$\not{T}$ interactions and chiral symmetry

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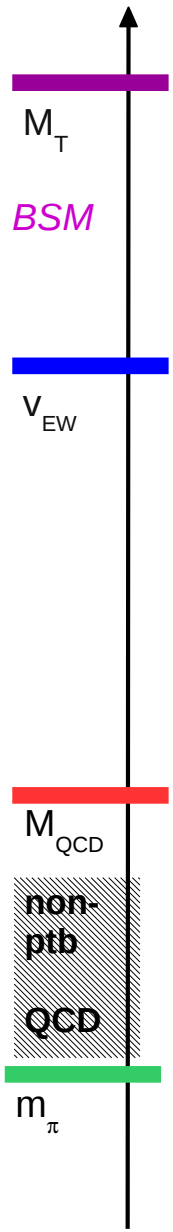
Introduction



- probing $\not{CP}$ with EDM entails physics at very different scales

  $M_{\not{T}} \gg v_{\rm ew} \gg M_{\rm QCD} \gg m_\pi \gg \ldots$
- understanding nature of $\not{CP}$ requires

- several, "orthogonal" probes
- robust theoretical tools

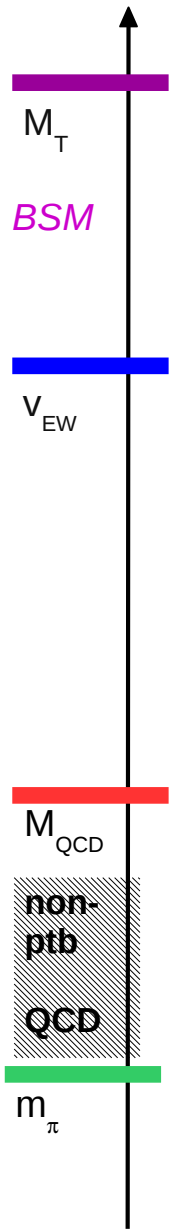
Nucleon d_n, d_p

Light nuclei d_d, d_t, d_h

atoms $d_{^{199}\rm Hg}, d_{^{205}\rm Tl}, \ldots$

molecules $d_{\rm ThO}, \ldots$

Introduction



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Light nuclei	d_d, d_t, d_h

- robust theoretical tools

treated in same theory framework

Chiral EFT

Introduction

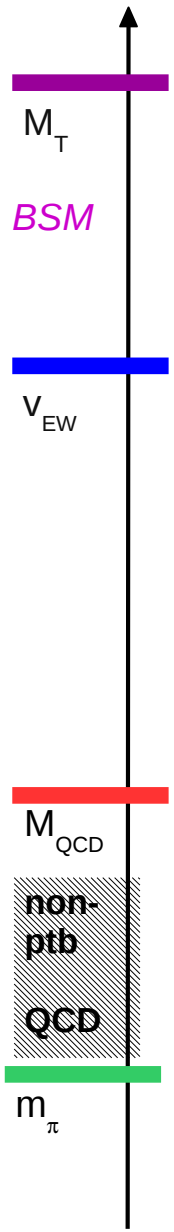


Table 3 Dependence of the deuteron, triton and helion EDMs on $\not{T}$ LECs for various PT potentials. Entries are dimensionless in the first two columns and in units of e fm in the remaining columns. "—" indicates very small numbers.

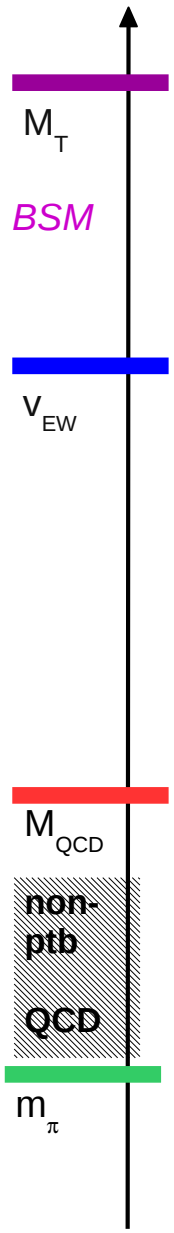
	Potential (Ref.)	d_n	d_p	$\bar{g}_0/F_\pi$	$\bar{g}_1/F_\pi$	$\bar{C}_1 F_\pi^3$	$\bar{C}_2 F_\pi^3$	$\bar{\Delta}/F_\pi m_N$
d_d	Pert. Pion (80, 130)	1	1	—	−0.23	—	—	—
	Av18 (81–83, 117)	1	1	—	−0.19	—	—	—
	CD Bonn (82, 83)	1	1	—	−0.19	—	—	—
	N^{2}LO (82, 83)	1	1	—	−0.18	—	—	—
d_t	Av18 (81, 118)	−0.05	0.90	0.15	−0.28	0.01	−0.02	n/a
	Av18+UIX (83, 120)	−0.05	0.90	0.07	−0.14	0.002	−0.005	0.02
	CD Bonn+TM' (83)	−0.04	0.88	0.09	−0.14	0.02	−0.04	0.02
	N^{2}LO (83)	−0.03	0.92	0.11	−0.14	0.05	−0.10	0.02
d_h	Av18 (81, 118)	0.88	−0.05	−0.15	−0.28	−0.01	0.02	n/a
	Av18+UIX (83, 120)	0.88	−0.05	−0.07	−0.14	−0.002	0.005	0.02
	CD Bonn+TM' (83)	0.90	−0.04	−0.09	−0.15	−0.02	0.04	0.02
	N^{2}LO (83)	0.90	−0.03	−0.11	−0.14	−0.05	0.11	0.02

summary of recent calculations of light nuclei EDM,
from U. van Kolck, EM, *in preparation*

$\sim$ 10 % nuclear uncertainty

. . . when expressed in hadronic couplings

Introduction



- probing $\not{CP}$ with EDM entails physics at very different scales
  $M_{\not{T}} \gg v_{\rm ew} \gg M_{\rm QCD} \gg m_\pi \gg \ldots$
- understanding nature of $\not{CP}$ requires

- several, "orthogonal" probes

  Nucleon d_n, d_p

  Light nuclei $d_d, d_{^3\rm H}, d_{^3\rm He}$

- robust theoretical tools

  treated in same theory framework

  Chiral EFT

- missing link:

$$\boxed{\text{LECs from QCD}}$$

What do we learn from **symmetry** ?

$\not{T}$ at the quark-gluon level

- QCD θ term

$$\mathcal{L}_4 = -\theta \frac{g_s^2}{32\pi^2} \varepsilon^{\mu\nu\alpha\beta} \mathrm{Tr} G_{\mu\nu} G_{\alpha\beta} - \bar{q}_L M e^{i\rho} q_R - \bar{q}_R M e^{-i\rho} q_L,$$

- dimension six

$$\begin{aligned}\mathcal{L}_6 = & -\frac{1}{2}\bar{q}\, i\sigma^{\mu\nu}\gamma^5 \left(d_0 + d_3\tau_3\right) q\, F_{\mu\nu} - \frac{1}{2}\bar{q}\, i\sigma^{\mu\nu}\gamma^5 \left(\tilde{d}_0 + \tilde{d}_3\tau_3\right) G_{\mu\nu} q \\ & + \frac{d_W}{6} f^{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu} + \frac{1}{4}\mathrm{Im}\Sigma_{1(8)} \left(\bar{q}q\, \bar{q}i\gamma^5 q - \bar{q}\boldsymbol{\tau} q \cdot \bar{q}\boldsymbol{\tau} i\gamma^5 q\right) \\ & + \frac{1}{4}\,\mathrm{Im}\,\Xi_{1(8)} \varepsilon^{3ij} \left(\bar{q}\gamma^\mu \tau^i q\, \bar{q} i\gamma_\mu \gamma^5 \tau^j q - \bar{q}\gamma^\mu \tau^i q\, \bar{q} i\gamma_\mu \gamma^5 \tau^j q\right)\end{aligned}$$

see Jordy's talk

- quark electric (qEDM) and chromo-electric dipole moment (qCEDM)

$$d_{0,3} = \frac{\bar{m}\delta_{0,3}}{M^2_{\not{T}}}, \qquad \tilde{d}_{0,3} = \frac{\bar{m}\tilde{\delta}_{0,3}}{M^2_{\not{T}}}$$

