# $T$ violation in Chiral Effective Theory

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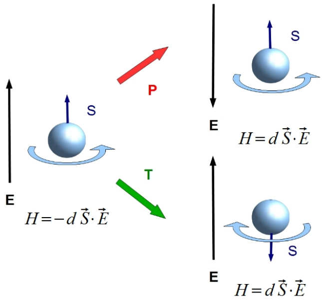
BERKELEY LAB Lawrence Berkeley National Laboratory

A permanent Electric Dipole Moment (EDM)

- signal of $T$ and $P$ violation
- signal $T$ violation in the flavor diagonal sector
- relatively insensitive to the CKM phase
- easily produced in BSM models

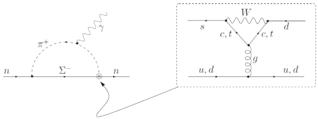


# Motivations and Introduction

A permanent Electric Dipole Moment (EDM)

- signal of $T$ and $P$ violation
- signal $T$ violation in the flavor diagonal sector
- relatively insensitive to the CKM phase
- easily produced in BSM models

**Standard Model**:




$d_n \sim 10^{-19}\ e$ fm

for review: M. Pospelov and A. Ritz, '05

**Current bounds**:

- neutron $|d_n| < 2.9 \times 10^{-13}\ e$ fm

  UltraCold Neutron Experiment @ ILL

  C. A. Baker *et al.*, '06

- proton $|d_p| < 7.9 \times 10^{-12}\ e$ fm

  $^{199}$Hg EDM @ Univ. of Washington

  W. C. Griffith *et al.*, '09

**Large window for new physics and intense experimental activity!**

# Motivations and Introduction

1. Neutron EDM

   UltraCold Neutron experiment @ PSI

- currently taking data
- 2013: $d_n \sim 5 \times 10^{-14}$ $e$ fm
- 2016: $d_n \sim 5 \times 10^{-15}$ $e$ fm

   UCN experiments @ SNS, TRIUMF: same sensitivity by 2020

2. Proton, Deuteron & Helium EDM

   Storage Ring Experiment

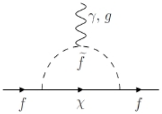
- 2020?: $d_p, d_d \sim 10^{-16}$ $e$ fm
- where?: BNL, COSY, Fermilab

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?**




**Several issues . . .**

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

**our strategy**

Symmetries & Effective Theories

# Strategy

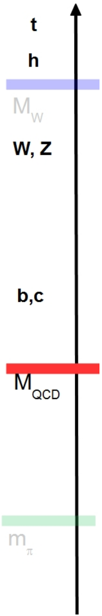

1. "integrate out" new physics

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

$\mathcal{O}_{\not T\, n}$ 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 $\mathcal{O}_{\not{T},n}$

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

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

# The QCD Theta Term

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

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

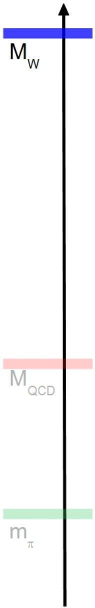
- $\bar{\theta}$ and $m$ break chiral symmetry in a very specific way

**intimate relation with isospin breaking**

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

- $SO(4)$ vector
- $SO(4)$ vector

# Sources of $T$ Violation at the EW Scale




- 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 . . .

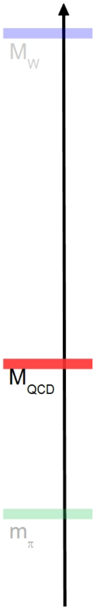
- 16 flavor diagonal operators . . . . . . *plus* flavor changing

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

- $\Gamma$ complex-valued matrices in flavor space

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

# Sources of $T$ Violation at the QCD Scale




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

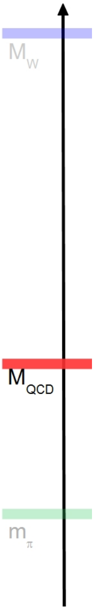
Wilczek and Zee, '77; Weinberg, '89; Braaten *et al.*, '90; De Rujula *et al.*, '91; Degrassi *et al.*, '05; An *et al.*, '10; Hisano *et al.*, '12; Dekens and de Vries.

- 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)

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



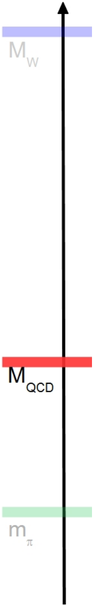

# Sources of $T$ Violation at the QCD Scale

- four TV 4-quark operators

$$
\begin{aligned}
\mathcal{L}_{6,\,qqqq} \quad = \quad & \frac{1}{4}\mathrm{Im}\Sigma_1 \left(\bar{q}q\,\bar{q}i\gamma^5 q - \bar{q}\boldsymbol{\tau}q\cdot\bar{q}\boldsymbol{\tau}i\gamma^5 q\right) \\
& + \frac{1}{4}\mathrm{Im}\Sigma_8 \left(\bar{q}\lambda^a q\,\bar{q}i\gamma^5\lambda^a q - \bar{q}\boldsymbol{\tau}\lambda^a q\cdot\bar{q}\boldsymbol{\tau}i\gamma^5\lambda^a q\right) \\
& + \frac{1}{4}\,\mathrm{Im}\,\Xi_1 \left(\bar{q}q\,\bar{q}i\gamma^5\tau_3 q - \bar{q}\tau_3 q\,\bar{q}i\gamma^5 q\right) \\
& + \frac{1}{4}\,\mathrm{Im}\,\Xi_8 \left(\bar{q}\lambda^a q\,\bar{q}i\gamma^5\tau_3\lambda^a q - \bar{q}\tau_3\lambda^a q\,\bar{q}i\gamma^5\lambda^a q\right)
\end{aligned}
$$

