T violation in Chiral Effective Theory

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Project X Physics Study

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Motivations and Introduction

Observation of Nucleon, Deuteron or Helium EDM

strong CP violation?

$$\mathcal{L}_\theta = -\theta \frac{g_s^2}{64\pi^2} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu}$$

beyond SM?

$$\mathcal{L}_{\not{T}} = \sum_n \frac{c_n}{M_{\not{T}}^{d_n-4}} \mathcal{O}_{\not{T}\,n}\,(A_\mu, G_\mu, q)$$

$$M_{\not{T}} \gg M_W$$

Several issues . . .

- modelling beyond SM physics
- running to the QCD scale
- estimating nuclear matrix elements

our strategy

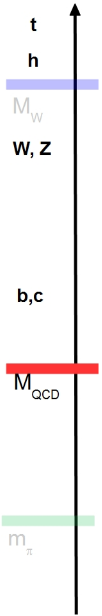
Symmetries &
Effective Theories

1. "integrate out" new physics

$$\mathcal{L}_{\not T} = \mathcal{L}_{\theta} + \sum_n \frac{c_n}{M_{\not T}^{d_n - 4}} \mathcal{O}_{\not T\, n}\left(A_\mu, G_\mu, W_\mu, q, l, h\right)$$

$\mathcal{O}_{\not T\, n}$ gauge-invariant, CP-odd, operators
only depend on SM fields

Strategy



1. "integrate out" new physics
2. break gauge symmetry &
   "integrate out" heavy quarks, gauge-bosons and higgs

$$\mathcal{L}_{\not{T}} = \mathcal{L}_{\theta} + \sum_{n} \frac{\tilde{c}_n \left(M_W,\, m_h,\, m_Q\right)}{M_{\not{T}}^{d_n-4}} \mathcal{O}_{\not{T}\, n}\left(A_\mu, G_\mu, q\right)$$

Strategy

1. "integrate out" new physics
2. break gauge symmetry &
   "integrate out" heavy quarks, gauge-bosons and higgs
3. construct hadronic operators with chiral properties of $\mathcal{O}_{\not{T},n}$

$$\mathcal{L}_{\not{T}} = \sum_{f,\Delta} \mathcal{L}^{(\Delta)}_{\not{T},f}\,[\boldsymbol{\pi}, N]$$

4. hide non perturbative ignorance in few unknown coefficients
5. look for qualitatively different low energy effects of various TV sources

different properties under $SU_L(2) \times SU_R(2)$ $\Downarrow$ different relations between low-energy TV observables

The QCD Theta Term

$$\mathcal{L}_4 = -\theta \frac{g_s^2}{64\pi^2} \varepsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta} - \bar{q}_R M q_L - \bar{q}_L M^* q_R,$$

$$M = \bar{m} e^{i\rho} \begin{pmatrix} 1-\varepsilon & 0 \\ 0 & 1+\varepsilon \end{pmatrix} \qquad \begin{array}{c} \bar{m} = (m_u + m_d)/2 \\ \varepsilon = (m_d - m_u)/(m_d + m_u) \end{array}$$

- $\theta, \rho \neq 0$ break P and T
- $M \neq 0$ explicitly breaks chiral symmetry

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- $\theta, \rho \neq 0$ break P and T
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- eliminate θ with (anomalous) $SU_A(2) \times U_A(1)$ axial rotation

$$\mathcal{L}_4 = -\bar{m}\, r(\bar{\theta})\, \bar{q}q + \varepsilon \bar{m}\, r^{-1}(\bar{\theta})\, \bar{q}\tau_3 \bar{q} + m_\star \sin\bar{\theta}\, r^{-1}(\bar{\theta})\, i\bar{q}\gamma^5 q,$$

with

$$\bar{\theta} = 2\rho + \theta, \qquad m_\star = \frac{m_u m_d}{m_u + m_d} = \frac{\bar{m}}{2}\left(1 - \varepsilon^2\right), \quad r(\bar{\theta}) = \sqrt{\frac{1 + \varepsilon^2 \tan^2 \frac{\bar{\theta}}{2}}{1 + \tan^2 \frac{\bar{\theta}}{2}}}$$

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$$\mathcal{L}_4 = -\bar{m}\, r(\bar{\theta})\, S_4 + \varepsilon \bar{m}\, r^{-1}(\bar{\theta})\, P_3 + m_\star \, \sin\bar{\theta}\, r^{-1}(\bar{\theta})\, P_4,$$

- $\bar{\theta}$ and m break chiral symmetry in a very specific way

$$S = \begin{pmatrix} -i\bar{q}\gamma^5 \boldsymbol{\tau} q \\ \bar{q}q \end{pmatrix} \qquad P = \begin{pmatrix} \bar{q}\,\boldsymbol{\tau} q \\ i\bar{q}\gamma^5 q \end{pmatrix}$$

- $SO(4)$ vector
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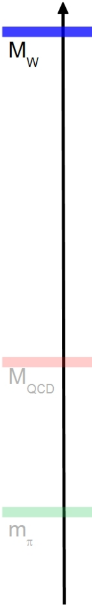
Sources of T violation



- no dimension 5 operator with quarks/gluons
- several **dimension 6** operators

$$\mathcal{L}_6 = \mathcal{L}_{6,\,XX\varphi\varphi} + \mathcal{L}_{6,\,qq\varphi X} + \mathcal{L}_{6,XXX} + \mathcal{L}_{6,\,qq\varphi\varphi} + \mathcal{L}_{6,\,qqqq}$$

Buchmuller & Wyler ‘86, Weinberg ‘89, de Rujula *et al.* ‘91, Grzadkowski *et al.* ‘10 . . .

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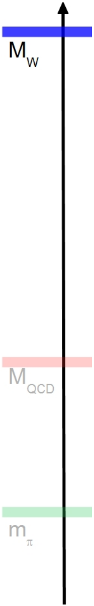

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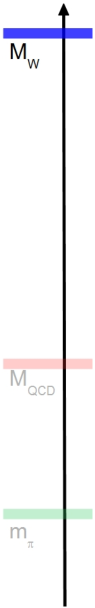
$$\mathcal{L}_{6,\,XX\varphi\varphi} = -2\frac{\varphi^\dagger\varphi}{v^2}\left\{\theta'\,\frac{g_s^2}{64\pi^2}\epsilon^{\mu\nu\alpha\beta}\,G^a_{\mu\nu}G^a_{\alpha\beta} + \bar{q}_L Y'^{\,u}\tilde{\varphi}u_R + \bar{q}_L Y'^{\,d}\varphi d_R\right\}$$

