The EDM inverse problem: Identifying the sources of CP violation and PQ breaking with EDMs

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Kiwoon Choi, SHI, Krzysztof Jodlowski, JHEP 04 (2024) 007, arXiv 2308.01090
Kiwoon Choi, SHI in preparation

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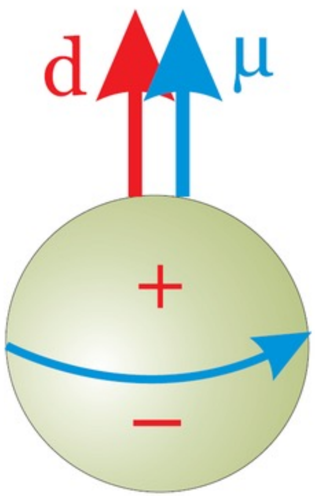
Outline

- CP violation and Electric Dipole Moments (EDMs)
- New Physics (NP) sources for CP violation
- Nuclear and Atomic EDMs
- Identifying NP sources from EDM data

Electromagnetic dipole moments of a particle

An elementary particle or an atom can have permanent electric dipole moment (d) and magnetic dipole moment (μ) along the direction of its spin.



$$H = -d\,\vec{S}\cdot\vec{E} - \mu\,\vec{S}\cdot\vec{B}$$

Charge conjugation $C : \mathbf{E} \to -\mathbf{E},\ \mathbf{B} \to -\mathbf{B},\ \mathbf{S} \to -\mathbf{S}$

Parity inversion $P : \mathbf{E} \to -\mathbf{E},\ \mathbf{B} \to +\mathbf{B},\ \mathbf{S} \to +\mathbf{S}$

Time reversal $T : \mathbf{E} \to +\mathbf{E},\ \mathbf{B} \to -\mathbf{B},\ \mathbf{S} \to -\mathbf{S}$

A non-zero electric dipole moment (d) violates the P and T $(= CP)$ invariance, while a magnetic dipole moment (μ) does not.

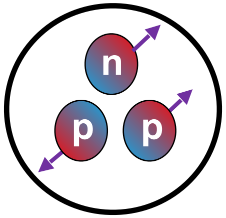
CP violation is an important condition in the early universe to generate the asymmetry between matter and antimatter.

Observed asymmetry : $$Y_B = \frac{n_B}{s} \sim 10^{-10}$$

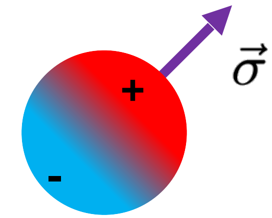
SM prediction : $$Y_{B,\,\mathrm{SM}} \lesssim 10^{-15}$$

e.g. Konstandin, Prokopec, G. Schmidt '03

SM does not provide a sufficient CP violation, and we need new physics beyond the SM with a new CP phase, which may give rise to sizable EDMs of SM particles.



EDM probes for New Physics



None of permanent electric dipole moments (EDMs) of any elementary particles and atoms has been observed so far.

SM prediction

$$d_N \sim (10^{-32}\sin\delta_{\rm KM} + 10^{-16}\,\bar{\theta})\ \text{e cm}$$
$$d_e \sim (10^{-44}\sin\delta_{\rm KM} + 10^{-27}\,\bar{\theta})\ \text{e cm}$$

$\delta_{\rm KM} \sim O(1)$

Experimental status

$$d_n < 1.8 \times 10^{-26}\ \text{e cm}$$
$$d_e < 4.1 \times 10^{-30}\ \text{e cm}$$

Abel et al '20

Roussy et al '22

$\bar{\theta} \lesssim 10^{-10}$ ← (strong CP problem)