- chiral breaking, assume $\propto m_u + m_d$
- $\delta_{0,3}$, $\tilde{\delta}_{0,3}$ are $\mathcal{O}(1)$

$\not{T}$ at the quark-gluon level

- dimension four: QCD θ term

$$\mathcal{L}_4 = -\theta \frac{g_s^2}{32\pi^2} \varepsilon^{\mu\nu\alpha\beta} \mathrm{Tr} G_{\mu\nu} G_{\alpha\beta} - \bar{q}_L M e^{i\rho} q_R - \bar{q}_R M e^{-i\rho} q_L,$$

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$$\begin{aligned}\mathcal{L}_6 = & -\frac{1}{2}\bar{q}\, i\sigma^{\mu\nu}\gamma^5 \left(d_0 + d_3\tau_3\right) q\, F_{\mu\nu} - \frac{1}{2}\bar{q}\, i\sigma^{\mu\nu}\gamma^5 \left(\tilde{d}_0 + \tilde{d}_3\tau_3\right) G_{\mu\nu} q \\ & + \frac{d_W}{6} f^{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu} + \frac{1}{4}\mathrm{Im}\Sigma_{1(8)} \left(\bar{q}q\, \bar{q}i\gamma^5 q - \bar{q}\boldsymbol{\tau} q \cdot \bar{q}\boldsymbol{\tau} i\gamma^5 q\right) \\ & + \frac{1}{4}\,\mathrm{Im}\,\Xi_{1(8)} \varepsilon^{3ij} \left(\bar{q}\gamma^\mu \tau^i q\, \bar{q} i\gamma_\mu \gamma^5 \tau^j q - \bar{q}\gamma^\mu \tau^i q\, \bar{q} i\gamma_\mu \gamma^5 \tau^j q\right)\end{aligned}$$

see Jordy's talk

- gluon chromo-electric dipole moment (gCEDM) & χI four-quark

$$(d_W, \Sigma_{1,8}) = \{w, \sigma_1, \sigma_8\} \frac{1}{M_{\not{T}}^2}$$

- chiral invariant

$\not{T}$ at the quark-gluon level

- dimension four: QCD θ term

$$\mathcal{L}_4 = -\theta \frac{g_s^2}{32\pi^2} \varepsilon^{\mu\nu\alpha\beta} \mathrm{Tr} G_{\mu\nu} G_{\alpha\beta} - \bar{q}_L M e^{i\rho} q_R - \bar{q}_R M e^{-i\rho} q_L,$$

- dimension six

$$\begin{aligned}\mathcal{L}_6 = & -\frac{1}{2}\bar{q}\, i\sigma^{\mu\nu}\gamma^5 \left(d_0 + d_3\tau_3\right) q\, F_{\mu\nu} - \frac{1}{2}\bar{q}\, i\sigma^{\mu\nu}\gamma^5 \left(\tilde{d}_0 + \tilde{d}_3\tau_3\right) G_{\mu\nu} q \\ & + \frac{d_W}{6} f^{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu} + \frac{1}{4}\mathrm{Im}\Sigma_{1(8)} \left(\bar{q}q\, \bar{q}i\gamma^5 q - \bar{q}\boldsymbol{\tau} q \cdot \bar{q}\boldsymbol{\tau} i\gamma^5 q\right) \\ & + \frac{1}{4}\,\mathrm{Im}\,\Xi_{1(8)} \varepsilon^{3ij} \left(\bar{q}\gamma^\mu \tau^i q\, \bar{q} i\gamma_\mu \gamma^5 \tau^j q - \bar{q}\gamma^\mu \tau^i q\, \bar{q} i\gamma_\mu \gamma^5 \tau^j q\right)\end{aligned}$$

see Jordy's talk

- left-right four-quark (FQLR) operators

$$\Xi_{1,8} = \xi \frac{1}{M_{\not{T}}^2}$$

- isospin breaking, not $\propto v_{ew}$

$\not{T}$ at the hadronic level

- include dim-four and dim-six $\not{T}$ in χPT Lagrangian ✓

$$\begin{aligned}\mathcal{L}_{\not{T}} &= -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S^\mu v^\nu N F_{\mu\nu} - \frac{\bar{g}_0}{F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{F_\pi}\pi_3\bar{N}N \\ &\quad -\frac{\bar{\Delta}}{F_\pi}\pi_3\boldsymbol{\pi}^2 + \bar{C}_1\bar{N}N\,\partial_\mu\left(\bar{N}S^\mu N\right) + \bar{C}_2\bar{N}\boldsymbol{\tau}N\,\partial_\mu\left(\bar{N}S^\mu\boldsymbol{\tau}N\right)\end{aligned}$$

- at LO, EDMs expressed in terms of a few couplings

$\bar{d}_0, \bar{d}_1$	neutron & proton EDM, one-body contribs. to A $\geq$ 2 nuclei
$\bar{g}_0, \bar{g}_1, \bar{\Delta}$	pion loop to nucleon & proton EDMs leading $\not{T}$ OPE potential
$\bar{C}_1, \bar{C}_2$	short-range $\not{T}$ potential

- relative size depends on $\not{T}$ source
  $\Longrightarrow$ different signals for one, two, three-nucleon EDMs
- Can we go beyond NDA?

QCD Theta Term

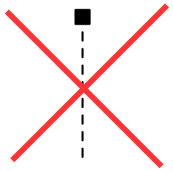
$$\mathcal{L}_4 = -\theta \frac{g_s^2}{32\pi^2} \varepsilon^{\mu\nu\alpha\beta} \mathrm{Tr} G_{\mu\nu} G_{\alpha\beta} - \bar{q}_L M e^{i\rho} q_R - \bar{q}_R M e^{-i\rho} q_L,$$

- rotate θ away

  physics depends on $\bar{\theta} = \theta - n_F \rho$

- perform vacuum alignment

  i.e. kill $\not{T}$ iso-breaking terms $\bar{q} i\gamma_5 \tau_3 q$



$$\boxed{\mathcal{L}_4 = -\bar{m} r(\bar{\theta}) \bar{q} q + r^{-1}(\bar{\theta}) \left(\bar{m}\varepsilon\, \bar{q}\tau_3 q + m_* \sin\bar{\theta}\, \bar{q} i\gamma_5 q \right)}$$

- CP-even quark mass and mass difference
- CP-odd isoscalar mass term

$$\begin{aligned} 2\bar{m} &= m_u + m_d, \\ 2\bar{m}\varepsilon &= m_d - m_u \end{aligned}$$

QCD Theta Term

$$\mathcal{L}_4 = -\theta \frac{g_s^2}{32\pi^2} \varepsilon^{\mu\nu\alpha\beta} \mathrm{Tr} G_{\mu\nu} G_{\alpha\beta} - \bar{q}_L M e^{i\rho} q_R - \bar{q}_R M e^{-i\rho} q_L,$$