- $SU_L(2)\times U(1)$ invariant, generated at EW scale

# Sources of $T$ Violation at the QCD Scale

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\begin{aligned}
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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)\\
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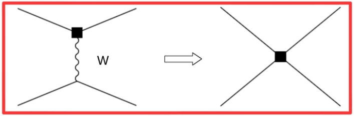
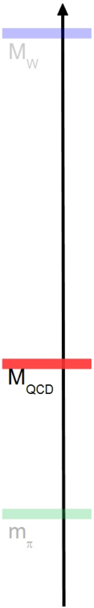
\end{aligned}
$$

- $SU_L(2)\times U(1)$ invariant, generated at EW scale
- break $SU_L(2)\times U(1)$,
  integrate out $W$ & QCD running



# Quark-Gluon TV Lagrangian. Summary




$$\mathcal{L}_{\not{T}}(\mu \sim 1\,\mathrm{GeV}) = -\frac{1}{2}\bar{m}(1-\varepsilon^2)\bar{\theta}\,\bar{q}i\gamma^5 q + \frac{d_W}{6} f^{abc}\varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu}$$
$$-\frac{1}{2}\,\bar{q}\,i\sigma^{\mu\nu}\gamma^5\,(d_0 + d_3\tau_3)\,q\,F_{\mu\nu} - \frac{1}{2}\,\bar{q}\,i\sigma^{\mu\nu}\gamma^5\left(\tilde{d}_0 + \tilde{d}_3\tau_3\right)G_{\mu\nu}q$$
$$+\frac{1}{4}\mathrm{Im}\Sigma_{1(8)}\left(\bar{q}q\,\bar{q}i\gamma^5 q - \bar{q}\boldsymbol{\tau}q\cdot\bar{q}\boldsymbol{\tau}i\gamma^5 q\right) + \frac{1}{4}\,\mathrm{Im}\,\Xi_{1(8)}\left(\bar{q}q\,\bar{q}i\gamma^5\tau_3 q - \bar{q}\tau_3 q\,\bar{q}i\gamma^5 q\right)$$

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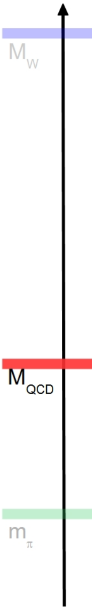


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- Coefficients (at $\mu \sim 1$ GeV)

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

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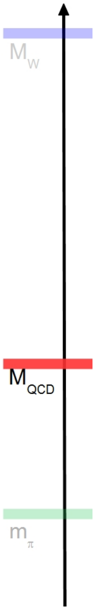


$$\mathcal{L}_{\not T}(\mu \sim 1\,\mathrm{GeV}) = -\frac{1}{2}\bar{m}(1-\varepsilon^2)\bar{\theta}\,\bar{q}i\gamma^5 q + \frac{d_W}{6} f^{abc}\varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\ \rho}_{\nu}$$
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- depend on details of 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

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

- $\tilde{V}$, $\tilde{W}$ 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. $\Xi_{1,8}$

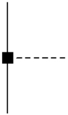
$$\mathcal{L}_{6,\,qqqq} = +\frac{1}{4}\,\mathrm{Im}\,\Xi_1 T_{34}^{(1)} + \frac{1}{4}\,\mathrm{Im}\,\Xi_8 T_{34}^{(8)}$$

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

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

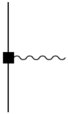
# TV Chiral Lagrangian: ingredients

- pion-nucleon TV interactions



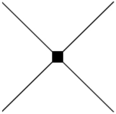
$$\mathcal{L}_{\not{T},f=2} = -\frac{\bar{g}_0}{F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{F_\pi}\pi_3\bar{N}N$$

- 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 $Q/M_{QCD}$

More than NDA?

- 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 | $\varepsilon \frac{m_\pi^2}{M_{QCD}^2}$ | $\frac{Q^2}{M_{QCD}^2}$ | $\frac{Q^2}{M_{QCD}^2}$ |

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More than NDA?

- relation to isospin violating coupling

$$\bar{g}_0 = \frac{\delta m_N}{2\varepsilon}(1-\varepsilon^2)\bar{\theta}, \qquad \frac{\delta m_N}{2\varepsilon} = 2.8 \pm 0.7 \pm 0.6\,\text{MeV}$$

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 | $\varepsilon \frac{m_\pi^2}{M_{QCD}^2}$ | $\frac{Q^2}{M_{QCD}^2}$ | $\frac{Q^2}{M_{QCD}^2}$ |
| $\tilde{\delta}_3 \times \frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}$ | $\varepsilon$ | 1 | $\frac{Q^2}{M_{QCD}^2}$ | $\varepsilon \frac{Q^2}{M_{QCD}^2}$ |
| $(\xi_1, \xi_8) \times \frac{M_{QCD}^3}{M_{\not{T}}^2}$ | $\varepsilon$ | 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 | $\varepsilon \frac{m_\pi^2}{M_{QCD}^2}$ | $\frac{Q^2}{M_{QCD}^2}$ | $\frac{Q^2}{M_{QCD}^2}$ |
| $\tilde{\delta}_3 \times \frac{m_\pi^2 M_{QCD}}{M_{\not T}^2}$ | $\varepsilon$ | 1 | $\frac{Q^2}{M_{QCD}^2}$ | $\varepsilon \frac{Q^2}{M_{QCD}^2}$ |
| $(\xi_1, \xi_8) \times \frac{M_{QCD}^3}{M_{\not T}^2}$ | $\varepsilon$ | 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 & $\Xi_{1,8}$