Typical BSM prediction

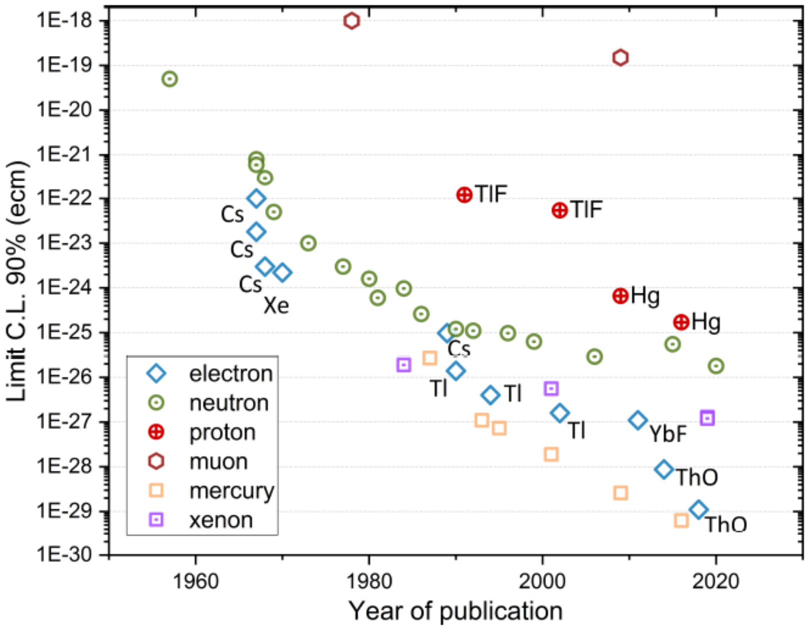
$$d_N \sim \frac{1}{16\pi^2}\frac{f_\pi}{\Lambda_{\rm BSM}^2}$$
$$d_e \sim \frac{1}{16\pi^2}\frac{m_e}{\Lambda_{\rm BSM}^2}$$

$\Lambda_{\rm BSM} \gtrsim O(10\sim100)$ TeV

Powerful probe for new physics!

Experimental prospect

2003.00717



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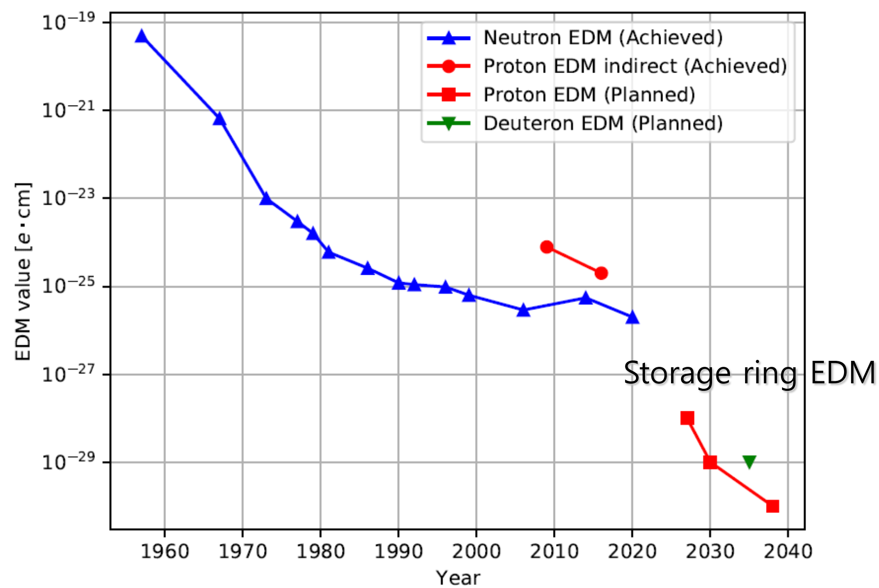


In a decade, the experimental sensitivity on EDMs of electrons, nucleons, atoms, and molecules is going to be improved by several orders of magnitude.

CP violating UV sources

$$\mathcal{L}_{\rm CPV}(m_W < \mu < \Lambda_{\rm BSM}) = \mathcal{L}_{\rm KM} + \frac{g_s^2}{32\pi^2}\bar{\theta}G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} + \mathcal{L}_{\rm dim\ 6} + \cdots$$

$$\mathcal{L}_{\rm dim\ 6} = |H|^2 G\widetilde{G} + f^{abc}G^a G^b \widetilde{G}^c + H\bar{Q}_L\sigma^{\mu\nu}G_{\mu\nu}d_R + H\bar{Q}_L\sigma^{\mu\nu}B_{\mu\nu}d_R + \bar{L}_L e_R \bar{d}_R Q_L + \cdots$$

EWSB and integrating out heavy SM fields

Around the QCD scale ~ 1 GeV

Gluon Chromo-EDM (Weinberg operator)

$$f^{abc}G^a G^b \widetilde{G}^c + \bar{q}\sigma^{\mu\nu}i\gamma_5 G_{\mu\nu}q + \bar{q}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}q + \bar{e}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}e + \bar{q}q\bar{q}q + \bar{e}e\bar{q}q$$