- θ', Yukawa couplings corrections to θ and the quark masses

$$\theta',\, Y'^{\,u,d} = \mathcal{O}\left(\frac{v^2}{M^2_{\not T}}\right)$$

- *CP*-odd Higgs-gluons, Higgs-quark couplings, not very relevant at low energy

Sources of T violation



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$$\mathcal{L}_{6,\,XXX} = \frac{d_W}{6} f^{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu} + \dots$$

$$\mathcal{L}_{6,\,qq\varphi X} = -\frac{1}{\sqrt{2}} \bar{q}_L \sigma^{\mu\nu} \left\{ \tilde{\Gamma}^u \lambda^a G^a_{\mu\nu} + \Gamma^u_B B_{\mu\nu} + \Gamma^u_W \boldsymbol{\tau} \cdot \mathbf{W}_{\mu\nu} \right\} \frac{\tilde{\varphi}}{v} u_R$$
$$- \frac{1}{\sqrt{2}} \bar{q}_L \sigma^{\mu\nu} \left\{ \tilde{\Gamma}^d \lambda^a G^a_{\mu\nu} + \Gamma^d_B B_{\mu\nu} + \Gamma^d_W \boldsymbol{\tau} \cdot \mathbf{W}_{\mu\nu} \right\} \frac{\varphi}{v} d_R$$

- Γ complex-valued matrices in flavor space

$$d_W = \mathcal{O}\left(\frac{1}{M^2_{\not T}}\right), \quad \tilde{\Gamma}^{u,d} = \mathcal{O}\left(\frac{m_{u,d}}{M^2_{\not T}}\right),$$

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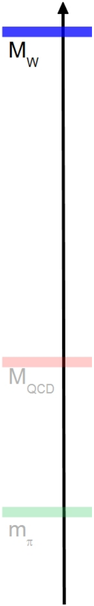

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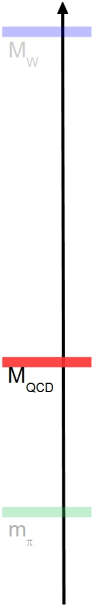
$$\mathcal{L}_{6,\,qq\varphi\varphi} = \Xi\, \bar{u}_R \gamma^\mu d_R \left(\tilde{\varphi}^\dagger i D_\mu \varphi\right) + \text{h.c.},$$

$$\mathcal{L}_{6,\,qqqq} = \Sigma_1 \left(\bar{q}_L^J u_R\right) \varepsilon_{JK} \left(\bar{q}_L^K d_R\right) + \Sigma_8 \left(\bar{q}_L^J \lambda^a u_R\right) \varepsilon_{JK} \left(\bar{q}_L^K \lambda^a d_R\right) + \text{h.c.},$$

- Ξ and $\Sigma_{1,8}$ complex-valued matrices in flavor space

$$\Xi = \mathcal{O}\left(\frac{1}{M_{\not{T}}^2}\right), \quad \Sigma_{1,8} = \mathcal{O}\left(\frac{1}{M_{\not{T}}^2}\right),$$

Matching & Running



- break EW symmetry, $\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$
- integrate out heavy particles

At tree level:

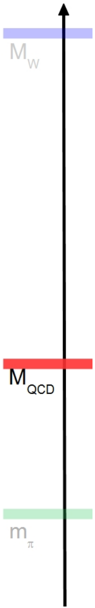
- gluon chromo-EDM (gCEDM)

$$\mathcal{L}_{6,\,XXX} = \frac{d_W}{6} f^{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu}$$

- quark EDM (qEDM) and chromo-EDM (qCEDM)

$$\mathcal{L}_{6,\,qq\varphi X} = -\frac{1}{2}\,\bar{q}\, i\sigma^{\mu\nu}\gamma^5\,(d_0 + d_3\tau_3)\, q\, F_{\mu\nu} - \frac{1}{2}\,\bar{q}\, i\sigma^{\mu\nu}\gamma^5 \left(\tilde{d}_0 + \tilde{d}_3\tau_3\right) G_{\mu\nu} q$$

Matching & Running



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$$\tilde{d}_{0,3}(\mu = M_W) \quad = \quad \frac{1}{2}\left(\mathrm{Im}\,\tilde{\Gamma}^u \pm \mathrm{Im}\,\tilde{\Gamma}^d\right)$$

$$d_{0,3}(\mu = M_W) \quad = \quad \frac{1}{2}\left(\left(\mathrm{Im}\,\Gamma^u_B \pm \mathrm{Im}\,\Gamma^d_B\right)\cos\theta_W + \left(\mathrm{Im}\,\Gamma^u_W \mp \mathrm{Im}\,\Gamma^d_W\right)\sin\theta_W\right)$$

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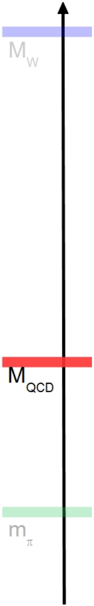

- TV 4-quark operators

$$
\begin{aligned}
\mathcal{L}_{6,\,qqqq} \quad = \quad & \frac{1}{4}\mathrm{Im}\Sigma_1\left(\bar{q}q\,\bar{q}i\gamma^5 q - \bar{q}\boldsymbol{\tau}q\cdot\bar{q}\boldsymbol{\tau}i\gamma^5 q\right)\\
&+\frac{1}{4}\mathrm{Im}\Sigma_8\left(\bar{q}\lambda^a q\,\bar{q}i\gamma^5\lambda^a q - \bar{q}\boldsymbol{\tau}\lambda^a q\cdot\bar{q}\boldsymbol{\tau}i\gamma^5\lambda^a q\right)\\
&+\frac{1}{4}\,\mathrm{Im}\,\Xi_1\left(\bar{q}q\,\bar{q}i\gamma^5\tau_3 q - \bar{q}\tau_3 q\,\bar{q}i\gamma^5 q\right)\\
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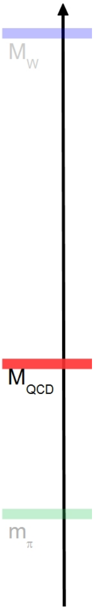
\end{aligned}
$$

Matching & Running



- TV 4-quark operators

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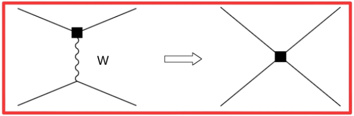
& + \frac{1}{4}\,\mathrm{Im}\,\Xi_1\left(\bar{q}q\,\bar{q}i\gamma^5\tau_3 q - \bar{q}\tau_3 q\,\bar{q}i\gamma^5 q\right)\\
& + \frac{1}{4}\,\mathrm{Im}\,\Xi_8\left(\bar{q}\lambda^a q\,\bar{q}i\gamma^5\tau_3\lambda^a q - \bar{q}\tau_3\lambda^a q\,\bar{q}i\gamma^5\lambda^a q\right)
\end{aligned}$$



$$\begin{aligned}
\mathrm{Im}\,\Xi_1(\mu = M_W) &= V_{ud}\,\mathrm{Im}\,\Xi,\\
\mathrm{Im}\,\Xi_8(\mu = M_W) &= -3V_{ud}\,\mathrm{Im}\,\Xi.
\end{aligned}$$