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

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

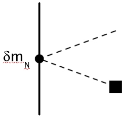
- very similar couplings

  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

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

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

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

  extra $m_\pi^2/M_{QCD}^2$ 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

Theta Term

- traditionally:
  one-boson exchange

$$V_{\not{T},\mathrm{min}}(\mathbf{r}) = -\frac{g_A \bar{g}_0}{F_\pi^2} \boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)} \left(\sigma^{(1)} - \sigma^{(2)}\right) \cdot \nabla \frac{e^{-m_\pi r}}{4\pi r} + \left(\sigma^{(1)} - \sigma^{(2)}\right) \cdot \nabla \delta(\mathbf{r}) \left[\bar{C}_1 + \bar{C}_2 \boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)}\right]$$

- $\bar{C}_1$ from $\omega$, $\eta$ exchanges:

  $\bar{C}_1 \sim \bar{g}_{0\eta}/m_\eta^2, \bar{g}_{0\omega}/m_\omega^2,$
- $\bar{C}_2$ from $\rho$ exchange:

  $\bar{C}_2 \sim \bar{g}_{0\rho}/m_\rho^2$

At our accuracy: LO TV potential and TV currents

# TV Potentials & Currents

Theta Term

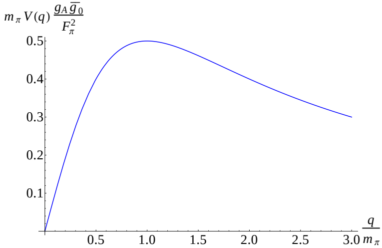
- traditionally:
  one-boson exchange

- Chiral EFT
  LO: purely pion exchange

$$V_{\not{T},\min}(\mathbf{r}) = -\frac{g_A \bar{g}_0}{F_\pi^2} \boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)} \left(\sigma^{(1)} - \sigma^{(2)}\right) \cdot \nabla \frac{e^{-m_\pi r}}{4\pi r}$$

$$+\left(\sigma^{(1)} - \sigma^{(2)}\right) \cdot \nabla \delta(\mathbf{r}) \left[\bar{C}_1 + \bar{C}_2 \boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)}\right]$$

- $\bar{C}_1, \bar{C}_2 \ll \bar{g}_0 / F_\pi^2$




At our accuracy: LO TV potential and TV currents

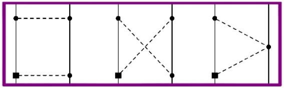
# TV Potentials & Currents

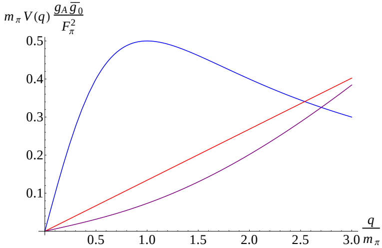
Theta Term

- traditionally:
  one-boson exchange
- Chiral EFT
  LO: purely pion exchange
- Chiral EFT
  N$^2$LO: OPE, contact, TPE

$$V_{\not T,\mathrm{min}}(\mathbf{r}) = -\frac{g_A \bar{g}_0}{F_\pi^2} \boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)} \left(\sigma^{(1)} - \sigma^{(2)}\right) \cdot \nabla \left( \frac{e^{-m_\pi r}}{4\pi r} + U_{TPE}(r) \right) + \left(\sigma^{(1)} - \sigma^{(2)}\right) \cdot \nabla \delta(\mathbf{r}) \left[ \bar{C}_1 + \bar{C}_2 \boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)} \right]$$

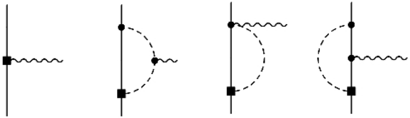
- $\bar{C}_1$, $\bar{C}_2$ contribute at N$^2$LO
- at the same order, medium range TPE potential





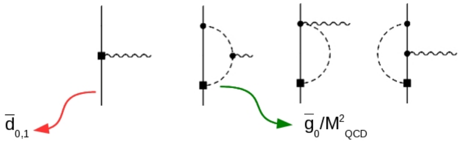

At our accuracy: LO TV potential and TV currents

# Nucleon EDM. Theta Term, qCEDM & $\Xi_{1,8}$.



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

# Nucleon EDM. Theta Term, qCEDM & $\Xi_{1,8}$.




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

$\mathbf{F_0(q^2)}$

- purely short-distance
- momentum independent

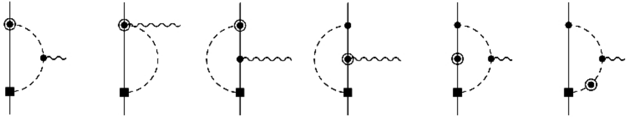
$\mathbf{F_1(q^2)}$

- short-distance & charged pions in the loops

  $\bar{g}_0$ only relevant $\pi$-N coupling!

| |
|---|
| nucleon EDFF cannot distinguish between Theta Term, qCEDM & $\Xi_{1,8}$ |

