sim 4\pi F_\pi \sim m_N$$

3. interactions: realize the symmetry non-linearly, encode the pions into a matrix & build "chiral covariant" objects

S. Weinberg, '79

- can be applied only to low-energy processes, $Q \ll 1$ GeV!
- to have consistent power counting, is convenient to use non-relativistic formulation

E. Jenkins and A. Manohar, '90

- but HBχPT is not a unique choice

infrared regularization T. Becher and H. Leutwyler, '99,
extended on-mass-shell scheme T. Fuchs, J. Gegelia, G. Japaridze, S. Scherer, '03

The 1-nucleon sector: (Heavy) Baryon Chiral Perturbation Theory

- e.g. at lowest order in π-N sector, there are only 2 chiral-invariant interactions

$$\mathcal{L} = N^\dagger iD_0 N + g_A N^\dagger \vec{\sigma} \cdot \vec{u} N = N^\dagger \left\{ i\partial_0 - \frac{1}{4F_\pi^2} (\boldsymbol{\pi} \times \partial_0 \boldsymbol{\pi}) \cdot \boldsymbol{\tau} - \frac{g_A}{2F_\pi} \vec{\sigma} \cdot \vec{\nabla} \boldsymbol{\tau} \cdot \boldsymbol{\pi} \right\} N + \dots$$

- chiral invariance constrains pion-nucleon interactions to be prop. to the pion momentum ✓
- chiral invariance constrains the coefficient of the 2-pion – nucleon LO coupling ✓
- the 1-pion–nucleon coupling is chiral invariant by itself

$\Longrightarrow$ comes with an independent "**low-energy constant**" (LEC) g_A, $g_A = \mathcal{O}(1)$

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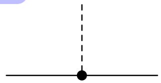
$\Longrightarrow$ comes with an independent "**low-energy constant**" (LEC) g_A, $g_A = \mathcal{O}(1)$

- g_A depends on the dynamics of the high-energy theory
- cannot be predicted purely from low-energy
- g_A can be computed in Lattice QCD *and/or* extracted from experiment

Power counting example: corrections to the pion-nucleon coupling

- leading order contribution: 1 derivative, tree-level

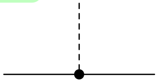
LO



$$= \frac{g_A}{F_\pi} S \cdot q = \mathcal{O}\left(\frac{Q}{F_\pi}\right)$$

- at NLO: 1 derivative, tree level

NLO

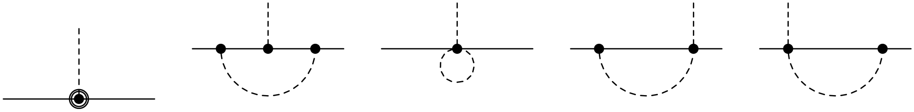


$$= -\frac{g_A}{F_\pi}\frac{v\cdot q}{2m_N} S \cdot (p_1 + p_2) = \mathcal{O}\left(\frac{Q}{F_\pi} \times \frac{Q}{\Lambda_\chi}\right)$$

fixed by Lorentz invariance
(reparameterization invariance)

Example: corrections to the pion-nucleon coupling

- at N^{2}LO: 2 derivatives or 1 loop



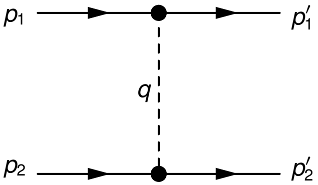
tree = $\mathcal{O}(\frac{Q}{F_\pi} \times \frac{Q^2}{\Lambda_\chi^2})$ loop = $\frac{Q}{F_\pi} \times \frac{Q^4}{(4\pi)^2} \frac{1}{Q^2 F_\pi^2} = \frac{Q}{F_\pi} \times \frac{Q^2}{(4\pi F_\pi)^2} = \mathcal{O}\left(\frac{Q}{F_\pi} \times \frac{Q^2}{\Lambda_\chi^2}\right)$

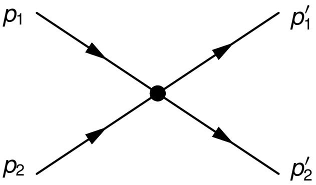
- $Q^4/(4\pi)^2$ for each loop
- Q/F_π for each pion-N vertex
- Q^{-2} for each pion and Q^{-1} for each nucleon propagator

In single nucleon sector

- observables have an expansion in Q/Λ_χ
- can be evaluated in perturbation theory

Two nucleon sector.