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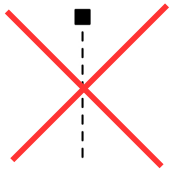

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- CP-even quark mass and mass difference
- CP-odd isoscalar mass term

$$m_* = \frac{m_u m_d}{m_u + m_d} = \bar{m} \frac{1 - \varepsilon^2}{2}$$

$$r(\bar{\theta}) = 1 - \frac{1 - \varepsilon^2}{2} \bar{\theta}^2 + \ldots$$

The QCD Theta Term. Chiral Lagrangian and NDA

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

Chiral properties of $\bar{\theta}$ determine size of LECs

- breaks chiral symmetry

  isoscalar $\bar{g}_0$ at LO

- but not isospin

  isobreaking requires insertion of $\bar{m}\varepsilon$
  $\bar{g}_1$ and $\bar{\Delta}$ suppressed

- higher dimensionality of Nγ and NN operators costs $Q/M_{\rm QCD}$

QCD Theta Term. Symmetry

$$\boxed{\mathcal{L}_4 = -\bar{m} r(\bar{\theta}) \bar{q} q + r^{-1}(\bar{\theta}) \left(\bar{m} \varepsilon \, \bar{q} \tau_3 q + m_* \sin\bar{\theta} \, \bar{q} i \gamma_5 q \right)}$$

- $\bar{\theta}$ term and mass splitting are chiral partners

$$\begin{pmatrix} \bar{q} i \gamma_5 q \\ \bar{q} \boldsymbol{\tau} q \end{pmatrix} \xrightarrow{SU_A(2)} \begin{pmatrix} -\bar{q} \boldsymbol{\alpha} \cdot \boldsymbol{\tau} q \\ \boldsymbol{\alpha} \, \bar{q} i \gamma_5 q \end{pmatrix}$$

- nucleon matrix elements are related
- *i.e.* one spurion enough to construct iso- and T-breaking couplings

$$\frac{\text{T violation}}{\text{isospin breaking}} = \frac{1-\varepsilon^2}{2\varepsilon} \sin\bar{\theta} \equiv \rho_{\bar{\theta}}$$

- powerful at LO
- breaks down at $\mathcal{O}(Q^2/M_{\text{QCD}}^2)$

× ignorance of CP-even LECs

× too many operators when including EM

QCD Theta Term. $\bar{g}_0$

$$\mathcal{L}^{(1)} = \Delta m_N \left(1 - \frac{2\boldsymbol{\pi}^2}{F_\pi^2}\right) \bar{N}N + \frac{1}{2}\delta m_N \left[\bar{N}\left(\tau_3 - \frac{\pi_3 \boldsymbol{\pi}\cdot\boldsymbol{\tau}}{F_\pi^2}\right) N - 2\rho_{\bar{\theta}} \bar{N} \frac{\boldsymbol{\pi}\cdot\boldsymbol{\tau}}{F_\pi} N\right]$$

Δm_N nucleon sigma term

$\delta m_N = (m_n - m_p)_{\mathrm{st}}$, strong mass splitting

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

QCD Theta Term. $\bar{g}_0$

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Δm_N nucleon sigma term

$\delta m_N = (m_n - m_p)_{\text{st}}$, strong mass splitting

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

- δm_N not directly accessible experimentally, $\delta_{\text{em}} m_N \sim \delta m_N$
- accessible via existing lattice calculations

$\delta m_N = 2.39 \pm 0.21$ MeV

A. Walker-Loud, '14; Borsanyi *et al*, '14.

$\varepsilon = 0.37 \pm 0.03$ MeV

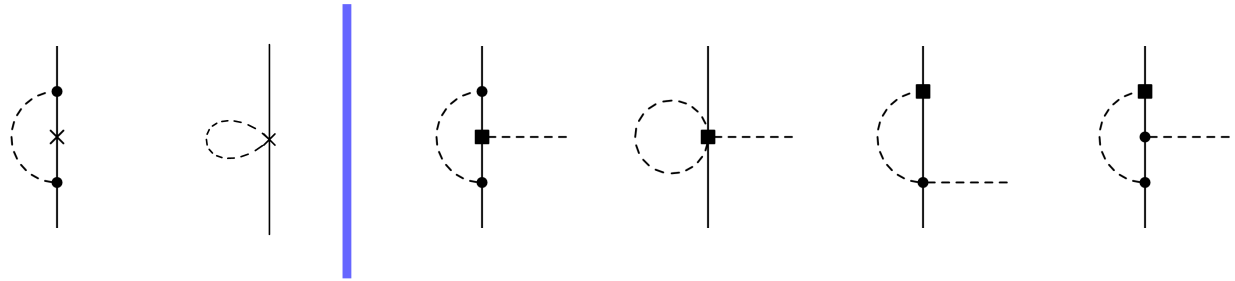
Aoki '13, FLAG Working group.

- precise ($\sim 10\%$) determination of $\bar{g}_0$

$$\frac{\bar{g}_0}{F_\pi} = (15 \pm 2)\cdot 10^{-3}\sin\bar{\theta}$$

errors from lattice only

QCD Theta Term. $\bar{g}_0$



$$\frac{\bar{g}_0}{F_\pi} = \frac{\bar{g}_0}{F_\pi}\left[1+\frac{m_\pi^2}{(2\pi F_\pi)^2}\left(\left(3g_A^2+\frac{1}{2}\right)\log\frac{\mu^2}{m_\pi^2}+g_A^2+\frac{1}{2}\right)\right]+\frac{\delta^{(3)}m_N}{F_\pi}\rho_{\bar{\theta}}+\frac{\delta\bar{g}_0}{F_\pi}$$

$$(m_n-m_p)_{\rm st} = \delta m_N\left[1+\frac{m_\pi^2}{(2\pi F_\pi)^2}\left(\left(3g_A^2+\frac{1}{2}\right)\log\frac{\mu^2}{m_\pi^2}+g_A^2+\frac{1}{2}\right)\right]+\delta^{(3)}m_N$$

- same loop corrections to $\bar{g}_0$ and δm_N
- finite LEC $\delta\bar{g}_0$ only correct πN coupling

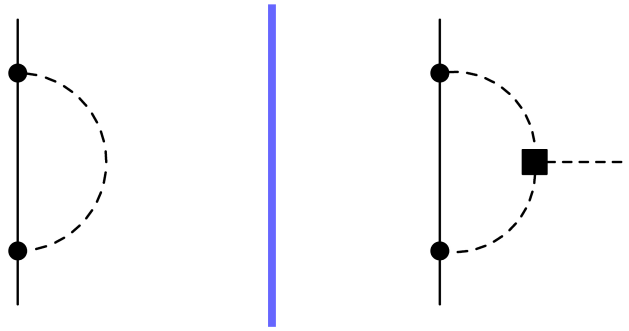
$$\cancel{\frac{\text{T violation}}{\text{isospin breaking}} = \frac{1-\varepsilon^2}{2\varepsilon}\sin\bar{\theta} \equiv \rho_{\bar{\theta}}} \qquad \ldots\text{but}\ldots$$

- corrections appear at NNLO
- and are not log enhanced

QCD Theta term. $\bar{g}_0$

- what about strangeness?
- in $SU(3)$ χPT

$$\frac{\bar{g}_0}{F_\pi} = \rho_{\bar{\theta}} \frac{\delta m_N}{F_\pi} \qquad \textbf{and} \qquad \frac{\bar{g}_0}{F_\pi} = \frac{m_\Xi - m_\Sigma}{m_s - \bar{m}} \frac{\bar{m}(1-\varepsilon^2)}{2F_\pi} = 22 \cdot 10^{-3} \sin\bar{\theta}$$