# Nucleon EDM. Theta Term, qCEDM & $\Xi_{1,8}$



**Next-to-Leading Order**

- first non-analytic contribution & momentum dependence to $F_0(\mathbf{q}^2)$

$$d_0 = \bar{d}_0 + \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2} \pi \frac{3 m_\pi}{4 m_N} \left(1 + \frac{\bar{g}_1}{3\bar{g}_0}\right) \qquad S_0' = -\frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2} \frac{1}{6 m_\pi^2} \pi \frac{\delta m_N}{2 m_\pi}$$

- recoil corrections to $F_1$

$$d_1 = \bar{d}_1 + \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2} \left[ L - \ln \frac{m_\pi^2}{\mu^2} + \frac{5\pi}{4} \frac{m_\pi}{m_N} \left(1 + \frac{\bar{g}_1}{5\bar{g}_0}\right)\right],$$

$$S_1' = \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2} \frac{1}{6 m_\pi^2} \left[1 - \frac{5\pi}{4} \frac{m_\pi}{m_N}\right]$$

LO: R. Crewther *et al.*, ‘79, W. Hockings and U. van Kolck, ‘05.
NLO: Ottnad *et al.*, ‘09, EM *et al.*, ‘10

# Nucleon EDM. Theta Term, qCEDM & $\Xi_{1,8}$

- EDM depends on $\bar{g}_0$, and short-distance LECs $\bar{d}_{0,1}$
- neutron EDM

$$|d_n| = |d_0 - d_1| \gtrsim \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2} \left[ \ln \frac{m_N^2}{m_\pi^2} + \frac{\pi}{2} \frac{m_\pi}{m_N} \right] \qquad \simeq (0.13 + 0.01)\, \frac{\bar{g}_0}{F_\pi}\, e\,\text{fm}$$

$$\simeq 2 \times 10^{-3}\, \bar{\theta}\, e\,\text{fm}$$

  - good convergence of perturbative series
  - $\bar{\theta} \lesssim 10^{-10}$

- NLO bound on isoscalar EDM

$$|d_0| \gtrsim \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\, \pi \frac{3 m_\pi}{4 m_N} \simeq 0.012\, \frac{\bar{g}_0}{F_\pi}\, e\,\text{fm}.$$

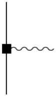
- $S'_{0,1}$ only depends on $\bar{g}_0$

$$S'_0 = -\frac{e g_A \bar{g}_0}{12 (2\pi F_\pi)^2} \frac{\pi \delta m_N}{m_\pi^2} = -0.3 \cdot 10^{-3}\, \frac{\bar{g}_0}{F_\pi}\, e\,\text{fm}^3,$$

$$S'_1 = \frac{e g_A \bar{g}_0}{6 (2\pi F_\pi)^2} \frac{1}{m_\pi^2} \left[ 1 - \frac{5\pi}{4} \frac{m_\pi}{m_N} \right] = (11.2 - 6.5) \cdot 10^{-3}\, \frac{\bar{g}_0}{F_\pi}\, e\,\text{fm}^3,$$

contribs. to Schiff moment
relevant for atomic EDMs

# Nucleon EDM and EDFF. qEDM & TV $\chi$I sources



- EDFF purely short-distance & momentum independent at LO
- EDFF acquires momentum dependence at NNLO

  - purely short distance for qEDM
  - with long distance component for TV $\chi$I sources

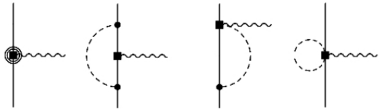
- isoscalar

$$F_0(\mathbf{q}^2) = d_0 = \bar{d}_0^{(n)}, \qquad S'_0 = 0$$

- isovector

$$F_1(\mathbf{q}^2) = d_1 = \bar{d}_1^{(n)}, \quad S'_1 = 0.$$

# Nucleon EDM and EDFF. qEDM & TV $\chi$I sources



- EDFF purely short-distance & momentum independent at LO
- EDFF acquires momentum dependence at NNLO

- purely short distance for qEDM
- with long distance component for TV $\chi$I sources

- isoscalar

$$d_0 = \bar{d}_0^{(n)} + \bar{\bar{d}}_0^{(n+2)}, \quad S'_0 = \bar{S}'_0{}^{(n+2)}$$

- isovector

$$d_1 = \bar{d}_1^{(n)} + \bar{\bar{d}}_1^{(n+2)}, \quad S'_1 = \bar{S}'_1{}^{(n+2)}$$

# Nucleon EDM and EDFF. Sum up

| Source | $\bar{\theta}$ | qCEDM & $\Xi_{1,8}$ | qEDM | TV $\chi$I |
|---|---|---|---|---|
| $M_{QCD}\, d_n/e$ | $\mathcal{O}\left(\bar{\theta}\,\frac{m_\pi^2}{M_{QCD}^2}\right)$ | $\mathcal{O}\left(\tilde{\delta}\,\frac{m_\pi^2}{M_{\not T}^2}\right)$ | $\mathcal{O}\left(\delta\,\frac{m_\pi^2}{M_{\not T}^2}\right)$ | $\mathcal{O}\left(w\,\frac{M_{QCD}^2}{M_{\not T}^2}\right)$ |
| $d_p/d_n$ | $\mathcal{O}(1)$ | $\mathcal{O}(1)$ | $\mathcal{O}(1)$ | $\mathcal{O}(1)$ |
| $m_\pi^2 S_1'/d_n$ | $\mathcal{O}(1)$ | $\mathcal{O}(1)$ | $\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$ | $\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$ |
| $m_\pi^2 S_0'/d_n$ | $\mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)$ | $\mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)$ | $\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$ | $\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$ |