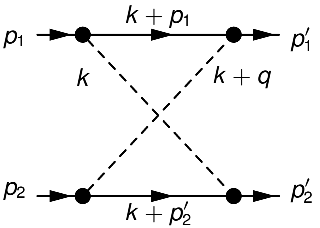
$$p_{1,2} = \frac{P}{2} \pm p$$
$$p'_{1,2} = \frac{P}{2} \pm p'$$
$$q = p - p'$$

- for on-shell nucleons $E_{1,2} = 0$, $E'_{1,2} = 0$, $q^0 = 0$
- the tree level amplitude for NN scattering is

$$i\mathcal{A}^{(0)} = i\frac{g_A^2}{4F_\pi^2}\left[\vec{\sigma}^{(1)} \cdot \vec{q}\, \vec{\sigma}^{(2)} \cdot \vec{q}\right]\left[\boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)}\right]\frac{1}{\vec{q}^2 + m_\pi^2} - i\left(C_S - C_T\vec{\sigma}^{(1)} \cdot \vec{\sigma}^{(2)}\right)$$
$$+ \text{exchange diagram}$$

- $\mathcal{A}^{(0)}$ scales as $1/F_\pi^2$

Two nucleon sector.



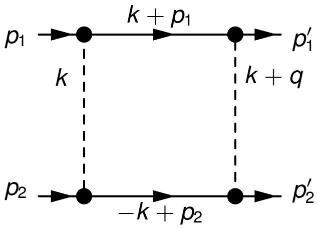


Diagram 1 Can we power count it?

Two nucleon sector.

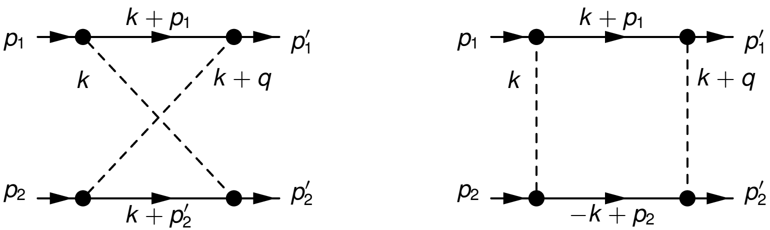


Diagram 1 Can we power count it?

$$\frac{Q^4}{(4\pi)^2} \times \left(\frac{Q}{F_\pi}\right)^4 \times \left(\frac{1}{Q^2}\right)^2 \times \left(\frac{1}{Q}\right)^2 = \frac{1}{F_\pi^2} \times \frac{Q^2}{(4\pi F_\pi)^2}$$

- suppressed by 2 powers in the χPT power counting
- explicit evaluation of Diagram 1 yields a result of the correct size
- Diagram 2, however, leads us into troubles...

Two nucleon sector. One loop corrections

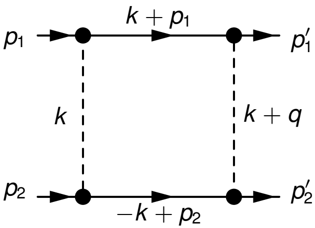


Diagram 2

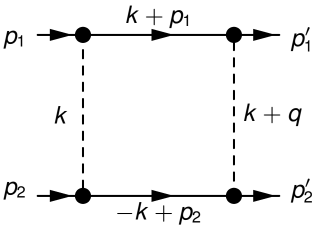
$$iA_2^{(1)} = \frac{g_A^4}{F_\pi^4}\int\frac{d^dk}{(2\pi)^d}\left[S^{(1)}\cdot(k+q)S^{(1)}\cdot k\right]\left[S^{(2)}\cdot(k+q)S^{(2)}\cdot k\right]\left[\tau^{(1)a}\tau^{(1)b}\right]\left[\tau^{(2)a}\tau^{(2)b}\right]$$
$$\times\frac{1}{v\cdot k+i\varepsilon}\,\frac{1}{-v\cdot k+i\varepsilon}\,\frac{1}{k^2-m_\pi^2+i\varepsilon}\,\frac{1}{(k+q)^2-m_\pi^2+i\varepsilon}$$

- no way to avoid the pole at $v\cdot k=0$

$$v\cdot k=\mp i\varepsilon,\qquad v\cdot k=\pm\left(\sqrt{\vec{k}^2+m_\pi^2}-i\varepsilon\right),\qquad v\cdot k=\pm\left(\sqrt{(\vec{k}+\vec{q})^2+m_\pi^2}-i\varepsilon\right)$$

diagram does not make sense...

Two-nucleon sector



we made a mistake in setting up the EFT!