J. de Vries, EM, A. Walker-Loud, *in progress*

- large $\mathcal{O}(m_K/M_{\rm QCD})$ corrections to $m_n - m_p$ ($m_{K^+} - m_{K^0}$, η-π mixing) and $\bar{g}_0$ (πKK, $\pi\pi\eta$ CP-odd vertex)

QCD Theta term. $\bar{g}_0$

- what about strangeness?
- in $SU(3)$ χPT

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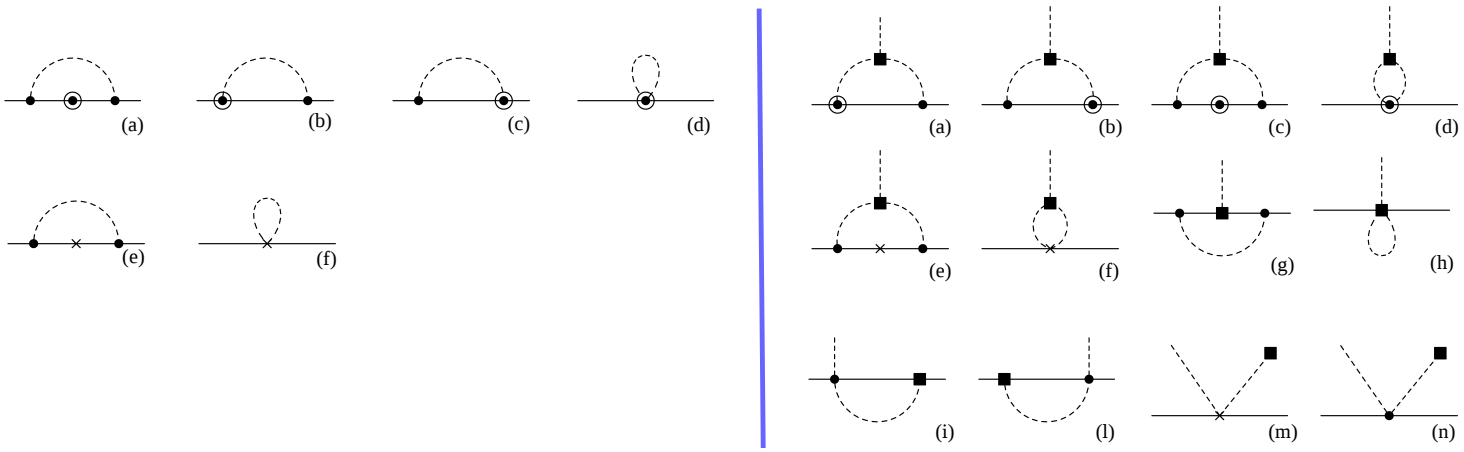


- large (...too large ...) $\mathcal{O}(m_K/M_{\rm QCD})$ corrections to

  $m_n - m_p$ ($m_{K^+} - m_{K^0}$, η-π mixing)

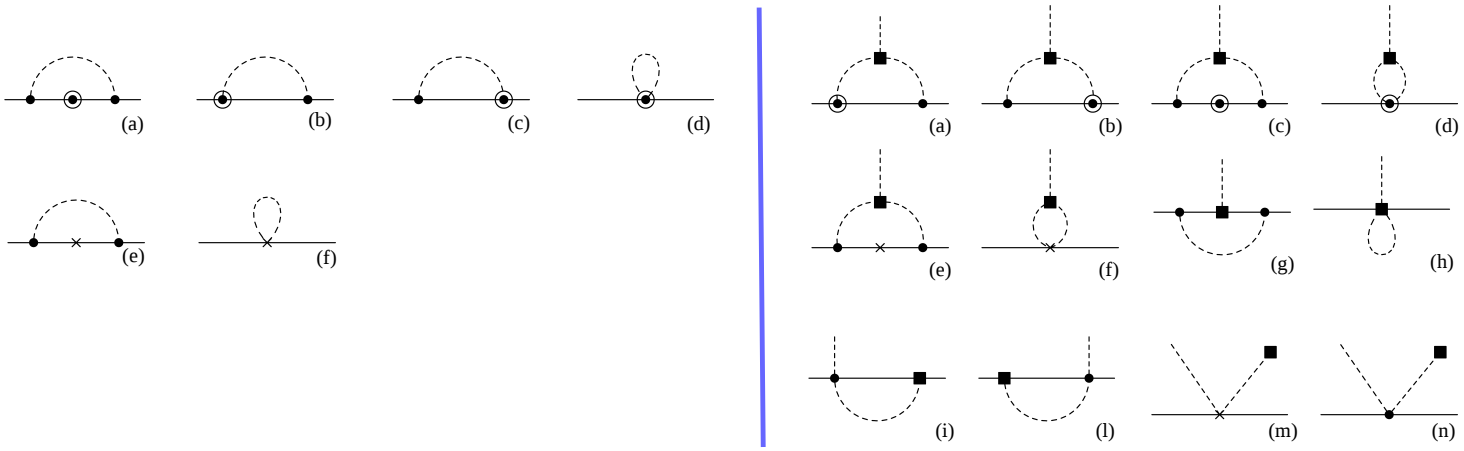
  and $\bar{g}_0$ (πKK, $\pi\pi\eta$ CP-odd vertex)

- under control NNLO corrections

QCD Theta term. $\bar{g}_0$

- what about strangeness?
- in $SU(3)$ χPT

$$\frac{\bar{g}_0}{F_\pi} = \rho_{\bar{\theta}} \frac{\delta m_N}{F_\pi} \qquad \textbf{and} \qquad \frac{\bar{g}_0}{F_\pi} = \frac{m_\Xi - m_\Sigma}{m_s - \bar{m}} \frac{\bar{m}(1-\varepsilon^2)}{2F_\pi} = 22 \cdot 10^{-3} \sin\bar{\theta}$$



- *same* divergent loop corrections to $m_n - m_p$ and $\bar{g}_0$
- *different* loop corrections to $m_\Xi - m_\Sigma$ and $\bar{g}_0$, starting at NLO

$\cancel{\bar{g}_0 \propto m_\Xi - m_\Sigma}$

at NLO

$\bar{g}_0 \propto \delta m_N$ violated by NNLO finite LECs,

but $\delta\bar{g}_0 \sim \bar{m}^2$, **not** $m_s\,\bar{m}$

QCD Theta Term. $\bar{g}_1$ and $\bar{\Delta}$

$$\mathcal{L}^{(2)} = \delta_{\rm st} m_\pi^2 \left(\frac{1}{2}\pi_3^2 - \rho_{\bar{\theta}} \frac{\pi_3 \boldsymbol{\pi}^2}{F_\pi} \right)$$

- $\delta_{\rm st} m_\pi^2$ strong contrib. to $m_{\pi^+}^2 - m_{\pi^0}^2$

$$\delta_{\rm st} m_\pi^2 = 87 \pm 55 \quad \text{MeV}^2$$

fit to meson data G. Amoros, J. Bijnens, P. Talavera, '01.

$$\mathcal{L}^{(3)} = -2\Delta m_N \frac{\delta m_{\rm st}^2}{m_\pi^2} \rho_{\bar{\theta}} \frac{\pi_3}{F_\pi} \bar{N}N - c^{(3)}_{\pi\pi N} \left[\frac{1}{2} \frac{\pi_3^2}{F_\pi^2} + \rho_{\bar{\theta}} \frac{\pi_3}{F_\pi} \right] \bar{N}N$$