- measurement of $d_n$ and $d_p$ can be fitted by any source.
  No signal @ PSI, SNS, TRIUMF:

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

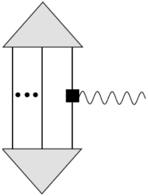
Theta Term & qCEDM

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

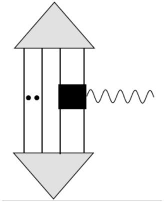
qEDM & TV $\chi$I

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

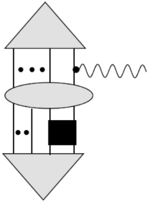
# EDMs of Light Nuclei. Power Counting



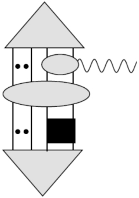
$d_{0,1}$



$$\frac{\bar{g}_0}{m_N^2}\,\frac{Q}{M_{NN}}$$



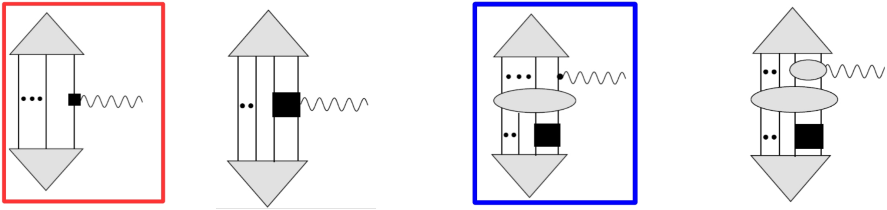
$$\frac{\bar{g}_{0,1}}{Q^2},\,\bar{C}_{1,2}F_\pi^2 \times \frac{Q}{M_{NN}}$$



$$\frac{\bar{g}_{0,1}}{m_N^2}\,\frac{Q^2}{M_{NN}^2}$$

$$M_{NN} = \frac{g_A^2 m_N}{4\pi F_\pi^2}$$

# EDMs of Light Nuclei. Power Counting

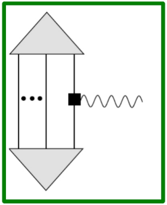


$d_{0,1}$ | $\frac{\bar{g}_0}{m_N^2}\frac{Q}{M_{NN}}$ | $\frac{\bar{g}_{0,1}}{Q^2}, \bar{C}_{1,2}F_\pi^2 \times \frac{Q}{M_{NN}}$ | $\frac{\bar{g}_{0,1}}{m_N^2}\frac{Q^2}{M_{NN}^2}$

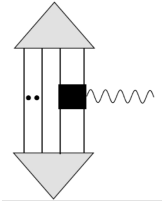
- Theta & qCEDM: pion-exchange dominates
- qEDM: contribs. from neutron and proton EDMs dominate
- $\chi$I: one-body, pion-exchange & short range equally important.

selection rules! especially for Theta Term

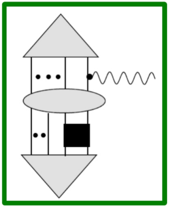
# EDMs of Light Nuclei. Power Counting



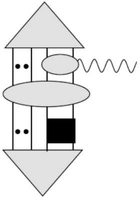
$d_{0,1}$



$\frac{\bar{g}_0}{m_N^2} \frac{Q}{M_{NN}}$



$\frac{\bar{g}_{0,1}}{Q^2}, \bar{C}_{1,2} F_\pi^2 \times \frac{Q}{M_{NN}}$



$\frac{\bar{g}_{0,1}}{m_N^2} \frac{Q^2}{M_{NN}^2}$

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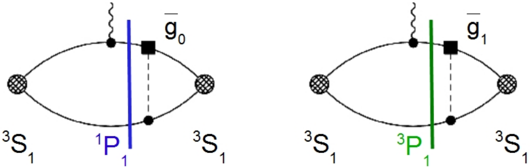
Theta Term

## Deuteron EDM and MQM

Spin 1, Isospin 0 particle

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

$d_d$: deuteron EDM $\mathcal{M}_d$: deuteron magnetic quadrupole moment (MQM).




dEDM

- isoscalar ($\bar{g}_0$, $\bar{C}_{1,2}$) TV corrections to wavefunction vanish at LO.

dMQM

- both isoscalar & isovector corrections contribute

# Deuteron EDM and MQM

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

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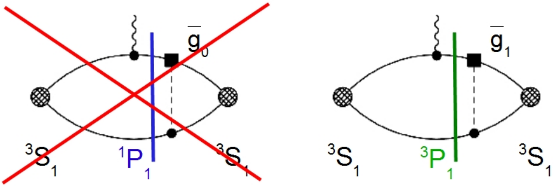



dEDM

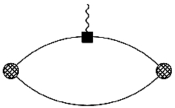
- isoscalar ($\bar{g}_0$, $\bar{C}_{1,2}$) TV corrections to wavefunction vanish at LO.

dMQM

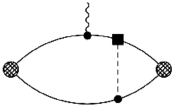
- both isoscalar & isovector corrections contribute

# Deuteron EDM

One-body



TV corrections to wavefunction



- only sensitive to isoscalar nucleon EDM

$$F_D(\mathbf{q}^2) = 2d_0 \frac{4\gamma}{|\mathbf{q}|} \arctan\left(\frac{|\mathbf{q}|}{4\gamma}\right) = 2d_0 \left(1 - \frac{1}{3}\left(\frac{|\mathbf{q}|}{4\gamma}\right)^2 + \dots\right)$$

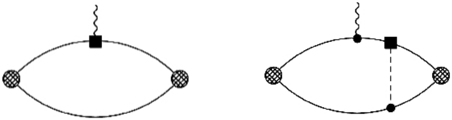
- sensitive to **isobreaking** $\bar{g}_1$

$$F_D(\mathbf{q}^2) = -\frac{2}{3} e \frac{g_A \bar{g}_1}{m_\pi^2} \frac{m_N m_\pi}{4\pi F_\pi^2} \frac{1+\xi}{(1+2\xi)^2} \left(1 - 0.45\left(\frac{|\mathbf{q}|}{4\gamma}\right)^2 + \dots\right), \qquad \xi = \frac{\gamma}{m_\pi}$$

- relative size different for different sources!