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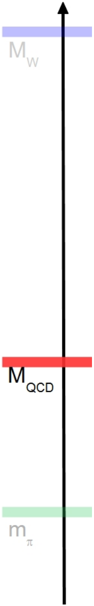

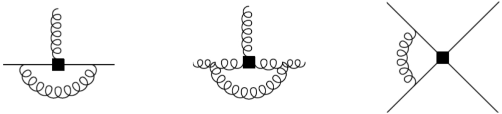

$$\frac{dC_i}{d\ln\mu} = \gamma_{ij}\, C_j$$

Wilczek and Zee, '77; Weinberg, '89; Braaten *et al.*, '90; Degrassi *et al.*, '05; An *et al.*, '10; Hisano *et al.*, '12; Dekens and de Vries, private communication

- gCEDM, $\Sigma_{1,8}$ mix onto qCEDM
- qCEDM mixes onto qEDM
- $\Xi_{1,8}$ run into each other

- QCD evolution **does not** generate additional low-energy operators

  other *CP*-odd four-quark operators suppressed by $\bar{m}$

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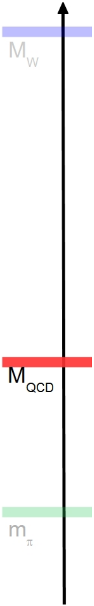

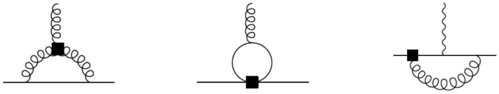

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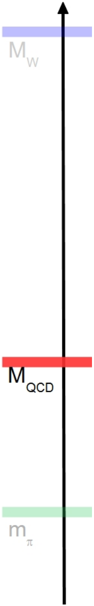
Quark-Gluon TV Lagrangian. Summary



$$\mathcal{L}_{\not T}(\mu \sim 1\,\text{GeV}) = -\frac{1}{2}\bar{m}(1-\varepsilon^2)\bar{\theta}\,\bar{q}i\gamma^5 q + \frac{d_W}{6} f^{abc}\varepsilon^{\mu\nu\alpha\beta}G^a_{\alpha\beta}G^b_{\mu\rho}G^{c\ \rho}_{\nu}$$
$$-\frac{1}{2}\,\bar{q}\,i\sigma^{\mu\nu}\gamma^5\,(d_0+d_3\tau_3)\,q\,F_{\mu\nu} - \frac{1}{2}\,\bar{q}\,i\sigma^{\mu\nu}\gamma^5\left(\tilde{d}_0+\tilde{d}_3\tau_3\right)G_{\mu\nu}q$$
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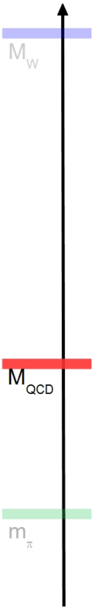

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- Coefficients (at $\mu \sim 1$ GeV)

$$d_W \equiv 4\pi\frac{w}{M^2_{\not T}}, \qquad d_{0,3} \equiv e\delta_{0,3}\frac{\bar{m}}{M^2_{\not T}}, \qquad \tilde{d}_{0,3} \equiv 4\pi\tilde{\delta}_{0,3}\frac{\bar{m}}{M^2_{\not T}},$$
$$\mathrm{Im}\,\Sigma_{1,8} \equiv (4\pi)^2\frac{\sigma_{1,8}}{M^2_{\not T}}, \qquad \mathrm{Im}\,\Xi_{1,8} \equiv (4\pi)^2\frac{\xi_{1,8}}{M^2_{\not T}}.$$

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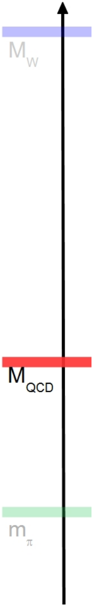

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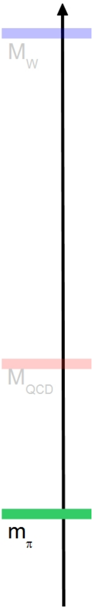
- depend on details of BSM TV mechanism

very model dependent!

- contain info on QCD running & heavy SM particles

Chiral properties of TV sources



1. QCD Theta Term

$$\mathcal{L}_4 = \frac{1}{2}\bar{m}(1-\varepsilon^2)\bar{\theta}\, P_4$$

- breaks $SU_L(2) \times SU_R(2)$ as 4$^{\text{th}}$ component of a vector P
- does not break isospin

2. qCEDM & qEDM

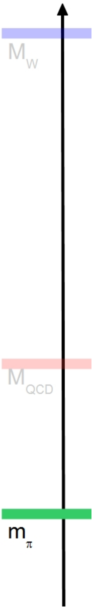
$$\mathcal{L}_{6,\, qq\varphi X} \quad = \quad -\tilde{d}_0 \tilde{V}_4 + \tilde{d}_3 \tilde{W}_3 - d_0 V_4 + d_3 W_3$$

- $\tilde{V}$, $\tilde{W}$ and V, W are $SO(4)$ vectors

$$\tilde{W} = \frac{1}{2}\begin{pmatrix} -i\bar{q}\sigma^{\mu\nu}\gamma^5\boldsymbol{\tau}\lambda^a q \\ \bar{q}\sigma^{\mu\nu}\lambda^a q \end{pmatrix} G^a_{\mu\nu}, \qquad \tilde{V} = \frac{1}{2}\begin{pmatrix} \bar{q}\sigma^{\mu\nu}\boldsymbol{\tau}\lambda^a q \\ i\bar{q}\sigma^{\mu\nu}\gamma^5\lambda^a q \end{pmatrix} G^a_{\mu\nu}.$$

- $\tilde{V}_4$, V_4 break chiral symmetry
- $\tilde{W}_3$, W_3 break chiral symmetry & isospin

Chiral properties of TV sources



3. gCEDM & $\Sigma_{1,8}$

$$\mathcal{L}_{6,\,XXX} + \mathcal{L}_{6,\,qqqq} = d_W I_W + \mathrm{Im}\Sigma_1\, I_{qq}^{(1)} + \mathrm{Im}\Sigma_8\, I_{qq}^{(8)}$$

- $I_W,\, I_{qq}^{(1,8)}$ respect chiral symmetry & isospin

$$I_{qq}^{(1)} = \bar{q}q\,\bar{q}i\gamma^5 q - \bar{q}\boldsymbol{\tau}q\cdot\bar{q}\boldsymbol{\tau}i\gamma^5 q = S_4 P_4 + \boldsymbol{S}\cdot\boldsymbol{P}.$$

4. $\Xi_{1,8}$

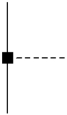
$$\mathcal{L}_{6,\,qqqq} = +\frac{1}{4}\,\mathrm{Im}\,\Xi_1 T_{34}^{(1)} + \frac{1}{4}\,\mathrm{Im}\,\Xi_8 T_{34}^{(8)}$$