- tadpole induced, related to nucleon sigma term
- $c^{(3)}_{\pi\pi N}$ tiny contrib. to π-N scattering
  beyond accuracy of current analysis

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$$\delta_{\rm st} m_\pi^2 = 87 \pm 55 \quad \text{MeV}^2$$

fit to meson data G. Amoros, J. Bijnens, P. Talavera, '01.

$$\mathcal{L}^{(3)} = -(3 \pm 2) \cdot 10^{-3} \sin\bar{\theta}\, \pi_3 \bar{N} N - c^{(3)}_{\pi\pi N} \left[\frac{1}{2} \frac{\pi_3^2}{F_\pi^2} + \rho_{\bar{\theta}} \frac{\pi_3}{F_\pi} \right] \bar{N} N$$

- tadpole induced, related to nucleon sigma term
- $c^{(3)}_{\pi\pi N}$ tiny contrib. to π-N scattering
  beyond accuracy of current analysis
- $\bar{g}_1$ poorly determined

  but somewhat larger than expected, & extremely important for deuteron

QCD Theta Term. $\bar{d}_0$ and $\bar{d}_1$

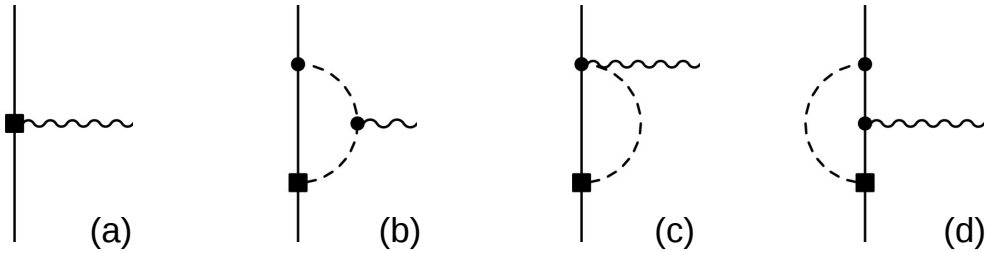
- symmetry relation breaks down

$$\begin{aligned}\mathcal{L}^{(3)}_{N\gamma} &= -2\left[(c_{1\gamma}+c_{2\gamma})\frac{2\pi_3}{F_\pi}+c_{1\gamma}\rho_{\bar{\theta}}\right]\bar{N}S^\mu v^\nu N\, eF_{\mu\nu} \\ &\quad -2\bar{N}\left[(c_{3\gamma}+c_{4\gamma})\frac{2\boldsymbol{\pi}\cdot\boldsymbol{\tau}}{F_\pi}+c_{4\gamma}\rho_{\bar{\theta}}\tau_3\right]S^\mu v^\nu N\, eF_{\mu\nu}\end{aligned}$$

- too much isospin violation
  from EM & quark masses
- no info on $\bar{d}_{0,1}$ from CP-even pion photoproduction
- needs genuine "CP-odd" non-ptb information:

fit to data **or** fit to lattice

QCD Theta Term. $\bar{d}_0$ and $\bar{d}_1$



At NLO

$$F_1(Q^2) = \bar{d}_1 + \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\left[L + \log\frac{\mu^2}{m_\pi^2} + \frac{5\pi}{4}\frac{m_\pi}{m_N}\right] + e\frac{g_A\bar{g}_0}{(2\pi F_\pi)^2}\frac{Q^2}{6m_\pi^2}\left(1 - \frac{5\pi}{4m_N} + h\left(\frac{Q^2}{m_\pi^2}\right)\right)$$

$$F_0(Q^2) = \bar{d}_0 + \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\left[\frac{3\pi}{4}\frac{m_\pi}{m_N}\right]$$

- EDFF at various m_π and Q^2 allows to simultaneously fit $\bar{g}_0$, $\bar{d}_{1,0}$

when more precision

- extract $\bar{d}_{0,1}$
- check $\bar{g}_0$ from symmetry

$\Longrightarrow$ Tom & Taku's talk

QCD Theta Term. Summary

	$\bar{g}_0$	$\bar{g}_1$	$\bar{\Delta}/F_\pi$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$	
$\bar{\theta} \times \frac{m_\pi^2}{M_{QCD}}$	1	$\varepsilon \frac{m_\pi^2}{M_{\rm QCD}^2}$	$\varepsilon \frac{Q}{M_{\rm QCD}}$	$\frac{Q^2}{M_{\rm QCD}^2}$	$\frac{Q^2}{M_{\rm QCD}^2}$	NDA
$\bar{\theta} \times 10^{-3} F_\pi$	15	3	3	×	×	symm.

- symmetry consideration very powerful at low order
- $\bar{g}_0$ well known
- $\bar{\Delta}$ and $\bar{g}_1$ known with large errors

no evident way to improve on $\bar{g}_1$

× need experiment/lattice to determine $\bar{d}_{0,1}$

× four-nucleon $\bar{C}_{1,2}$ are harder,

...but power counting relegates them to subleading role

Improving of lattice will allow to determine $\bar{d}_{0,1}$
& check $\bar{g}_0$ in the near future

Quark CEDM

$$\mathcal{L}_6 = -\frac{1}{2}\,\bar{q}\sigma^{\mu\nu}g_s G_{\mu\nu}\left(\tilde{c}_0 + i\gamma_5\tau_3\tilde{d}_3\right)q - \frac{1}{2}\,\bar{q}\sigma^{\mu\nu}g_s G_{\mu\nu}\left(\tilde{c}_3\tau_3 + i\gamma_5\tilde{d}_0\right)q$$
$$+r\,\bar{q}i\gamma_5\tilde{d}_3\left(\tau_3 - \varepsilon\right)q$$

- qCEDM has CP-even chiral partner

$$\frac{1}{2}\begin{pmatrix} \bar{q}\sigma^{\mu\nu}g_s G_{\mu\nu}q \\ -\bar{q}\sigma^{\mu\nu}i\gamma^5\boldsymbol{\tau}g_s G_{\mu\nu}q \end{pmatrix}$$

- isovector qCEDM
  & isoscalar qCMDM

$$\frac{1}{2}\begin{pmatrix} \bar{q}\sigma^{\mu\nu}i\gamma^5 g_s G_{\mu\nu}q \\ \bar{q}\sigma^{\mu\nu}\boldsymbol{\tau}g_s G_{\mu\nu}q \end{pmatrix}$$

- isoscalar qCEDM
  & isovector qCMDM

Quark CEDM

$$\mathcal{L}_6 = -\frac{1}{2}\,\bar{q}\sigma^{\mu\nu} g_s G_{\mu\nu}\left(\tilde{c}_0 + i\gamma_5\tau_3\tilde{d}_3\right) q - \frac{1}{2}\,\bar{q}\sigma^{\mu\nu} g_s G_{\mu\nu}\left(\tilde{c}_3\tau_3 + i\gamma_5\tilde{d}_0\right) q$$
$$+ r\,\bar{q} i\gamma_5\tilde{d}_3\left(\tau_3 - \varepsilon\right) q$$

- qCEDM has CP-even chiral partner

$$\frac{1}{2}\begin{pmatrix} \bar{q}\sigma^{\mu\nu} g_s G_{\mu\nu} q \\ -\bar{q}\sigma^{\mu\nu} i\gamma^5 \boldsymbol{\tau} g_s G_{\mu\nu} q \end{pmatrix} \qquad \frac{1}{2}\begin{pmatrix} \bar{q}\sigma^{\mu\nu} i\gamma^5 g_s G_{\mu\nu} q \\ \bar{q}\sigma^{\mu\nu} \boldsymbol{\tau} g_s G_{\mu\nu} q \end{pmatrix}$$

- isovector qCEDM & isoscalar qCMDM
- isoscalar qCEDM & isovector qCMDM

- $\tilde{d}_3$ causes vacuum misalignment
- re-alignment causes the appearance of a mass term

$$r = \frac{1}{2}\frac{\langle\bar{q}\sigma^{\mu\nu} g_s G_{\mu\nu} q\rangle}{\langle\bar{q}q\rangle} = \frac{\tilde{\Delta} m_\pi^2}{m_\pi^2}\,\frac{\bar{m}}{\tilde{c}_0}$$

- need to know matrix elements of $\bar{q}\sigma^{\mu\nu} i\gamma_5 G_{\mu\nu} q$ **and** $\bar{q} i\gamma_5 q$!