# Deuteron EDM. qCEDM & $\Xi_{1,8}$

qCEDM: chiral breaking & isospin breaking



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

$$\mathcal{O}\left(\frac{\tilde{\delta}}{M_{\not{T}}^2} \frac{m_\pi^2}{M_{QCD}}\right) \qquad \mathcal{O}\left(\frac{\tilde{\delta}}{M_{\not{T}}^2} \frac{m_\pi^2}{M_{QCD}} \frac{M_{QCD}^2}{m_\pi M_{NN}}\right)$$

deuteron EDM enhanced w.r.t. nucleon!

- $\bar{g}_1$ leading interaction
- $d_0$ suppressed by two powers of $M_{QCD}$

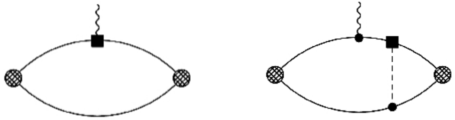
$$\frac{d_d}{d_n + d_p} \lesssim 10 \, \frac{\bar{g}_1}{\bar{g}_0}$$

using non-analytic piece of $d_0$

# Deuteron EDM. Theta Term & TV $\chi$I Sources

Theta term: chiral breaking & isospin symmetric
TV $\chi$I Sources: chiral invariant

$\bar{g}_1$ suppressed!
$d_0$ enhanced!



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

$$\mathcal{O}\left(\bar{\theta} \frac{m_\pi^2}{M_{QCD}^3}\right) \qquad \mathcal{O}\left(\bar{\theta}\varepsilon \frac{m_\pi^2}{M_{QCD}^3} \frac{m_\pi}{M_{NN}}\right)$$

- $\bar{g}_1$ & $d_0$ appear at the same level in the Lagrangian
- dEDM well approximated by $d_n + d_p$

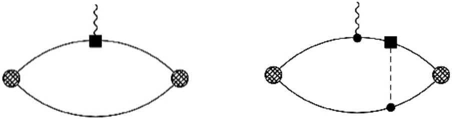
# Deuteron EDM. Theta Term & TV $\chi$I Sources

Theta term: chiral breaking & isospin symmetric

TV $\chi$I Sources: chiral invariant

$\bar{g}_1$ suppressed!

$d_0$ enhanced!



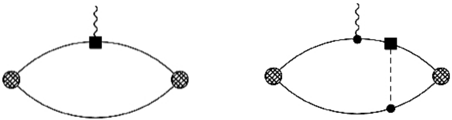
$$d_d = 2d_0 - \frac{2}{3} e \frac{g_A \bar{g}_1}{m_\pi^2} \frac{m_N m_\pi}{4\pi F_\pi^2} \frac{1+\xi}{(1+2\xi)^2} = d_n + d_p - 0.23 \frac{\bar{g}_1}{F_\pi} e\,\mathrm{fm}$$

$$\approx 0.02 \frac{\bar{g}_0}{F_\pi} e\,\mathrm{fm} \qquad \approx 0.23 \times 0.01 \frac{\bar{g}_0}{F_\pi} e\,\mathrm{fm}$$

- $\bar{g}_1$ & $d_0$ appear at the same level in the Lagrangian
- dEDM well approximated by $d_n + d_p$

# Deuteron EDM. qEDM

qEDM: $\pi - N$ coupling suppressed by $\alpha_{\rm em}$



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

$$\mathcal{O}\left( \frac{\delta}{M_{\not{T}}^2} \frac{m_\pi^2}{M_{QCD}} \right)$$

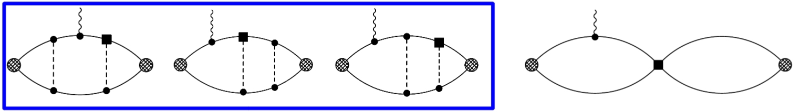
- dEDM well approximated by $d_n + d_p$

# Deuteron EDM. NLO

Is it reliable?

Perturbative pion @ NLO

- needed to check convergence of perturbative pion expansion



- iteration of the pion-exchange potential
- momentum-dependent short-range operators

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Perturbative pion @ NLO

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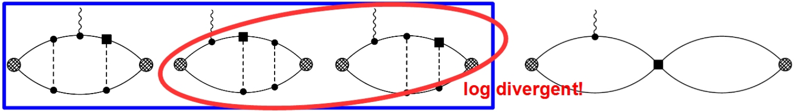


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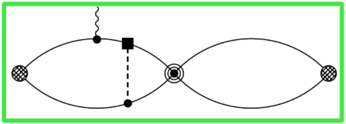

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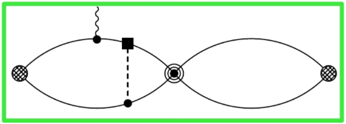