- for $A \geq 1$, we can pions with both “soft” momentum modes

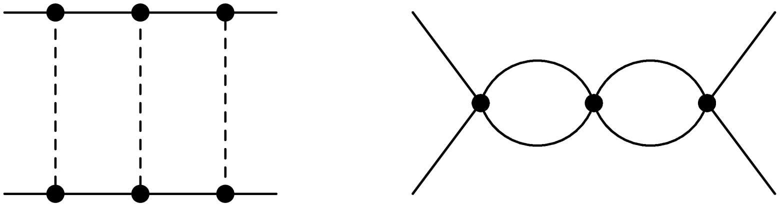
$$(k^0, \vec{k}) \sim (Q, Q)$$

- and “potential” modes

$$\left(k^0, \vec{k}\right) \sim \left(\frac{Q^2}{2m_N}, Q\right)$$

- Weinberg’s power counting formula only applies to **soft** modes
- for the potential scaling, we need use non-relativistic propagators $E \sim p^2/m_N$ and change the power counting accordingly

Infrared enhancement



- we can power count the pion-exchange series as

$$iA^{(2)} = \frac{g_A^2}{F_\pi^2}\left(\frac{Q^5}{4\pi m_N}\right)^L \left(\frac{g_A^2}{F_\pi^2}\right)^L \left(\frac{m_N}{Q^2}\right)^{2L} = \frac{g_A^2}{F_\pi^2}\left(\frac{g_A^2 Q m_N}{4\pi F_\pi^2}\right)^L = \frac{g_A^2}{F_\pi^2} \times [\mathcal{O}(1)]^L$$

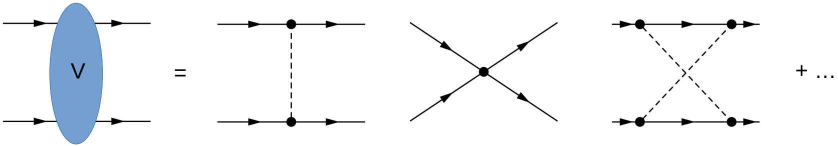
- for the contact series

$$iA^{(2)} = C\left(\frac{Q^5}{4\pi m_N}\right)^L (C)^L \left(\frac{m_N}{Q^2}\right)^{2L} = C \times \left(\frac{m_N Q}{4\pi} C\right)^L = C \times [\mathcal{O}(1)]^L$$

- the L^{th} loop is not suppressed

the full series needs to be resummed!

Weinberg's recipe



S. Weinberg '90, S. Weinberg '91

1. identify "irreducible diagrams"
- do not have a purely A-nucleon intermediate state
- internal nucleon energies $E_N \sim Q \sim m_\pi$

2. the potential V is the sum of irreducible diagrams
- can be calculated perturbatively in a power expansion in Q/Λ_χ following χPT counting rules

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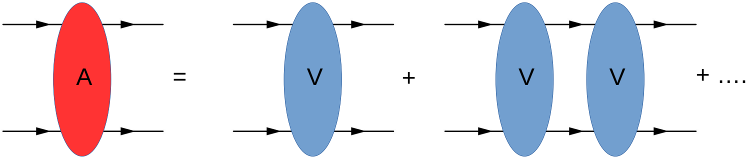

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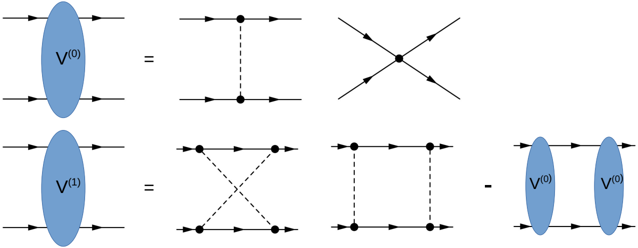
3. calculate the full amplitude by "stitching" together irreducible diagrams with A-nucleon Green's functions
- equivalent to solving the Schroedinger or Lippmann-Schwinger equation with V

Weinberg's recipe



- **steps 1** and **2** are equivalent to integrating out "soft" and "potential" modes and matching onto a theory with nucleons interacting via instantaneous potentials (chiral EFT)

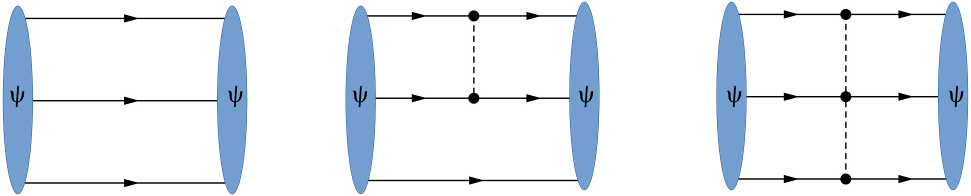
happens in several other EFTs with > 1 heavy particles: NRQCD, NRQED
similar ideas also in Soft Collinear Effective Theory