Quark CEDM

$$\mathcal{L}_6 = -\frac{1}{2}\,\bar{q}\sigma^{\mu\nu} g_s G_{\mu\nu}\left(\tilde{c}_0 + i\gamma_5\tau_3\tilde{d}_3\right) q - \frac{1}{2}\,\bar{q}\sigma^{\mu\nu} g_s G_{\mu\nu}\left(\tilde{c}_3\tau_3 + i\gamma_5\tilde{d}_0\right) q$$
$$+ r\,\bar{q} i\gamma_5\left(\tilde{d}_0 + \tilde{d}_3\tau_3\right) q$$

- qCEDM has CP-even chiral partner

$$\frac{1}{2}\begin{pmatrix} \bar{q}\sigma^{\mu\nu} g_s G_{\mu\nu} q \\ -\bar{q}\sigma^{\mu\nu} i\gamma^5 \boldsymbol{\tau} g_s G_{\mu\nu} q \end{pmatrix}$$

- isovector qCEDM
  & isoscalar qCMDM

$$\frac{1}{2}\begin{pmatrix} \bar{q}\sigma^{\mu\nu} i\gamma^5 g_s G_{\mu\nu} q \\ \bar{q}\sigma^{\mu\nu} \boldsymbol{\tau} g_s G_{\mu\nu} q \end{pmatrix}$$

- isoscalar qCEDM
  & isovector qCMDM

- if PQ solves strong CP problem $\bar{\theta} \propto \tilde{d}_0, \tilde{d}_3$
- isoscalar and isovector resume their original meaning

$$r = \frac{1}{2}\frac{\langle \bar{q}\sigma^{\mu\nu} g_s G_{\mu\nu} q\rangle}{\langle \bar{q} q\rangle} = \frac{\tilde{\Delta} m_\pi^2}{m_\pi^2}\,\frac{\bar{m}}{\tilde{c}_0}$$

Quark CEDM. Chiral Lagrangian and NDA

	$\bar{g}_0$	$\bar{g}_1$	$\bar{\Delta}/F_\pi$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$	
$\bar{\theta} \times \frac{m_\pi^2}{M_{\rm QCD}}$	1	$\varepsilon \frac{m_\pi^2}{M_{\rm QCD}^2}$	$\varepsilon \frac{Q}{M_{\rm QCD}}$	$\frac{Q^2}{M_{\rm QCD}^2}$	$\frac{Q^2}{M_{\rm QCD}^2}$	NDA
$\left(\tilde{\delta}_0 \frac{M_{\rm QCD}^2}{M_{\not T}^2}\right) \times \frac{m_\pi^2}{M_{\rm QCD}}$	1	$\varepsilon \frac{m_\pi^2}{M_{\rm QCD}^2}$	$\varepsilon \frac{Q}{M_{\rm QCD}}$	$\frac{Q^2}{M_{\rm QCD}^2}$	$\frac{Q^2}{M_{\rm QCD}^2}$	NDA
$\left(\tilde{\delta}_3 \frac{M_{\rm QCD}^2}{M_{\not T}^2}\right) \times \frac{m_\pi^2}{M_{\rm QCD}}$	ε	1	$\frac{Q}{M_{\rm QCD}}$	$\frac{Q^2}{M_{\rm QCD}^2}$	$\frac{Q^2}{M_{\rm QCD}^2}$	no PQ
$\left(\tilde{\delta}_3 \frac{M_{\rm QCD}^2}{M_{\not T}^2}\right) \times \frac{m_\pi^2}{M_{\rm QCD}}$	$\varepsilon \frac{m_\pi^2}{M_{\rm QCD}^2}$	1	$\frac{Q}{M_{\rm QCD}}$	$\frac{Q^2}{M_{\rm QCD}^2}$	$\frac{Q^2}{M_{\rm QCD}^2}$	PQ

- assume $\tilde{d}_u \propto m_u$, $\tilde{d}_d \propto m_d$; $\tilde{d}_{0,3} = \mathcal{O}\left(\tilde{\delta}_{0,3} \frac{\bar{m}}{M_{\not T}^2}\right)$
- Chiral Lagrangian very similar to $\bar{\theta}$
- but now iso-breaking !
  - if $\tilde{\delta}_0 \sim \tilde{\delta}_3$, $\bar{g}_0 \sim \bar{g}_1$, important for deuteron, $N = Z$ nuclei

Quark CEDM. $\bar{g}_0$, and $\bar{g}_1$

- no PQ mechanism

$$
\begin{aligned}
\bar{g}_0 &= \tilde{\delta} m_N \frac{\tilde{d}_0}{\tilde{c}_3} - \delta m_N \frac{\tilde{\Delta} m_\pi^2}{m_\pi^2} \frac{\tilde{d}_3}{\tilde{c}_0}, \\
\bar{g}_1 &= 2 \left(\tilde{\Delta} m_N - \Delta m_N \frac{\tilde{\Delta} m_\pi^2}{m_\pi^2} \right) \frac{\tilde{d}_3}{\tilde{c}_0},
\end{aligned}
$$

- $\tilde{\delta} m_N$ correction to $m_n - m_p$ from $\tilde{c}_3$
- $\tilde{\Delta} m_\pi^2$, $\tilde{\Delta} m_N$ corrections to m_π^2 and sigma term from $\tilde{c}_0$

Quark CEDM. $\bar{g}_0$, and $\bar{g}_1$

- PQ mechanism

$$\bar{g}_0 = \left(\tilde{\delta} m_N + \delta m_N \frac{\tilde{\Delta} m_\pi^2}{m_\pi^2} \frac{\tilde{c}_3}{\tilde{c}_0 \varepsilon} \right) \frac{\tilde{d}_0}{\tilde{c}_3},$$

$$\bar{g}_1 = 2 \left(\tilde{\Delta} m_N - \Delta m_N \frac{\tilde{\Delta} m_\pi^2}{m_\pi^2} \right) \frac{\tilde{d}_3}{\tilde{c}_0},$$

- $\tilde{\delta} m_N$ correction to $m_n - m_p$ from $\tilde{c}_3$
- $\tilde{\Delta} m_\pi^2$, $\tilde{\Delta} m_N$ corrections to m_π^2 and sigma term from $\tilde{c}_0$
- $\bar{g}_0$ only depends on $\tilde{d}_0$

Do these hold beyond LO?