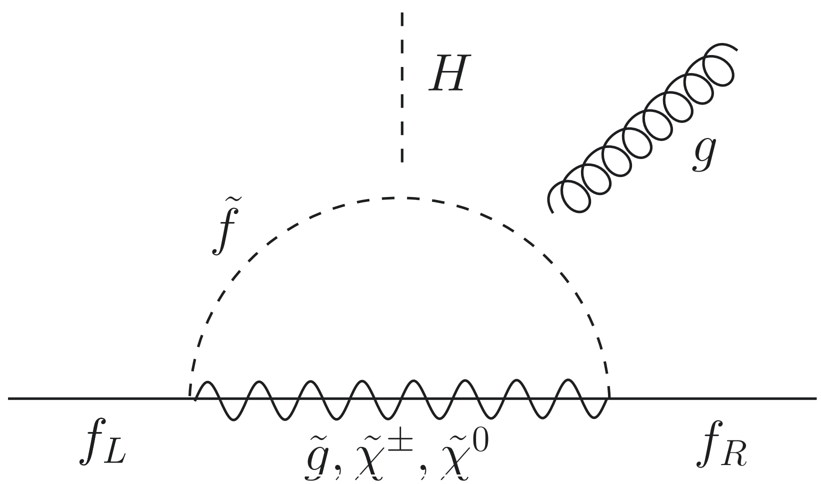
Quark Chromo-EDMs (CEDMs)

Quark EDMs | Electron EDM | 4-Fermi operators

Potentially dominant CPV operators around the QCD scale ~ 1 GeV

$$\underbrace{\frac{g_s^2}{32\pi^2}\bar{\theta}G\widetilde{G}}_{\text{SM}} + \underbrace{f^{abc}G^aG^b\widetilde{G}^c + \bar{q}\sigma^{\mu\nu}i\gamma_5 G_{\mu\nu}q + \bar{q}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}q + \bar{e}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}e + \bar{q}q\bar{q}q + \bar{e}e\bar{q}q + \cdots}_{\text{BSM}}$$

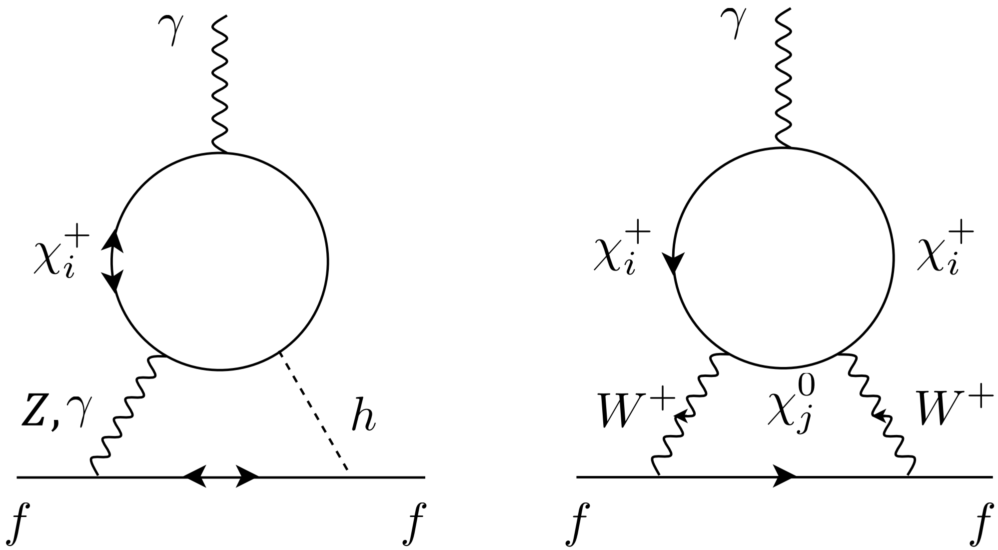
BSM example :
MSSM with a universal SUSY breaking scale