- the same recipe can be applied to operators that mediate BSM processes

$\Longrightarrow$ calculate matrix elements of BSM operators between nuclear wavefunctions

- the scaling of short-range operators **assumes** Weinberg's ν (naive dimensional analysis)

Power counting for three nucleon interactions



- diagram 0

$$\propto \left(\frac{Q^5}{4\pi m_N}\right)^2 \left(\frac{m_N}{Q^2}\right)^3 \sim \frac{Q^4 m_N}{(4\pi)^2}$$

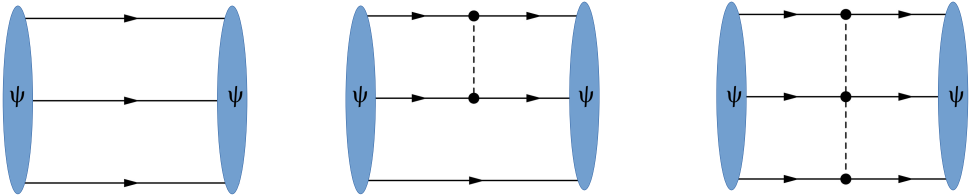
- diagram 1

$$\propto \left(\frac{Q^5}{4\pi m_N}\right)^2 \left(\frac{m_N}{Q^2}\right)^3 \times \left(\frac{Q^5}{4\pi m_N}\right) \left(\frac{m_N}{Q^2}\right)^2 \left(\frac{g_A Q}{F_\pi}\right)^2 \frac{1}{Q^2} \sim \frac{Q^4 m_N}{(4\pi)^2} \times \frac{m_N Q}{4\pi F_\pi^2}$$

- diagram 2

$$\propto \left(\frac{Q^5}{4\pi m_N}\right)^3 \left(\frac{m_N}{Q^2}\right)^5 \left(\frac{g_A Q}{F_\pi}\right)^2 \frac{1}{Q^2} \times \frac{Q^5}{4\pi m_N} \frac{m_N}{Q^2} \frac{1}{Q^2} \frac{Q^2}{F_\pi^2 \Lambda_\chi} \sim \frac{Q^4 m_N}{(4\pi)^2} \times \frac{m_N Q}{4\pi F_\pi^2} \times \frac{Q^3}{4\pi F_\pi^2 \Lambda_\chi}$$

Three nucleon interactions



- in the last diagram, the $\pi\pi NN$ vertex brings in a factor of Q/Λ_χ either from $v \cdot q$ factor in $\mathcal{L}^{(1)}_{\pi N}$ or from $\mathcal{L}^{(2)}_{\pi N}$

a. standard Weinberg's counting

"it's down by Q^3" $\Longrightarrow$ assumes $\frac{Q^3}{\Lambda_\chi^3}$ $\Longrightarrow$ book in the N^{2}LO potential

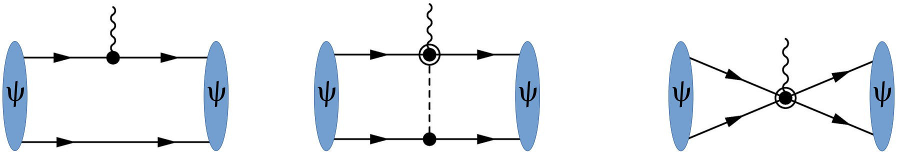
b. "Friar's counting" J. Friar '96

"it's down by $Q/F_\pi \times Q^2/\Lambda_\chi^2$" $\Longrightarrow$ $\frac{Q^2}{\Lambda_\chi^2}$ $\Longrightarrow$ book in the NLO potential

three nucleon forces are important to reproduce nuclear properties

Power counting of two-body currents

Two nucleon contributions: axial current



- the first interaction with an axial current appears in the NLO Lagrangian

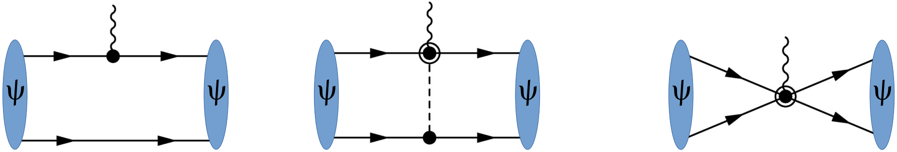
$$\mathcal{L}^{p}_{NN} = -\frac{c_D}{2\Lambda_\chi F_\pi^2}\bar{N}S\cdot uN\,\bar{N}N = \frac{c_D}{2\Lambda_\chi F_\pi^2}\bar{N}\sigma^i\tau^a N\,\bar{N}N\left(\frac{\partial_i\pi^a}{F_\pi} - \bar{\ell}^a_i + \bar{r}^a_i + \dots\right),$$