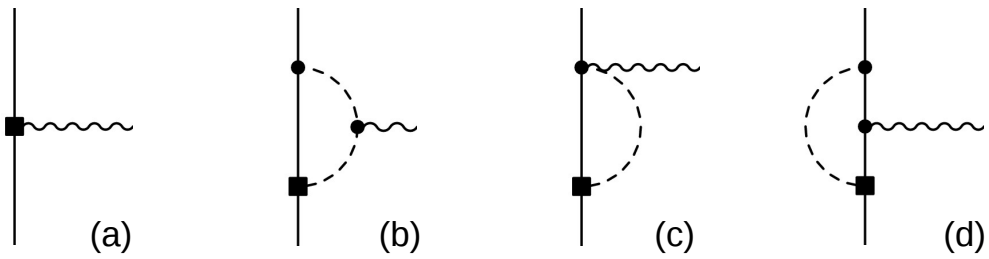
$\bar{g}_0$: yes for SU(2) & SU(3) loops
violated by finite LECs

$\bar{g}_1$: yes for SU(2) loops. SU(3) ?
violated by finite LECs

$\bar{g}_{0,1}$ known if $\tilde{\delta} m_N$, $\tilde{\Delta} m_\pi^2$ and $\tilde{\Delta} m_N$

Quark CEDM. $\bar{d}_0$ and $\bar{d}_1$

- no symmetry relation; need lattice or experiment



$$
\begin{aligned}
F_1(Q^2) &= \bar{d}_1 + \frac{e g_A \bar{g}_0}{(2\pi F_\pi^2)} \left[L + \log \frac{\mu^2}{m_\pi^2} + \frac{5\pi}{4} \frac{m_\pi}{m_N} \left(1 + \frac{\bar{g}_1}{5\bar{g}_0} \right) \right] \\
&\quad + e \frac{g_A \bar{g}_0}{(2\pi F_\pi)^2} \frac{Q^2}{6 m_\pi^2} \left(1 - \frac{5\pi}{4 m_N} + h\left(\frac{Q^2}{m_\pi^2} \right) \right) \\
F_0(Q^2) &= \bar{d}_0 + \frac{e g_A \bar{g}_0}{(2\pi F_\pi^2)} \left[\frac{3\pi}{4} \frac{m_\pi}{m_N} \left(1 + \frac{\bar{g}_1}{3\bar{g}_0} \right) \right]
\end{aligned}
$$

- $\bar{g}_1$ appears at NLO, only for d_p
- EDFF at various m_π and Q^2 allows to simultaneously fit $\bar{g}_0$, $\bar{d}_{1,0}$, & $\bar{g}_1$?

Four quark Left-Right Operators

$$\begin{aligned}\mathcal{L}_6 \quad = \quad & \mathrm{Re}\Xi_1 \left(\bar{q}\gamma^\mu q\, \bar{q}\gamma_\mu q - \bar{q}\gamma^\mu\gamma_5 q\, \bar{q}\gamma_\mu\gamma_5 q\right)\left(\boldsymbol{\tau}\cdot\boldsymbol{\tau} - \tau_3\,\tau_3\right) \\ & + \mathrm{Im}\Xi_1 \left(\bar{q}\gamma^\mu q\, \bar{q}\gamma_\mu\gamma_5 q\right)\left(\boldsymbol{\tau}\times\boldsymbol{\tau}\right)_3\end{aligned}$$

- more complicated transformation properties,
  34 component of a symmetric tensor

$$X = \frac{1}{4}\begin{pmatrix} \tau^i\gamma^\mu \otimes \tau^j\gamma_\mu - \tau^i\gamma^\mu\gamma_5 \otimes \tau^j\gamma_\mu\gamma_5 & -\epsilon^{jkl}\tau^k\gamma^\mu \otimes \tau^l\gamma_\mu\gamma_5 \\ -\epsilon^{ikl}\tau^k\gamma^\mu \otimes \tau^l\gamma_\mu\gamma_5 & \boldsymbol{\tau}\gamma^\mu \otimes \boldsymbol{\tau}\gamma_\mu - \boldsymbol{\tau}\gamma^\mu\gamma_5 \otimes \boldsymbol{\tau}\gamma_\mu\gamma_5 \end{pmatrix},$$

Four quark Left-Right Operators

$$\begin{aligned}\mathcal{L}_6 \quad &= \quad \mathrm{Re}\Xi_1\ (X_{44} - X_{33}) - \mathrm{Im}\Xi_1 X_{34} \\ &\quad + r_{LR}\,\bar{q} i\gamma_5 \mathrm{Im}\Xi_1 (\tau_3 - \varepsilon) q\end{aligned}$$

- more complicated transformation properties,
  34 component of a symmetric tensor

$$X = \frac{1}{4}\begin{pmatrix} \tau^i\gamma^\mu \otimes \tau^j\gamma_\mu - \tau^i\gamma^\mu\gamma_5 \otimes \tau^j\gamma_\mu\gamma_5 & -\epsilon^{jkl}\tau^k\gamma^\mu \otimes \tau^l\gamma_\mu\gamma_5 \\ -\epsilon^{ikl}\tau^k\gamma^\mu \otimes \tau^l\gamma_\mu\gamma_5 & \boldsymbol{\tau}\gamma^\mu \otimes \boldsymbol{\tau}\gamma_\mu - \boldsymbol{\tau}\gamma^\mu\gamma_5 \otimes \boldsymbol{\tau}\gamma_\mu\gamma_5 \end{pmatrix},$$

- $\mathrm{Im}\Xi_1$ causes vacuum misalignment
- re-alignment causes the appearance of a mass term

$$r_{LR} = \frac{\Delta_{LR} m_\pi^2}{m_\pi^2}\frac{\bar{m}}{\mathrm{Re}\Xi_1}$$

Four quark Left-Right Operators

$$\mathcal{L}_6 = \mathrm{Re}\Xi_1\ (X_{44} - X_{33}) - \mathrm{Im}\Xi_1 X_{34} + r_{LR}\,\bar{q} i\gamma_5 \mathrm{Im}\Xi_1 \tau_3 q$$

- more complicated transformation properties,
  34 component of a symmetric tensor

$$X = \frac{1}{4}\begin{pmatrix} \tau^i\gamma^\mu \otimes \tau^j\gamma_\mu - \tau^i\gamma^\mu\gamma_5 \otimes \tau^j\gamma_\mu\gamma_5 & -\epsilon^{jkl}\tau^k\gamma^\mu \otimes \tau^l\gamma_\mu\gamma_5 \\ -\epsilon^{ikl}\tau^k\gamma^\mu \otimes \tau^l\gamma_\mu\gamma_5 & \boldsymbol{\tau}\gamma^\mu \otimes \boldsymbol{\tau}\gamma_\mu - \boldsymbol{\tau}\gamma^\mu\gamma_5 \otimes \boldsymbol{\tau}\gamma_\mu\gamma_5 \end{pmatrix},$$

- $\mathrm{Im}\Xi_1$ causes vacuum misalignment
- re-alignment causes the appearance of a mass term
- if PQ, no isoscalar component

$$r_{LR} = \frac{\Delta_{LR} m_\pi^2}{m_\pi^2}\frac{\bar{m}}{\mathrm{Re}\Xi_1}$$

Four-quark LR Operators. Chiral Lagrangian and NDA

	$\bar{g}_0$	$\bar{g}_1$	$\bar{\Delta}/F_\pi$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$	
$\bar{\theta} \times \frac{m_\pi^2}{M_{\rm QCD}}$	1	$\varepsilon \frac{m_\pi^2}{M_{\rm QCD}^2}$	$\varepsilon \frac{Q}{M_{\rm QCD}}$	$\frac{Q^2}{M_{\rm QCD}^2}$	$\frac{Q^2}{M_{\rm QCD}^2}$	NDA
$\left(\xi \frac{M_{\rm QCD}^2}{M_{\not{T}}^2}\right) \times M_{\rm QCD}$	ε	1	$\frac{M_{\rm QCD}}{Q}$	$\frac{Q^2}{M_{\rm QCD}^2}$	$\frac{Q^2}{M_{\rm QCD}^2}$	no PQ
$\left(\xi \frac{M_{\rm QCD}^2}{M_{\not{T}}^2}\right) \times M_{\rm QCD}$	$\varepsilon \frac{m_\pi^2}{M_{\rm QCD}^2}$	1	$\frac{M_{\rm QCD}}{Q}$	$\frac{Q^2}{M_{\rm QCD}^2}$	$\frac{Q^2}{M_{\rm QCD}^2}$	PQ