- iteration of the pion-exchange potential
- momentum-dependent short-range operators

$$d_d = -\,(0.23 + 0.03 + 0.08)\,\frac{\bar{g}_1}{F_\pi}\, e\,\mathrm{fm} + \frac{1}{2}\frac{m_N}{4\pi}\bar{C}_3(\mu)(\mu - \gamma)$$

$\mathcal{O}(50\%)$ corrections

# Deuteron EDM. Non perturbative results

Is it reliable?
Iterate pions: "Hybrid approach"

- realistic potentials for TC interactions (AV18, Reid93, Nijmegen II)
- EFT potential & currents for TV interactions

ok...
if observable not too sensitive to short distance details

$$d_d = d_n + d_p - 0.19 \, \frac{\bar{g}_1}{F_\pi} e \, \mathrm{fm} \, ,$$

for AV18,
different potentials agree at $\sim 5\%$

- in good agreement with perturbative calculation

qCEDM

1. $\bar{g}_1$ contrib. agrees at $\sim 20\%$

Theta Term

2. formally LO pion-exchange, terms are small

# Deuteron EDM. Non perturbative results

Is it reliable?
Iterate pions: “Hybrid approach”

- realistic potentials for TC interactions (AV18, Reid93, Nijmegen II)
- EFT potential & currents for TV interactions

ok...
if observable not too sensitive to short distance details

$$d_d(\bar{\theta}) = d_n + d_p + \left[ -0.19 \, \frac{\bar{g}_1}{F_\pi} + \left( 0.2 - 0.7 \cdot 10^2 \, \beta_1 \right) \cdot 10^{-3} \, \frac{\bar{g}_0}{F_\pi} \right] \, e \, \mathrm{fm} \,,$$

TC & TV pion-exchange current
isospin breaking in TC $\pi$-nucleon coupling

for AV18,
different potentials agree at $\sim 5\%$

- in good agreement with perturbative calculation

qCEDM

1. $\bar{g}_1$ contrib. agrees at $\sim 20\%$

Theta Term

2. formally LO pion-exchange, terms are small

# Deuteron EDM. Summary

| Source | $\bar\theta$ | qCEDM & $\Xi_{1,8}$ | qEDM | TV $\chi$I |
|---|---|---|---|---|
| $M_{QCD}\, d_d/e$ | $\mathcal{O}\left(\bar\theta\,\frac{m_\pi^2}{M_{QCD}^2}\right)$ | $\mathcal{O}\left(\tilde\delta\,\frac{m_\pi M_{QCD}^2}{M_{NN} M_{\not T}^2}\right)$ | $\mathcal{O}\left(\delta\,\frac{m_\pi^2}{M_{\not T}^2}\right)$ | $\mathcal{O}\left(w\,\frac{M_{QCD}^2}{M_{\not T}^2}\right)$ |
| $d_d/d_n$ | $\mathcal{O}\,(1)$ | $\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi M_{NN}}\right)$ | $\mathcal{O}\,(1)$ | $\mathcal{O}\,(1)$ |

- deuteron EDM signal can be fitted by any source
- deuteron EDM well approximated by $d_n + d_p$ for $\bar\theta$, qEDM and TV $\chi$I sources
- only for qCEDM & $\Xi_{1,8}$, $d_d \gg d_n + d_p$

qCEDM

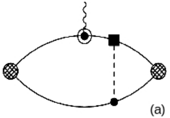
- deuteron EDM experiment more sensitive than neutron & proton EDM

$$d_d \lesssim 10^{-16}\, e\,\mathrm{fm} \Longrightarrow \frac{\tilde\delta}{M_{\not T}^2} \lesssim (3 \cdot 10^4\ \mathrm{TeV})^{-2}$$

- nucleon and deuteron EDM *qualitatively* pinpoint qCEDM.

# Deuteron MQM. qCEDM

Corrections to wavefunction




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

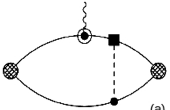
- $\bar{g}_0$ and $\bar{g}_1$ equally important
- dEDM and dMQM comparable

$$\left| \frac{m_d \mathcal{M}_d}{2 d_d} \right| = (1+\kappa_1) + \frac{3\bar{g}_0}{\bar{g}_1}(1+\kappa_0)$$

ratio independent of deuteron details!

# Deuteron MQM. Theta Term

## Corrections to wavefunction




$$m_d \mathcal{M}_d = -2e \frac{g_A \bar{g}_0}{m_\pi^2} \frac{m_N m_\pi}{2\pi F_\pi^2} (1+\kappa_0) \frac{1+\xi}{(1+2\xi)^2},$$

Theta Term

- only $\bar{g}_0$ contributes
- dMQM bigger than dEDM

$$\left| \frac{m_d \mathcal{M}_d}{d_d} \right| = \frac{8}{3}(1+\kappa_0) \frac{1+\xi}{(1+2\xi)^2} \left( \frac{m_N}{m_\pi} \right)^2 \lesssim 50$$

using non-analytic piece of $d_0$.

# EDM of $^3$He and $^3$H

- 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 $\chi$I sources!

# EDM of $^3$He and $^3$H. Summary

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

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 $\chi$I

- 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 qCEDM, $\Xi_{1,8}$ and Theta Term

   identify/exclude them in next generation of experiments?

4. not much hope to distinguish between qEDM and $\chi$I sources

   other observables? TV observables w/o photons?