- $T_{34}^{(1,8)}$ 3-4 component of symmetric tensors

$$T_{34}^{(1)} = \bar{q}q\,\bar{q}i\gamma^5\tau_3 q - \bar{q}\tau_3 q\,\bar{q}i\gamma^5 q = S_3 S_4 + P_3 P_4.$$

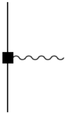
TV Chiral Lagrangian: ingredients

- pion-nucleon TV interactions



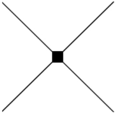
$$\mathcal{L}_{\not{T},f=2} = -\frac{\bar{g}_0}{F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{F_\pi}\pi_3\bar{N}N$$

- nucleon-photon TV interactions



$$\mathcal{L}_{\not{T}\gamma,f=2} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right)S^\mu v^\nu N F_{\mu\nu}$$

- nucleon-nucleon TV interactions



$$\mathcal{L}_{\not{T},f=4} \quad = \quad \bar{C}_1\bar{N}N\partial_\mu(\bar{N}S^\mu N) + \bar{C}_2\bar{N}\boldsymbol{\tau}N\cdot\mathcal{D}_\mu(\bar{N}\boldsymbol{\tau}S^\mu N)$$

TV Chiral Lagrangian. Theta Term

	$\bar{g}_0$	$\bar{g}_1$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$
$\bar{\theta} \times \frac{m_\pi^2}{M_{QCD}}$	1	$\varepsilon \frac{m_\pi^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$

Theta Term violates chiral symmetry & conserves isospin

- non-derivative coupling $\bar{g}_0$ appears @ LO
- needs extra insertion of $\bar{m}\varepsilon$ to generate $\bar{g}_1$
- higher dimensionality of $N\gamma$ and NN operators costs powers of Q/M_{QCD}
- relation to isospin violating coupling

$$\bar{g}_0 = \delta m_N \frac{1-\varepsilon^2}{2\varepsilon} \bar{\theta},$$

R. Crewther *et al.*, '79

TV Chiral Lagrangian. Theta Term

	$\bar{g}_0$	$\bar{g}_1$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$
$\bar{\theta} \times \frac{m_\pi^2}{M_{QCD}}$	1	$\varepsilon \frac{m_\pi^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$

Theta Term violates chiral symmetry & conserves isospin

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- higher dimensionality of $N\gamma$ and NN operators costs powers of Q/M_{QCD}
- relation to isospin violating coupling

$$\bar{g}_0 = \frac{\delta m_N}{2\varepsilon}(1-\varepsilon^2)\bar{\theta}, \qquad \frac{\delta m_N}{2\varepsilon} = 2.8\,\text{MeV}$$

S. Beane *et al.*, ‘07

- analogous relations for $\bar{g}_1$, $\bar{C}_{1,2}$

but TC LEC not well determined

- iso-breaking from EM spoils relation for $\bar{d}_{0,1}$

TV Chiral Lagrangian. qCEDM & $\Xi_{1,8}$

	$\bar{g}_0$	$\bar{g}_1$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$
$\tilde{\delta}_0 \times \frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}$	1	$\varepsilon \frac{m_\pi^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$
$\tilde{\delta}_3 \times \frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}$	ε	1	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$
$(\xi_1, \xi_8) \times \frac{M_{QCD}^3}{M_{\not{T}}^2}$	ε	1	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$

- $\tilde{\delta}_0$ generates same operators as $\bar{\theta}$

TV Chiral Lagrangian. qCEDM & $\Xi_{1,8}$

	$\bar{g}_0$	$\bar{g}_1$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$
$\tilde{\delta}_0 \times \frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}$	1	$\varepsilon \frac{m_\pi^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$
$\tilde{\delta}_3 \times \frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}$	ε	1	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$
$(\xi_1, \xi_8) \times \frac{M_{QCD}^3}{M_{\not{T}}^2}$	ε	1	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$

- $\tilde{\delta}_0$ generates same operators as $\bar{\theta}$

Isospin-breaking sources $\tilde{\delta}_3$ and $\xi_{1,8}$

- very similar couplings

  different chiral properties play a role for multi-pion vertices (> 2)

- $\bar{g}_1$ in LO

TV Chiral Lagrangian. qCEDM & $\Xi_{1,8}$

	$\bar{g}_0$	$\bar{g}_1$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$
$\tilde{\delta}_0 \times \frac{m_\pi^2 M_{QCD}}{M_{\not T}^2}$	1	$\varepsilon \frac{m_\pi^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$
$\tilde{\delta}_3 \times \frac{m_\pi^2 M_{QCD}}{M_{\not T}^2}$	ε	1	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$
$(\xi_1, \xi_8) \times \frac{M_{QCD}^3}{M_{\not T}^2}$	ε	1	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$

- $\tilde{\delta}_0$ generates same operators as $\bar{\theta}$

Isospin-breaking sources $\tilde{\delta}_3$ and $\xi_{1,8}$

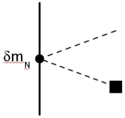
- very similar couplings

  different chiral properties play a role for multi-pion vertices (> 2)

- $\bar{g}_1$ in LO

- contribute to isoscalar couplings through pion tadpole

$$\mathcal{L}_{f=0} = \Delta \frac{F_\pi \pi_3}{2}$$



TV Chiral Lagrangian. gCEDM, $\Sigma_{1,8}$ & qEDM

	$\bar{g}_0$	$\bar{g}_1$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$
$(w, \sigma_1, \sigma_8) \times \frac{M_{QCD}}{M_{\not T}^2}$	m_π^2	$m_\pi^2 \varepsilon$	Q^2	Q^2
$\delta_{0,3} \times \frac{m_\pi^2 M_{QCD}}{M_{\not T}^2}$	$\frac{\alpha_{\rm em}}{4\pi}$	$\frac{\alpha_{\rm em}}{4\pi}$	$\frac{Q^2}{M_{QCD}^2}$	$\frac{\alpha_{\rm em}}{4\pi} \frac{Q^2}{M_{QCD}^2}$

gCEDM, $\Sigma_{1,8}$ respect chiral symmetry

- $\bar{g}_{0,1}$ generated through insertion of the quark mass and mass difference

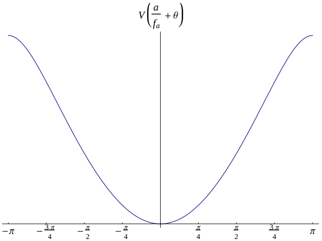
  extra m_π^2 / M_{QCD}^2 suppression!
- NN and $N\gamma$ couplings do not break chiral symmetry

  no extra suppression
- same importance for long & short range operators

qEDM

- hadronic operators suppressed by $\alpha_{\rm em}$
- only $\bar{d}_{0,1}$ relevant