- isobreaking couplings are more important
- large three-pion coupling
  - vector $\bar{q} i \gamma_5 \tau_3 q$ *vs* tensor X_{34}
    incomplete cancellation of π matrix elements,
  - important mainly for nuclei
    e.g three-body force, large correction to $\bar{g}_1$
- if PQ, no $\bar{g}_0$ at LO

Four-quark LR operators. $\bar{g}_0$, $\bar{g}_1$ and $\bar{\Delta}$

- no PQ mechanism

$$\bar{g}_0 = -\delta m_N \frac{\tilde{\Delta}_{LR}\, m_\pi^2}{m_\pi^2} \frac{\mathrm{Im}\Xi_1}{\mathrm{Re}\Xi_1}, \qquad \bar{\Delta} = \tilde{\Delta}_{LR}\, m_\pi^2 \frac{\mathrm{Im}\Xi_1}{\mathrm{Re}\Xi_1}$$

$$\bar{g}_1 = 2\left(\tilde{\Delta}_{LR} m_N - \Delta m_N \frac{\tilde{\Delta}_{LR}\, m_\pi^2}{m_\pi^2}\right) \frac{\mathrm{Im}\Xi_1}{\mathrm{Re}\Xi_1}$$

- $\tilde{\Delta}_{LR}\, m_\pi^2$, $\tilde{\Delta}_{LR}\, m_N$ corrections to m_π^2 and sigma term from $\mathrm{Re}\,\Xi_1$
- if PQ, no $\bar{g}_0$ at LO

Four-quark LR operators. $\bar{g}_0$, $\bar{g}_1$ and $\bar{\Delta}$

- PQ mechanism

$$\begin{aligned}
\bar{g}_0 &= 0, \qquad \bar{\Delta} = \tilde{\Delta}_{LR}\, m_\pi^2 \frac{\mathrm{Im}\Xi_1}{\mathrm{Re}\Xi_1} \\
\bar{g}_1 &= 2\left(\tilde{\Delta}_{LR} m_N - \Delta m_N \frac{\tilde{\Delta}_{LR}\, m_\pi^2}{m_\pi^2}\right) \frac{\mathrm{Im}\Xi_1}{\mathrm{Re}\Xi_1}
\end{aligned}$$

- $\tilde{\Delta}_{LR}\, m_\pi^2$, $\tilde{\Delta}_{LR}\, m_N$ corrections to m_π^2 and sigma term from $\mathrm{Re}\,\Xi_1$
- if PQ, no $\bar{g}_0$ at LO

Four-quark LR operators. $\bar{g}_0$, $\bar{g}_1$ and $\bar{\Delta}$

- PQ mechanism

$$\begin{aligned} \bar{g}_0 &= 0, \qquad \bar{\Delta} = \tilde{\Delta}_{LR}\, m_\pi^2 \frac{\mathrm{Im}\Xi_1}{\mathrm{Re}\Xi_1} \\ \bar{g}_1 &= 2\left(\tilde{\Delta}_{LR} m_N - \Delta m_N \frac{\tilde{\Delta}_{LR}\, m_\pi^2}{m_\pi^2}\right) \frac{\mathrm{Im}\Xi_1}{\mathrm{Re}\Xi_1} \end{aligned}$$

- $\tilde{\Delta}_{LR}\, m_\pi^2$, $\tilde{\Delta}_{LR}\, m_N$ corrections to m_π^2 and sigma term from $\mathrm{Re}\,\Xi_1$
- if PQ, no $\bar{g}_0$ at LO

$$\boxed{\bar{g}_{0,1} \text{ and } \bar{\Delta} \text{ known if } \tilde{\Delta}_{LR} m_N,\ \tilde{\Delta}_{LR} m_\pi^2}$$

- need to evaluate CP even four-quark
- already done?
- affected by loop corrections?

Chiral Invariant $\not{T}$ sources

	$\bar{g}_0$	$\bar{g}_1$	$\bar{\Delta}/F_\pi$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$	
$\bar{\theta} \times \frac{m_\pi^2}{M_{\rm QCD}}$	1	$\varepsilon \frac{m_\pi^2}{M_{\rm QCD}^2}$	$\varepsilon \frac{Q}{M_{\rm QCD}}$	$\frac{Q^2}{M_{\rm QCD}^2}$	$\frac{Q^2}{M_{\rm QCD}^2}$	NDA
$\left(w \frac{M_{\rm QCD}^2}{M_{\not{T}}^2}\right) \times M_{\rm QCD}$	$\frac{m_\pi^2}{M_{\rm QCD}^2}$	$\varepsilon \frac{m_\pi^2}{M_{\rm QCD}^2}$	$\varepsilon \frac{Q_\pi^3}{M_{\rm QCD}^3}$	$\frac{Q^2}{M_{\rm QCD}^2}$	$\frac{Q^2}{M_{\rm QCD}^2}$	NDA

$$\mathcal{L} = \frac{d_w}{6} g_s f^{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu} + \frac{g_s^2}{4} \mathrm{Im}\Sigma_{1,8} \left[\bar{q}q\, \bar{q}i\gamma_5 q - \bar{q}\boldsymbol{\tau} q \cdot \bar{q} i\gamma_5 \boldsymbol{\tau} q\right] (1 \otimes 1, t^a \otimes t^a)$$

- no CP-even partner
- π-N couplings suppressed by m_π^2
- nucleon EDFF dominated by $\bar{d}_{0,1}$, momentum independent

$$F_1(Q^2) = \bar{d}_1 + \mathcal{O}\left(\frac{Q^2}{M_{\rm QCD}^2}\right), \qquad F_0(Q^2) = \bar{d}_0 + \mathcal{O}\left(\frac{Q^2}{M_{\rm QCD}^2}\right).$$

- $\bar{g}_{0,1}$, $\bar{C}_{1,2}$ should be important for light nuclei
- but found small

de Vries, *et al*, '11; Bsaisou, *et al*, '14

Conclusions

Connection EDM to BSM physics

- several, "orthogonal" EDMs (*e.g.* d_n, d_p, d_d ...)
- robust theory at different physics scales
- first principle determination of d_n, d_p & $\not{T}$ pion-nucleon couplings

- chiral symmetry provides powerful constraints

$\bar{\theta}$	$\bar{g}_0$ from $\bar{\theta}$ determined by $(m_n - m_p)_{\rm st}$
qCEDM	$\bar{g}_0$ and $\bar{g}_1$ determined by corrections to meson and baryon spectrum induced by CP-even qCMDM
FQLR	$\bar{g}_0$, $\bar{g}_1$ & $\bar{\Delta}$ determined by CP-even FQLR operators

- no info from symmetry on d_n, d_p,
  genuine non-ptb "CP-odd" info needed

Lattice is (or is getting) there!

× no info on four-nucleon couplings $\bar{C}_{1,2}$,
little info on subleading couplings $\bar{g}_1(\bar{\theta})$