We can now power-count the relative importance of one- and two-body currents

- introduce the normalization factor (associate to the two-nucleon Z factor)

$$\mathcal{N} = \left(\frac{m_N^2}{4\pi Q}\right)^{-1}$$

Two nucleon contributions: axial current



- one body

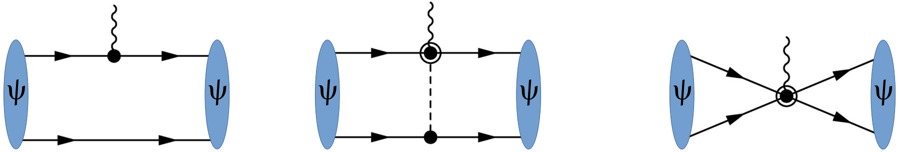
$$\mathcal{J}_1^i \propto g_A \mathcal{N} \times \left(\frac{Q^5}{4\pi m_N}\right) \times \frac{m_N^3}{Q^6} \approx g_A$$

- π-N vertices from $\mathcal{L}_{\pi N}^{p}$ do not give corrections to the space component of the axial current
- need vertices from $\mathcal{L}_{\pi N}^{p^2}$

$$\mathcal{J}_2^i \propto g_A \mathcal{N} \times \left(\frac{Q^5}{4\pi m_N}\right) \times \frac{m_N^3}{Q^6} \times \frac{Q^5}{4\pi m_N} \frac{m_N}{Q^2} \frac{Q}{F_\pi^2 Q^2} \frac{c_i Q}{\Lambda_\chi} \approx g_A c_i \frac{Q^3}{4\pi F_\pi^2 \Lambda_\chi}$$

booked as N^{2}LO or N^{3}LO in different schemes

Two nucleon contributions: axial current

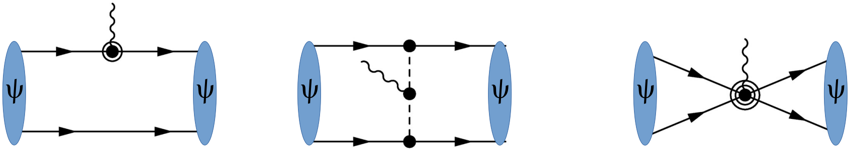


- the NN operator also comes from a NLO Lagrangian

$$\mathcal{J}_3^i \propto \mathcal{N} \times \left(\frac{Q^5}{4\pi m_N}\right) \times \frac{m_N^3}{Q^6} \times \frac{Q^5}{4\pi m_N}\,\frac{m_N}{Q^2}\,\frac{c_D}{F_\pi^2 \Lambda_\chi} \approx c_D \frac{Q^3}{4\pi F_\pi^2 \Lambda_\chi}$$

- same order as OPE
- c_D also enters the 3-body force,
  can be fit to either three-nucleon properties, or β decays (e.g. ^{3}H decay)

Two-nucleon contributions: scalar current



- in Weinberg's counting, *NN* scalar interactions appear in N^{2}LO NN Lagrangian

$$\mathcal{L}_{NN}^{(2)} = \frac{\mathrm{Tr}[\chi_+]}{\Lambda_\chi^2 F_\pi^2}\left[D_2^{^3S_1}\left(N^T P_{^3S_1} N\right)^\dagger N^T P_{^3S_1} N + D_2^{^1S_0}\left(N^T P_{^1S_0} N\right)^\dagger N^T P_{^1S_0} N\right] + \dots$$

- then

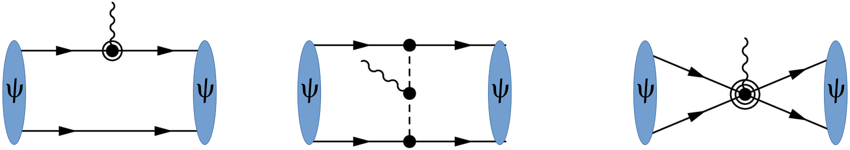
$$\mathcal{S}_1 \sim 4Bc_1\,, \qquad \mathcal{S}_2 \sim B\frac{Q}{4\pi F_\pi^2} \qquad \mathcal{S}_3 \sim B\frac{Q^3}{4\pi F_\pi^2\Lambda_\chi^2}$$

LO | LO$_{\mathrm{F}}$/NLO$_{\mathrm{W}}$ | N^{2}LO$_{\mathrm{F}}$/N^{3}LO$_{\mathrm{W}}$