Dimension 6 Sources and the Axion Mechanism

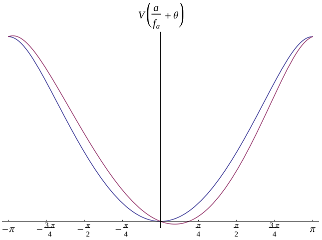


- no dim. 6 sources

$$V_0\left(\bar{\theta}+\frac{a}{f_a}\right) = -\frac{1}{4}m_\pi^2 F_\pi^2 r\left(\bar{\theta}+\frac{a}{f_a}\right)$$

$$\bar{\theta}+\frac{\langle a\rangle}{f_a} = 0$$

Dimension 6 Sources and the Axion Mechanism



e.g for qCEDM

- if dim. 6 sources

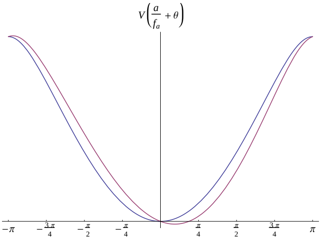
$$V\left(\bar{\theta}+\frac{a}{f_a}\right)=V_0\left(\bar{\theta}+\frac{a}{f_a}\right)+V_1\left(\bar{\theta}+\frac{a}{f_a}\right)$$

$$\bar{\theta}+\frac{\langle a\rangle}{f_a}=\bar{\theta}_{\text{ind}}$$

$$\bar{\theta}_{\text{ind}}=-\frac{2}{1-\varepsilon^2}\frac{\Delta m_\pi^2}{m_\pi^2\tilde{\Gamma}_0\cos\varphi_0}\left(\tilde{d}_0+\varepsilon\tilde{d}_3\right)$$

Δm_π^2: corrections to m_π^2 due to chromo-magnetic moment $\tilde{\Gamma}_0\cos\varphi_0$

Dimension 6 Sources and the Axion Mechanism



e.g for qCEDM

- if dim. 6 sources

$$V\left(\bar{\theta}+\frac{a}{f_a}\right) = V_0\left(\bar{\theta}+\frac{a}{f_a}\right) + V_1\left(\bar{\theta}+\frac{a}{f_a}\right)$$

$$\bar{\theta}+\frac{\langle a\rangle}{f_a} = \bar{\theta}_{\rm ind}$$

$$\bar{\theta}_{\rm ind} = -\frac{2}{1-\varepsilon^2}\frac{\Delta m_\pi^2}{m_\pi^2\,\tilde{\Gamma}_0\cos\varphi_0}\left(\tilde{d}_0+\varepsilon\tilde{d}_3\right)$$

Δm_π^2: corrections to m_π^2 due to chromo-magnetic moment $\tilde{\Gamma}_0\cos\varphi_0$

if
lattice:
determine χPT LEC in terms of quark-gluon couplings

and
data:
extract χPT LEC

test if axion mechanism at work?

Chiral Lagrangian. Summary.

		pion-nucleon	photon-nucleon $\times\, Q^2$	nucleon-nucleon $\times\, F_\pi^2 Q^2$
$\bar\theta$ term, qCEDM $\Xi_{1,8}$	$\bar\theta m_\pi^2/M_{QCD}$ $\tilde\delta m_\pi^2 M_{QCD}/M_{\not T}^2$ $\xi M_{QCD}^3/M_{\not T}^2$	1	Q^2/M_{QCD}^2	Q^2/M_{QCD}^2
gCEDM $\Sigma_{1,8}$	$w m_\pi^2 M_{QCD}/M_{\not T}^2$	1	1	1
qEDM	$\delta m_\pi^2 M_{QCD}/M_{\not T}^2$	$\alpha_{\rm em}/\pi$	Q^2/M_{QCD}^2	$\alpha_{\rm em} Q^2/\pi M_{QCD}^2$

- chiral-breaking sources
  TV π-N couplings have lowest chiral index

1. pion loops and short-range EDM operators equally important for nucleon EDM
2. pion-exchange dominate EDMs of light nuclei

...unless selection rules!

Chiral Lagrangian. Summary.

		pion-nucleon	photon-nucleon $\times Q^2$	nucleon-nucleon $\times F_\pi^2 Q^2$
$\bar{\theta}$ term, qCEDM $\Xi_{1,8}$	$\bar{\theta} m_\pi^2/M_{QCD}$ $\tilde{\delta} m_\pi^2 M_{QCD}/M_{\not T}^2$ $\xi M_{QCD}^3/M_{\not T}^2$	1	Q^2/M_{QCD}^2	Q^2/M_{QCD}^2
gCEDM $\Sigma_{1,8}$	$w m_\pi^2 M_{QCD}/M_{\not T}^2$	1	1	1
qEDM	$\delta m_\pi^2 M_{QCD}/M_{\not T}^2$	$\alpha_{\rm em}/\pi$	Q^2/M_{QCD}^2	$\alpha_{\rm em} Q^2/\pi M_{QCD}^2$

- chiral-breaking sources
  TV π-N couplings have lowest chiral index
- chiral-invariant sources
  same chiral index for all interactions

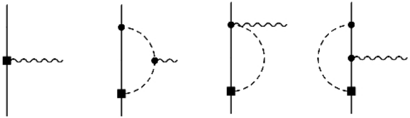
1. short-range EDM operators dominate nucleon EDM
2. one-body effects & pion-exchange at the same level in light nuclei

Chiral Lagrangian. Summary.

		pion-nucleon	photon-nucleon $\times Q^2$	nucleon-nucleon $\times F_\pi^2 Q^2$
$\bar\theta$ term, qCEDM $\Xi_{1,8}$	$\bar\theta m_\pi^2/M_{QCD}$ $\tilde\delta m_\pi^2 M_{QCD}/M_{\not T}^2$ $\xi M_{QCD}^3/M_{\not T}^2$	1	Q^2/M_{QCD}^2	Q^2/M_{QCD}^2
gCEDM $\Sigma_{1,8}$	$w m_\pi^2 M_{QCD}/M_{\not T}^2$	1	1	1
qEDM	$\delta m_\pi^2 M_{QCD}/M_{\not T}^2$	α_{em}/π	Q^2/M_{QCD}^2	$\alpha_{em} Q^2/\pi M_{QCD}^2$

- chiral-breaking sources
  TV π-N couplings have lowest chiral index
- chiral-invariant sources
  same chiral index for all interactions
- qEDM
  long-distance suppressed by α_{em}

1. nucleon and nuclei EDMs dominated by TV currents



$$J^{\mu}_{ed}(q) = 2i\,(S\cdot q v^{\mu} - S^{\mu} v\cdot q)\left(F_0(\mathbf{q}^2) + \tau_3 F_1(\mathbf{q}^2)\right),$$
$$F_i(\mathbf{q}^2) = d_i - S_i'\mathbf{q}^2 + H_i(\mathbf{q}^2), \qquad \mathbf{q}^2 = -q^2.$$

- at LO

$$d_0 = \bar{d}_0, \qquad S_0' = 0$$
$$d_1 = \bar{d}_1 + \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\left[L - \ln\frac{m_\pi^2}{\mu^2}\right], \qquad S_1' = \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\frac{1}{6 m_\pi^2}$$

LO: R. Crewther *et al.*, ‘79, W. Hockings and U. van Kolck, ‘05.