$$\tilde{d}_q \, g_s \, \bar{q}\sigma^{\mu\nu} i \, \gamma_5 G_{\mu\nu} q$$

Quark CEDMs domination

BSM example : Split supersymmetry

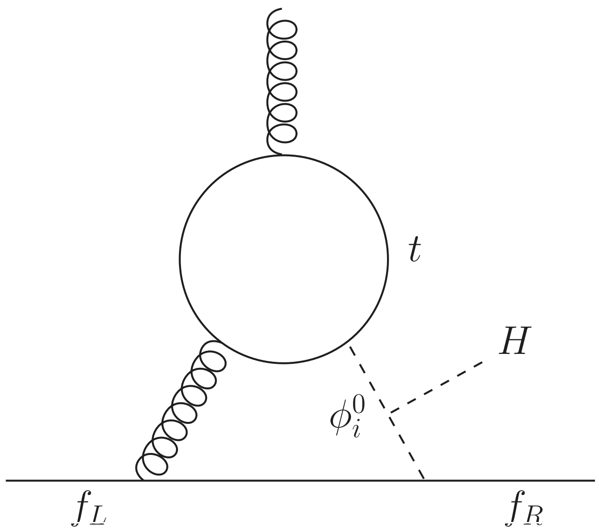


$$d_q\ \bar{q}\sigma^{\mu\nu} i\gamma_5 F_{\mu\nu} q + d_e\ \bar{e}\sigma^{\mu\nu} i\gamma_5 F_{\mu\nu} e$$

Quark EDMs and Electron EDM

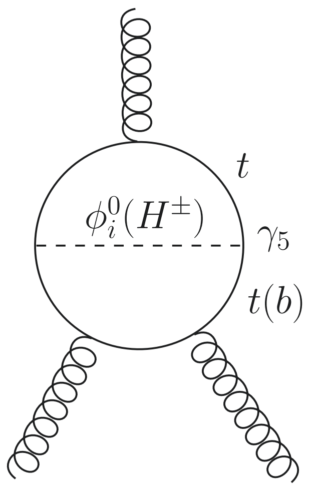
Giudice and Romanino '05

BSM example :
2 Higgs-doublet models



$\tilde{d}_q \, g_s \, \bar{q}\sigma^{\mu\nu} i \, \gamma_5 G_{\mu\nu} q$

Quark CEDMs

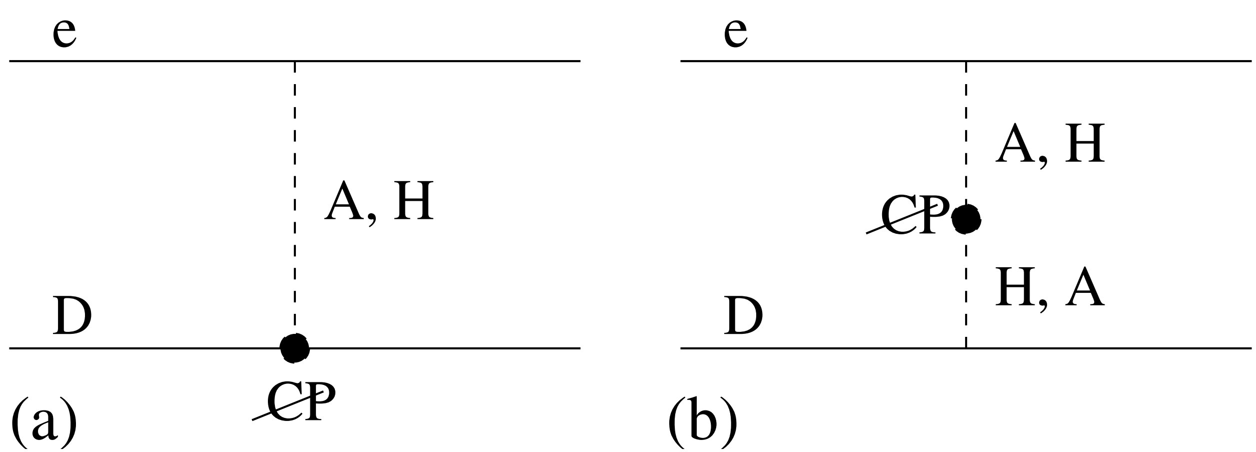


$w \, f^{abc} G^a G^b \tilde{G}^c$

Gluon CEDM
(Weinberg operator)

S. Weinberg '89, Gunion, Wyler '90
Chang, Keung, Yuan '90, Jung, Pich '14

BSM example :
SUSY or Type-II 2HDM with large tan β



$$C_{\bar{e}e\bar{d}d}\, i\bar{e}_L e_R \bar{d}_R d_L + \mathrm{h.}\,c.$$

Semi-leptonic 4-Fermi operator

Lebedev and Pospelov '02

BSM example: QCD axion

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

PQ breaking from quantum gravity

$$\bar{\theta}_{\rm QG} \sim \frac{f_a^{4+n}}{M_{\rm Pl}^n f_\pi^2 m_\pi^2} \sin\delta_{\rm QG1} + \kappa \frac{M_{\rm Pl}^4}{f_\pi^2 m_\pi^2} e^{-S_{\rm ins}} \sin\delta_{\rm QG2}$$