- c_1 is quite large $\Longrightarrow$ W-counting might reflect the actual relative sizes better
  pion two-body currents found to be actually pretty small

C. Körber, A. Nogga, J. de Vries, '17

Two-nucleon contributions: scalar current



- in renormalized chiral EFT, $D_2^{^1S_0}$ is promoted to $\mathcal{L}_{NN}^{(0)}$

$$\mathcal{S}_3 \sim B \frac{Q^3}{4\pi F_\pi^2 \Lambda_\chi^2} \to B \frac{Q^3}{4\pi F_\pi^4}$$

- short-distance operators might give important contributions to the scalar matrix elements
- would be important to pin them down with data!

Some details on π-N couplings and the CPV potential

Calculation of the CP-violating potential

$$\mathcal{L}_{\pi N} = -\frac{\bar{g}_0}{F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{F_\pi}\pi_3\bar{N}N - \frac{\bar{g}_2}{F_\pi}\bar{N}\left(\pi_3\tau_3 - \frac{1}{3}\right)\boldsymbol{\pi}\cdot\boldsymbol{\tau}N + \dots$$

- all pion-nucleon interactions break chiral symmetry
- $\bar{g}_1$ and $\bar{g}_2$ also break isospin by 1 and 2 units
- we can write down 5 S-P transition operators
- $\tilde{C}_{{}^3S_1-{}^1P_1}$ and $\tilde{C}^{(0)}_{{}^1S_0-{}^3P_0}$ conserve isospin (and chiral symmetry)
- $\tilde{C}_{{}^3S_1-{}^3P_1}$ and $\tilde{C}^{(1)}_{{}^1S_0-{}^3P_0}$ break isospin by 1 unit
- $\tilde{C}^{(2)}_{{}^1S_0-{}^3P_0}$ break isospin by 2 units

Pion-nucleon couplings

- pion-nucleon couplings can be related to spectroscopic quantities, so we have some info
- $\bar{\theta}$ term

$$\bar{g}_0 = 2\frac{m_n - m_p}{m_d - m_u}\frac{m_u m_d}{m_u + m_d}\bar{\theta} = g_S^{u-d}\bar{m}\theta \qquad \checkmark$$

$$\bar{g}_1 = \mathcal{O}(m_\pi^4)$$

- since $\bar{\theta}$ conserves isospin, $\bar{g}_1$ is only generated at subleading order

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$$\bar{g}_1 = \mathcal{O}(m_\pi^4)$$

- since $\bar{\theta}$ conserves isospin, $\bar{g}_1$ is only generated at subleading order
- qCEDM: need generalized sigma terms

$$\bar{g}_0 = \tilde{d}_0\left(\frac{d}{d\tilde{c}_3} + r\frac{d}{d\bar{m}\varepsilon}\right)(m_n - m_p) \qquad \bar{g}_1 = -\tilde{d}_3\left(\frac{d}{d\tilde{c}_0} - r\frac{d}{d\bar{m}}\right)(m_n + m_p)$$

with

$$\tilde{d}_{0,3} = \mathrm{Im}\,(\mathrm{C_{ug}} \pm \mathrm{C_{dg}})\,, \qquad \tilde{c}_{0,3} = \mathrm{Re}\,(\mathrm{C_{ug}} \pm \mathrm{C_{dg}})\,, \qquad r = -\frac{1}{2}\frac{\langle 0|\bar{q}\sigma G q|0\rangle}{\langle 0|\bar{q}q|0\rangle}$$

- only the "tadpole" piece is known — prop. to r and the scalar charges
- $\bar{g}_{0,1}$ are expected to be of the same size

Pion-nucleon couplings

- *LLRR* four-fermion operators

$$\bar{g}_0 = 0$$
$$\bar{g}_1 = \mathrm{Im}L^{\mathrm{V1LR}}_{uddu}\left(\frac{d}{d\mathrm{Re}L^{\mathrm{V1LR}}_{uddu}} + \frac{r^{\mathrm{LR}}}{4}\frac{d}{d\bar{m}}\right)(m_n + m_p)$$

  with r^{LR} some ratio of vacuum matrix elements
- r has been computed in Lattice QCD, for all the relevant operators
- the "direct" piece is not known
- since L^{V1LR}_{uddu} breaks isospin, $\bar{g}_1 \gg \bar{g}_0$

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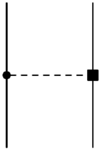
- the “direct” piece is not known
- since L^{V1LR}_{uddu} breaks isospin, $\bar{g}_1 \gg \bar{g}_0$