**To-do list**

1. beyond NDA
2. improve calculation
3. other observables,
   deuteron MQM,
   proton Schiff moment

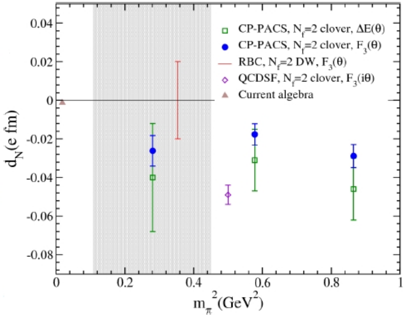
- compute LECs on the lattice
- evolution from EW scale
- NLO with perturbative pions
- fully consistent non ptb. calculation
- study atomic EDMs

# Backup Slides

# Lattice Evaluation of the Nucleon EDM

Theta Term

- $\sim$ 10 times bigger than $\chi$PT result
- still large error, large $m_\pi$
- EDFF mainly isovector




from: Eigo Shintani, talk at Project X Physics Study, June ‘12.

Dimension 6 sources: some preliminary work on qEDM

see: T. Bhattacharya, talk at Project X Physics Study, June ‘12.

# Lattice Evaluation of the Nucleon EDM

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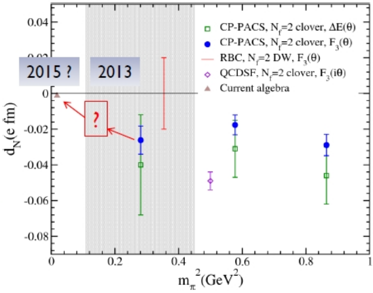



from: Eigo Shintani, talk at Project X Physics Study, June ‘12.

Dimension 6 sources: some preliminary work on qEDM

see: T. Bhattacharya, talk at Project X Physics Study, June ‘12.

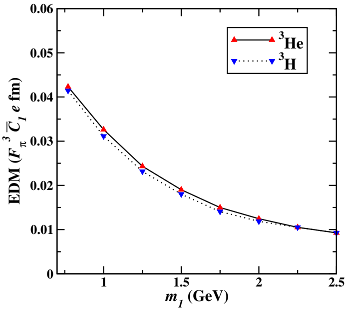
# Helion & Triton EDM. Details

- no core shell model:
  $\Omega = 20,\ 30,\ 40,\ 50$ MeV,
  $N_{max} = 50$
- PT potentials
  AV18, EFT
  NN interaction @ N$^3$LO, p

  Entem and Machleidt, '03

  NNN interaction @ N$^2$LO

  Epelbaum *et al*, '02




For EFT potential:

- $N_{max} = 40$
- still linear dependence on $m_{1,2}$ at $m_{1,2} \sim 2.5$ GeV

## Electromagnetic and $T$-violating operators

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

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

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

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

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

# Electromagnetic and $T$-violating operators

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

- $S_4$

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

- $S_4 \otimes T_{34}$

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

- 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

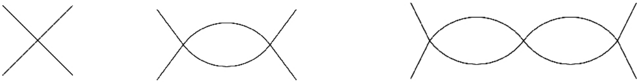
$T$-even sector

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

- 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



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

## Deuteron EDM and MQM. KSW Power Counting

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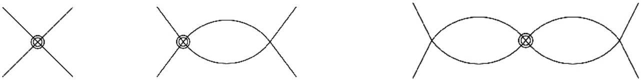
$$C_0^{^3S_1} = \mathcal{O}\left(\frac{4\pi}{m_N\mu}\right), \qquad \mu \sim Q$$

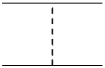
- iterate $C_0$ at all orders
- operators which connect $S$-waves get enhanced $C_2^{^3S_1} = \mathcal{O}\left(\frac{4\pi}{m_N\Lambda_{NN}}\frac{1}{\mu^2}\right)$

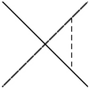


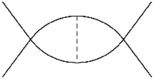
$C_0\,\frac{Q}{\Lambda_{NN}}$ $\qquad$ $C_0\,\frac{Q}{\Lambda_{NN}}\;\frac{m_NQ}{4\pi}C_0$ $\qquad$ $C_0\,\frac{Q}{\Lambda_{NN}}\;\left(\frac{m_NQ}{4\pi}C_0\right)^2$

# Deuteron EDM and MQM. KSW Power Counting

- treat pion exchange as a perturbation







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

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

Perturbative pion approach:

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

- successful for deuteron properties at low energies

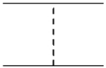
Kaplan, Savage and Wise, Phys. Rev. C **59**, 617 (1999);

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

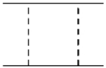
Fleming, Mehen, and Stewart, Nucl. Phys. **A 677**, 313 (2000);

# 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.

Perturbative pion approach:

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

$T$-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 |
|---|---|---|---|---|
| $C_{i,\not{T}}$ | $\frac{4\pi}{\mu m_N}\bar{\theta}\frac{m_\pi^2}{M_{QCD}\Lambda_{NN}^2}$ | $\frac{4\pi}{\mu m_N}\tilde{\delta}\frac{m_\pi^2}{M_{\not{T}}^2 M_{QCD}}$ | $0$ | $\frac{4\pi}{\mu m_N}\frac{w}{M_{\not{T}}^2}\Lambda_{NN}$ |

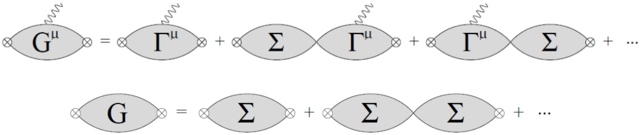
b. four-nucleon $T$-odd currents

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

- 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

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

- two-point function

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