- F_0 purely short-distance & momentum independent
- F_1 only senstitive to $\bar{g}_0$

Nucleon EDM and EDFF. Sum up

Source	$\bar{\theta}$	qCEDM & $\Xi_{1,8}$	qEDM	TV χI
d_p/d_n	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$m_\pi^2 S_1'/d_n$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\rm QCD}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\rm QCD}^2}\right)$
$m_\pi^2 S_0'/d_n$	$\mathcal{O}\left(\frac{m_\pi}{M_{\rm QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi}{M_{\rm QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\rm QCD}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\rm QCD}^2}\right)$

- Theta Term, qCEDM, $\Xi_{1,8}$: $\bar{g}_0/M_{QCD}^2 \sim \bar{d}_1$

$$\begin{aligned} d_0 &= \bar{d}_0 \qquad S_0' = 0 \\ d_1 &= \bar{d}_1 + \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\left[L - \ln\frac{m_\pi^2}{\mu^2}\right], \qquad S_1' = \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\frac{1}{6 m_\pi^2} \end{aligned}$$

- qEDM, TV χI: $\bar{g}_0/M_{QCD}^2 \ll \bar{d}_1$

$$\begin{aligned} d_0 &= \bar{d}_0 \qquad S_0' = 0 \\ d_1 &= \bar{d}_1, \qquad S_1' = 0 \end{aligned}$$

Nucleon EDM and EDFF

Source	$\bar{\theta}$	qCEDM & $\Xi_{1,8}$	qEDM	TV χI
d_p/d_n	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$m_\pi^2 S_1'/d_n$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\rm QCD}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\rm QCD}^2}\right)$
$m_\pi^2 S_0'/d_n$	$\mathcal{O}\left(\frac{m_\pi}{M_{\rm QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi}{M_{\rm QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\rm QCD}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\rm QCD}^2}\right)$

- measurement of d_n and d_p can be fitted by any source.
  No signal in the next generation of experiments:

$$\bar{\theta} \lesssim 10^{-12}, \qquad \frac{\tilde{\delta}, \delta}{M_{\not T}^2} \lesssim (10^3 \text{ TeV})^{-2}, \qquad \frac{w, \sigma, \xi}{M_{\not T}^2} \lesssim (5 \cdot 10^3 \text{ TeV})^{-2}$$

Theta Term & qCEDM

- S_1' come at the same order as d_i
- S_0' suppressed by m_π/M_{QCD} with respect to d_i
- scale for momentum variation of EDFF set by m_π

qEDM & TV χI

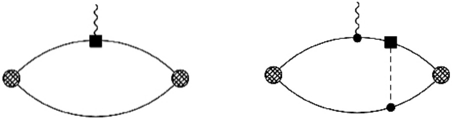
- $S_{1,0}'$ suppressed by m_π^2/M_{QCD}^2 with respect to d_i

Deuteron EDM and MQM

$$H_{\not T} = -2d_d \mathcal{D}^\dagger \mathbf{S}\cdot\mathbf{E}\mathcal{D} - \mathcal{M}_d \mathcal{D}^\dagger \{S^i, S^j\} \mathcal{D} \nabla^{(i} B^{j)}$$

dEDM

magnetic quadrupole moment (dMQM).



$$d_d = 2d_0 - \frac{2}{3} e \frac{g_A \bar{g}_1}{m_\pi^2} \frac{m_N m_\pi}{4\pi F_\pi^2} \frac{1+\xi}{(1+2\xi)^2} = d_n + d_p - 0.23 \frac{\bar{g}_1}{F_\pi}\, e\,\mathrm{fm}$$

with $\xi = \gamma/m_\pi$,
γ deuteron binding momentum

- dEDM sensitive to $\bar{g}_1$ & $d_n + d_p$

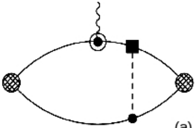
orthogonal to neutron EDM!

Deuteron EDM and MQM

$$H_{\not T} = -2d_d\mathcal{D}^\dagger \mathbf{S}\cdot\mathbf{E}\mathcal{D} - \mathcal{M}_d\mathcal{D}^\dagger\{S^i, S^j\}\mathcal{D}\nabla^{(i}B^{j)}$$

dEDM

magnetic quadrupole moment (dMQM).



$$\begin{aligned} m_d\mathcal{M}_d &= -2e\frac{g_A\bar{g}_0}{m_\pi^2}\frac{m_N m_\pi}{2\pi F_\pi^2}\left[(1+\kappa_0) + \frac{\bar{g}_1}{3\bar{g}_0}(1+\kappa_1)\right]\frac{1+\xi}{(1+2\xi)^2} \\ &= -1.43(1+\kappa_0)\frac{\bar{g}_0}{F_\pi}\, e\,\text{fm} - 0.48(1+\kappa_1)\frac{\bar{g}_1}{F_\pi}\, e\,\text{fm}, \end{aligned}$$

- dEDM sensitive to $\bar{g}_1$ & $d_n + d_p$

orthogonal to neutron EDM!

- no one-body piece for dMQM

Deuteron EDM and MQM

Source	$\bar{\theta}$	qCEDM & $\Xi_{1,8}$	qEDM	TV χI
d_d	$d_n + d_p$	$d_n + d_p - 0.2\frac{\bar{g}_1}{F_\pi}$	$d_n + d_p$	$d_n + d_p$
$m_d\mathcal{M}_d$	$-1.2\frac{\bar{g}_0}{F_\pi}$	$-1.2\frac{\bar{g}_0}{F_\pi} - 2.2\frac{\bar{g}_1}{F_\pi}$	$\ldots$	$\ldots$
$m_d\mathcal{M}_d/d_d$	$\mathcal{O}(10)$	$\mathcal{O}(10)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

- deuteron EDM signal can be fitted by any source
- deuteron EDM well approximated by $d_n + d_p$ for $\bar{\theta}$, qEDM and TV χI sources

qCEDM & $\Xi_{1,8}$

- only for qCEDM & $\Xi_{1,8}$, $d_d \gg d_n + d_p$
- nucleon and deuteron EDM can reveal isospin structure of TV source.

Deuteron EDM and MQM

Source	$\bar\theta$	qCEDM & $\Xi_{1,8}$	qEDM	TV χI
d_d	$d_n + d_p$	$d_n + d_p - 0.2\frac{\bar g_1}{F_\pi}$	$d_n + d_p$	$d_n + d_p$
$m_d\mathcal{M}_d$	$-1.2\frac{\bar g_0}{F_\pi}$	$-1.2\frac{\bar g_0}{F_\pi} - 2.2\frac{\bar g_1}{F_\pi}$	$\dots$	$\dots$
$m_d\mathcal{M}_d/d_d$	$\mathcal{O}(10)$	$\mathcal{O}(10)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

- deuteron EDM signal can be fitted by any source
- deuteron EDM well approximated by $d_n + d_p$ for $\bar\theta$, qEDM and TV χI sources

qCEDM & $\Xi_{1,8}$

- only for qCEDM & $\Xi_{1,8}$, $d_d \gg d_n + d_p$
- nucleon and deuteron EDM can reveal isospin structure of TV source.