- $GG\tilde{G}$ 3-gluon operator
- is chiral invariant, all π-N couplings are suppressed
- $\tilde{C}_{^3S_1-^1P_1}$ and $\tilde{C}^{(0)}_{^1S_0-^3P_0}$ contribute at lowest order

different chiral/isospin breaking patterns $\Longrightarrow$ different relative importance of $\bar{g}_0$, $\bar{g}_1$ and contact
...but need more quantitative determinations for any realistic analysis

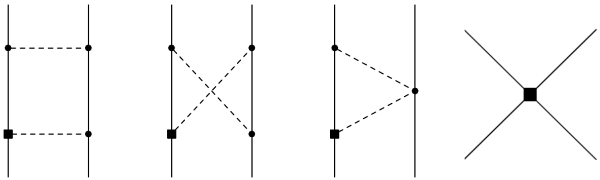
The CPV nucleon-nucleon potential. $\bar{\theta}$ term



$$V_{\bar{\theta}}^{(0)} = -\frac{\bar{g}_0 g_A}{F_\pi^2} \boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)} \left(\sigma^{(1)} - \vec{\sigma}^{(2)}\right) \cdot \vec{\nabla} \left(\frac{e^{-m_\pi r}}{4\pi r}\right)$$

- LO: isoscalar OPE
- NLO: TPE & short range, same structure as LO $\mathcal{O}(m_\pi^2/\Lambda_\chi^2)$

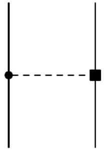
The CPV nucleon-nucleon potential. $\bar{\theta}$ term



$$V_{\bar{\theta}}^{(2)} = \boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)} \left(\sigma^{(1)} - \vec{\sigma}^{(2)}\right) \cdot \vec{\nabla} \left(-\frac{\bar{g}_0 g_A}{F_\pi^2} f_{\mathrm{TPE}}(r) + \bar{C}_2 \delta(\vec{r}) \right) + \frac{1}{2} \bar{C}_1 \left(\sigma^{(1)} - \vec{\sigma}^{(2)}\right) \cdot \vec{\nabla} \delta(\vec{r})$$

- LO: isoscalar OPE
- NLO: TPE & short range, same structure as LO $\mathcal{O}(m_\pi^2/\Lambda_\chi^2)$

The CPV nucleon-nucleon potential. $\bar{\theta}$ term

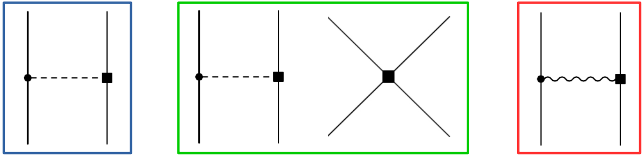


$$V^{(2)}_{\bar\theta} = -\frac{\bar g_0 g_A}{2F_\pi^2}\left[\left(\frac{\bar g_1}{\bar g_0} - \frac{\beta_1}{2g_A}\right)(\tau_3^{(1)}+\tau_3^{(2)})(\sigma^{(1)}-\sigma^{(2)}) + \left(\frac{\bar g_1}{\bar g_0} + \frac{\beta_1}{2g_A}\right)(\tau_3^{(1)}-\tau_3^{(2)})(\sigma^{(1)}+\sigma^{(2)})\right]\cdot\vec\nabla\left(\frac{e^{-m_\pi r}}{4\pi r}\right)$$

- LO: isoscalar OPE
- NLO: TPE & short range, same structure as LO $\mathcal{O}(m_\pi^2/\Lambda_\chi^2)$
- isospin breaking terms + relativistic corrections $\mathcal{O}(\varepsilon m_\pi^2/\Lambda_\chi^2, m_\pi^2/m_N^2)$

see J. de Vries *et al*, '20 for a review

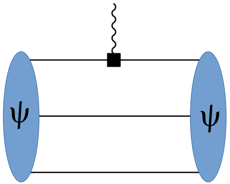
The CPV potential. Dimension-six operators



$$
\begin{aligned}
V_6 \quad = \quad & -\frac{\bar{g}_0 g_A}{F_\pi^2} \boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)} \left(\sigma^{(1)} - \vec{\sigma}^{(2)}\right) \cdot \vec{\nabla} \left(\frac{e^{-m_\pi r}}{4\pi r}\right) \\
& -\frac{\bar{g}_1 g_A}{2F_\pi^2} \left[(\tau_3^{(1)} + \tau_3^{(2)})(\sigma^{(1)} - \sigma^{(2)}) + (\tau_3^{(1)} - \tau_3^{(2)})(\sigma^{(1)} + \sigma^{(2)})\right] \cdot \vec{\nabla} \left(\frac{e^{-m_\pi r}}{4\pi r}\right) \\
& +\frac{1}{2} \left(\bar{C}_1 + \bar{C}_2 \boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)}\right) \left(\sigma^{(1)} - \vec{\sigma}^{(2)}\right) \cdot \vec{\nabla} \delta(\vec{r})
\end{aligned}
$$