Theta Term

- only for chiral breaking sources, $m_d\mathcal{M}_d \gg d_n + d_p$
- dEDM, dMQM give a way to fix $\bar g_0$, $\bar g_1$.

EDM of ^{3}He and ^{3}H

"*hybrid approach*"

- AV18, EFT potentials for TC interactions

code of I. Stetcu *et al.*, '08

- $d_{^3\text{He}}$ and $d_{^3\text{H}}$ depend on 6 TV coefficients

$$d_{^3\text{He}} = 0.88\, d_n - 0.047\, d_p - \left(0.15\, \frac{\bar{g}_0}{F_\pi} + 0.28\, \frac{\bar{g}_1}{F_\pi} + 0.01\, F_\pi^3 \bar{C}_1 - 0.02\, F_\pi^3 \bar{C}_2\right) e\,\text{fm}$$

$$d_{^3\text{H}} = -0.050\, d_n + 0.90\, d_p + \left(0.15\, \frac{\bar{g}_0}{F_\pi} - 0.28\, \frac{\bar{g}_1}{F_\pi} + 0.01\, F_\pi^3 \bar{C}_1 - 0.02\, F_\pi^3 \bar{C}_2\right) e\,\text{fm}\,,$$

numbers for AV18

- different potentials agree at 15% for one-body & pion-exchange contribs.
- no agreement for short range contribution ($\bar{C}_{1,2}$)
  for EFT potential, $\bar{C}_{1,2}$ contribs. five time bigger

need fully consistent calculation for χI sources!

EDM of ^{3}He and ^{3}H. Summary

Source	$\bar{\theta}$	qCEDM & $\Xi_{1,8}$	qEDM	TV χI
$d_{^3\mathrm{He}} + d_{^3\mathrm{H}}$	$d_n + d_p$	$d_n + d_p - 0.6\frac{\bar{g}_1}{F_\pi}$	$d_n + d_p$	$d_n + d_p$
$d_{^3\mathrm{He}} - d_{^3\mathrm{H}}$	$d_n - d_p - 0.3\frac{\bar{g}_0}{F_\pi}$	$d_n - d_p - 0.3\frac{\bar{g}_0}{F_\pi}$	$d_n - d_p$	$d_n - d_p$

qCEDM & $\Xi_{1,8}$

- **both** $d_{^3\mathrm{He}} + d_{^3\mathrm{H}}$ **and** $d_{^3\mathrm{He}} - d_{^3\mathrm{H}}$ significantly different from d_n, d_p

Theta Term

- **only** $d_{^3\mathrm{He}} - d_{^3\mathrm{H}}$ significantly different from $d_n - d_p$

qEDM & TV χI

- no deviation from one-body contributions

Summary & Conclusion

EFT approach

1. consistent framework to treat 1, 2, and 3 nucleon TV observables
2. qualitative relations between 1, 2, and 3 nucleon observables, specific to TV source
3. particularly promising for chiral breaking sources

   identify/exclude them in next generation of experiments?

4. not much hope to distinguish between qEDM and χI sources

   other observables? TV observables w/o photons?

Improvements

1. beyond NDA
2. improve calculation
3. other observables

- compute LECs on the lattice
- evolution from EW scale
- NLO with perturbative pions
- fully consistent non ptb. calculation
- atomic EDMs,
  TV in β decays

Backup Slides

Electromagnetic and T-violating operators

- chiral properties of $(P_3 + P_4) \otimes (I + T_{34})$
- lowest chiral order $\Delta = 3$
- $P_3 + P_4$

$$\mathcal{L}^{(3)}_{\not{\chi},f=2,\mathrm{em}} = c^{(3)}_{1,\mathrm{em}} \frac{1}{D} \left[\frac{2\pi_3}{F_\pi} + \rho \left(1 - \frac{\boldsymbol{\pi}^2}{F_\pi^2} \right) \right] \bar{N} \left(S^\mu v^\nu - S^\nu v^\mu \right) N \, e F_{\mu\nu}$$

- $(P_3 + P_4) \otimes T_{34}$

$$\mathcal{L}^{(3)}_{\not{\chi},f=2,\mathrm{em}} = c^{(3)}_{3,\mathrm{em}} \bar{N} \left[-\frac{2}{F_\pi D} \boldsymbol{\pi} \cdot \mathbf{t} - \rho \left(t_3 - \frac{2\pi_3}{F_\pi^2 D} \boldsymbol{\pi} \cdot \mathbf{t} \right) \right] \left(S^\mu v^\nu - S^\nu v^\mu \right) N \, e F_{\mu\nu}$$
$$+ \text{tensor}$$

- isoscalar and isovector EDM related to pion photo-production.

Electromagnetic and T-violating operators

At the same order $S_4 \otimes (1 + T_{34})$

- S_4

$$\mathcal{L}^{(3)}_{\not\chi, f=2,\text{em}} = c^{(3)}_{6,\text{em}} \left(-\frac{2}{F_\pi D} \right) \bar{N} \boldsymbol{\pi} \cdot \mathbf{t} \, (S^\mu v^\nu - S^\nu v^\mu) \, N \, eF_{\mu\nu}$$

- $S_4 \otimes T_{34}$

$$\mathcal{L}^{(3)}_{\not\chi, f=2,\text{em}} = c^{(3)}_{8,\text{em}} \frac{2\pi_3}{F_\pi D} \bar{N} \, (S^\mu v^\nu - S^\nu v^\mu) \, N \, eF_{\mu\nu} + \text{tensor}$$

- same chiral properties as partners of $\not{T}$ operator
- pion-photoproduction constrains only $c^{(3)}_{1,\,\text{em}} + c^{(3)}_{6,\,\text{em}}$ and $c^{(3)}_{3,\,\text{em}} + c^{(3)}_{8,\,\text{em}}$
- but $\not{T}$ only depends on $c^{(3)}_{1,\,\text{em}}$ and $c^{(3)}_{3,\,\text{em}}$

no T-conserving observable constrains short distance contrib. to nucleon EDM

- true only in $SU(2) \times SU(2)$
- larger symmetry of $SU(3) \times SU(3)$ leaves question open

Deuteron EDM and MQM. KSW Power Counting

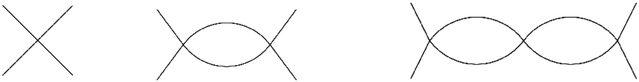
T-even sector

$$\mathcal{L}_{f=4} = -C_0^{^3S_1}(N^t P^i N)^\dagger N^t P^i N + \frac{C_2^{^3S_1}}{8}\left[(N^t P_i N)^\dagger N^t \mathbf{D}_-^2 P_i N + \text{h.c.}\right] + \dots, \qquad P^i = \frac{1}{\sqrt{8}}\sigma_2\sigma_i\tau_2$$

- enhance C_0 to account for unnaturaly large scattering lengths. In PDS scheme

$$C_0^{^3S_1} = \mathcal{O}\left(\frac{4\pi}{m_N\mu}\right), \qquad \mu \sim Q$$

- iterate C_0 at all orders



C_0 $\qquad$ $C_0\,\frac{m_N Q}{4\pi}\,C_0$ $\qquad$ $C_0\left(\frac{m_N Q}{4\pi}\,C_0\right)^2$

Deuteron EDM and MQM. KSW Power Counting

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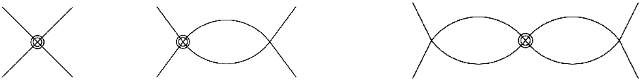
$$C_0^{^3S_1} = \mathcal{O}\left(\frac{4\pi}{m_N \mu}\right), \qquad \mu \sim Q$$

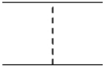
- iterate C_0 at all orders
- operators which connect S-waves get enhanced $C_2^{^3S_1} = \mathcal{O}\left(\frac{4\pi}{m_N \Lambda_{NN}}\frac{1}{\mu^2}\right)$



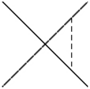
$$C_0 \frac{Q}{\Lambda_{NN}} \qquad C_0 \frac{Q}{\Lambda_{NN}} \frac{m_N Q}{4\pi} C_0 \qquad C_0 \frac{Q}{\Lambda_{NN}} \left(\frac{m_N Q}{4\pi} C_0\right)^2$$

Deuteron EDM and MQM. KSW Power Counting

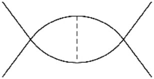
- treat pion exchange as a perturbation



$$C_0 \frac{g_A^2 m_N Q}{4\pi F_\pi^2}$$



$$C_0 \frac{g_A^2 m_N Q}{4\pi F_\pi^2} \; \frac{m_N Q}{4\pi} C_0$$



$$C_0 \frac{g_A^2 m_N Q}{4\pi F_\pi^2} \; \left(\frac{m_N Q}{4\pi} C_0 \right)^2$$

- identify $\Lambda_{NN} = 4\pi F_\pi^2 / m_N \sim 300$ MeV.

Perturbative pion approach:

- expansion in Q/Λ_{NN}, with $Q \in \{|\mathbf{q}|, m_\pi, \gamma = \sqrt{m_N B}\}$
- competing with the m_π / M_{QCD} of ChPT Lagrangian

- successful for deuteron properties at low energies

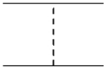
Kaplan, Savage and Wise, Phys. Rev. C **59**, 617 (1999);

- problems in $^3S_1$ scattering lenghts,
  ptb. series does not converge for $Q \sim m_\pi$

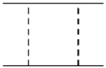
Fleming, Mehen, and Stewart, Nucl. Phys. **A 677**, 313 (2000);

Deuteron EDM and MQM. KSW Power Counting

- treat pion exchange as a perturbation



$$\frac{g_A^2}{F_\pi^2}$$



$$\frac{g_A^2}{F_\pi^2}\,\frac{g_A^2 m_N Q}{4\pi F_\pi^2}$$

- identify $\Lambda_{NN} = 4\pi F_\pi^2/m_N \sim 300$ MeV.

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Deuteron EDM and MQM. KSW Power Counting

T-odd sector

a. four-nucleon T-odd operators

$$\mathcal{L}_{\not{T},f=4} = C_{1,\not{T}}\bar{N}S\cdot(\mathcal{D}+\mathcal{D}^{\dagger})N\,\bar{N}N + C_{2,\not{T}}\bar{N}\boldsymbol{\tau}\,S\cdot(\mathcal{D}+\mathcal{D}^{\dagger})N\;\cdot\bar{N}\,\boldsymbol{\tau}N.$$

- in the PDS scheme

	1. Theta	2. qCEDM	3. qEDM	4. gCEDM
$C_{i,\not{T}}$	$\frac{4\pi}{\mu m_N}\bar{\theta}\frac{m_\pi^2}{M_{QCD}\Lambda_{NN}^2}$	$\frac{4\pi}{\mu m_N}\tilde{\delta}\frac{m_\pi^2}{M_{\not{T}}^2 M_{QCD}}$	0	$\frac{4\pi}{\mu m_N}\frac{w}{M_{\not{T}}^2}\Lambda_{NN}$

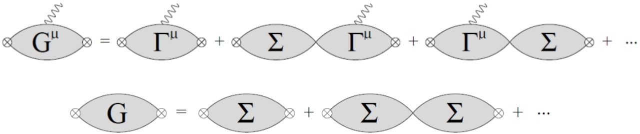
b. four-nucleon T-odd currents

$$\mathcal{L}_{\not{T},\,\mathrm{em},f=4} = C_{1,\not{T},\,\mathrm{em}}\bar{N}(S^\mu v^\nu - S^\nu v^\mu)N\bar{N}NF_{\mu\nu}.$$

- in the PDS scheme

	1. Theta	2. qCEDM	3. qEDM	4. gCEDM
$C_{i,\not{T},\mathrm{em}}$	$\frac{4\pi}{\mu^2 m_N}\bar{\theta}\frac{m_\pi^2}{M_{QCD}\Lambda_{NN}^2}$	$\frac{4\pi}{\mu^2 m_N}\tilde{\delta}\frac{m_\pi^2}{M_{\not{T}}^2 M_{QCD}}$	$\frac{4\pi}{\mu^2 m_N}\delta\frac{m_\pi^2}{M_{\not{T}}^2 M_{QCD}}$	$\frac{4\pi}{\mu^2 m_N}\frac{w}{M_{\not{T}}^2}\Lambda_{NN}$

Deuteron EDM. Formalism



- crossed blob: insertion of interpolating field $\mathcal{D}^i(x) = N(x) P_i^{{}^3S_1} N(x)$
- two-point and three-point Green's functions expressed in terms of *irreducible* function

irreducible: do not contain $C_0^{{}^3S_1}$

- by LSZ formula

$$\langle \mathbf{p}' j | J^{\mu}_{\mathrm{em},\not{T}} | \mathbf{p}\, i \rangle = i \left[\frac{\Gamma^{\mu}_{ij}\,(\bar{E}, \bar{E}', \mathbf{q})}{d\Sigma(\bar{E})/dE} \right]_{\bar{E}, \bar{E}' = -B}$$

- two-point function

$$\left. \frac{d\Sigma_{(1)}}{d\bar{E}} \right|_{\bar{E} = -B} = -i \frac{m_N^2}{8\pi\gamma}$$