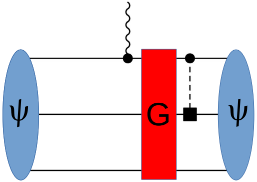
- qCEDM, LL RR and LR LR: isoscalar & isovector OPE
- gCEDM & LR LR : OPE & short range
- qEDM: photon-exchange (negligible)

EDMs of light nuclei: power counting



$$Z^{-1}\left[\frac{Q^5}{4\pi m_N}\right]^{N-1}\left[\frac{m_N}{Q^2}\right]^{N+1} d_{n,p}$$

$$\sim d_{n,p}$$



$$Z^{-1}\left[\frac{Q^5}{4\pi m_N}\right]^{N-1}\left[\frac{m_N}{Q^2}\right]^{N+1}\times\left[\frac{Q^5}{4\pi m_N}\right]\frac{m_N^2}{Q^4}\frac{1}{Q^2}\frac{g_A\bar{g}_i}{F_\pi^2}$$

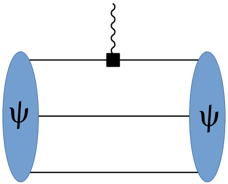
$$\sim \frac{m_N Q}{4\pi F_\pi^2} g_A\bar{g}_i \sim g_A\bar{g}_i$$

- for $\bar{\theta}$ term

$$d_{n,p} \sim \frac{\bar{g}_0 m_\pi^2}{\Lambda_\chi^2} \ll \bar{g}_0$$

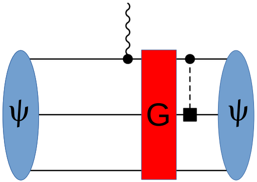
nuclear EDMs sensitive to $\bar{g}_0$ should be somewhat enhanced compared to d_n

EDMs of light nuclei: power counting



$$Z^{-1}\left[\frac{Q^5}{4\pi m_N}\right]^{N-1}\left[\frac{m_N}{Q^2}\right]^{N+1} d_{n,p}$$

$$\sim d_{n,p}$$



$$Z^{-1}\left[\frac{Q^5}{4\pi m_N}\right]^{N-1}\left[\frac{m_N}{Q^2}\right]^{N+1} \times \left[\frac{Q^5}{4\pi m_N}\right]\frac{m_N^2}{Q^4}\frac{1}{Q^2}\frac{g_A\bar{g}_i}{F_\pi^2}$$

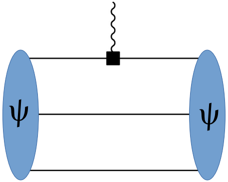
$$\sim \frac{m_N Q}{4\pi F_\pi^2} g_A\bar{g}_i \sim g_A\bar{g}_i$$

- for qCEDM

$$d_{n,p} \sim \frac{\bar{g}_0 m_\pi^2}{\Lambda_\chi^2} \ll \bar{g}_0, \bar{g}_1$$

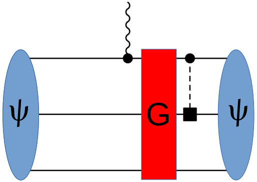
nuclear EDMs sensitive to $\bar{g}_0$ **and** $\bar{g}_1$ should be somewhat enhanced compared to d_n

EDMs of light nuclei: power counting



$$Z^{-1}\left[\frac{Q^5}{4\pi m_N}\right]^{N-1}\left[\frac{m_N}{Q^2}\right]^{N+1} d_{n,p}$$

$$\sim d_{n,p}$$



$$Z^{-1}\left[\frac{Q^5}{4\pi m_N}\right]^{N-1}\left[\frac{m_N}{Q^2}\right]^{N+1} \times \left[\frac{Q^5}{4\pi m_N}\right]\frac{m_N^2}{Q^4}\frac{1}{Q^2}\frac{g_A\bar{g}_i}{F_\pi^2}$$

$$\sim \frac{m_N Q}{4\pi F_\pi^2} g_A\bar{g}_i \sim g_A\bar{g}_i$$

- for gCEDM

$$d_{n,p} \sim \bar{g}_0$$

nuclear EDMs should be of the same size as d_n