PQ breaking from hadronic BSM CP violation

$$\bar{\theta}_{\rm BSM} \sim \frac{\sum_i \int d^4x \left\langle \frac{g_s^2}{32\pi^2} G\tilde{G}(x) \mathcal{O}_i(0) \right\rangle}{f_\pi^2 m_\pi^2}$$

$$\mathcal{O}_i = \left\{ \tilde{d}_G GG\widetilde{G}, \tilde{d}_q \bar{q}\sigma^{\mu\nu} i\gamma_5 G_{\mu\nu} q, c_q \bar{q}q\bar{q}i\gamma_5 q, \cdots \right\}$$

- Both quantum gravity effect and hadronic BSM CP violation can be observed by a non-vanishing $\bar{\theta}$.
- They may be able to be distinguished from each other, since hadronic BSM CP violating operators themselves directly contribute to EDMs not only via $\bar{\theta}$.

Potentially dominant CPV operators around the QCD scale ~ 1 GeV

$$\frac{g_s^2}{32\pi^2}\bar{\theta}G\widetilde{G} + w\, f^{abc}G^aG^b\widetilde{G}^c + \tilde{d}_q\, g_s\, \bar{q}\sigma^{\mu\nu}i\gamma_5 G_{\mu\nu}q$$

$$+ d_q\, \bar{q}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}q + d_e\, \bar{e}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}eq + C_{\bar{e}e\bar{d}d}\, i\bar{e}e\bar{d}d + \bar{q}q\bar{q}q + \cdots$$

SM or QCD axion (first term) | BSM (remaining terms)

Key question: If non-vanishing EDMs are observed, can we experimentally determine the source of the CP violation among those different possible UV sources ?

cf) J de Vries et al 1109.3604, 1809.10143, 2107.04046

We are extending the previous studies, discussing identification of the PQ breaking source for a non-zero axion VEV for the first time and more comprehensively covering the leading operators.

Nucleon EDMs from hadronic CPV

Naïve dimensional analysis (NDA) e.g. S. Weinberg '89

$$d_N \sim \frac{em_*}{\Lambda_\chi^2}\,\bar{\theta} + \frac{e\Lambda_\chi}{4\pi} w + e\,\tilde{d}_q$$

$$\Lambda_\chi = 4\pi f_\pi$$

$$m_* \simeq \frac{m_u m_d}{m_u + m_d}$$

$$\simeq 0.4\times 10^{-16}\,[e\ \mathrm{cm}]\,\bar{\theta} + 92\ \mathrm{MeV}\ e\ w + e\,\tilde{d}_q$$

at $\mu = 225$ MeV

QCD sum rules

Pospelov, Ritz '99 Hisano, Lee, Nagata, Shimizu '12
Yamanaka, Hiyama '20

$$d_p = -0.47(26)\times 10^{-16}[e\,cm]\,\bar{\theta}\; - 18(11)\text{ MeV } e\,w$$

$$+\underbrace{e(-0.17(10)\,\tilde{d}_u + 0.12(7)\,\tilde{d}_d + 0.010(6)\,\tilde{d}_s)}_{0.32(18)\,e\,\tilde{d}_d}$$

assuming $\tilde{d}_d = \frac{m_d}{m_s}\tilde{d}_s \gg \tilde{d}_u$

$$d_n = 0.31(18)\times 10^{-16}[e\,cm]\,\bar{\theta} + 20(12)\text{MeV } e\,w$$

$$+\underbrace{e(-0.13(7)\,\tilde{d}_u + 0.16(9)\,\tilde{d}_d - 0.007(4)\,\tilde{d}_s)}_{0.029(29)\,e\,\tilde{d}_d}$$

at $\mu = 1$ GeV

Ratio from QCD sum rules (small error)

$$\frac{d_p}{d_n} \simeq -1.5\ (\text{from } \bar{\theta}),\ -0.9\ (\text{from } w),\ +11(2)\ (\text{from } \tilde{d}_q)$$

If the QCD axion exists,

$$\bar{\theta} = \frac{\langle a \rangle}{f_a} = \bar{\theta}_{\mathrm{QG}} + \frac{\Lambda_\chi^2}{4\pi} w + \frac{0.8\ \mathrm{GeV}^2}{2} \sum_q \frac{\tilde{d}_q}{m_q}$$

NDA QCD sum rule (Pospelov, Ritz '00)

$$d_p^{\mathrm{PQ}} = -0.46(26)\times 10^{-16}[e\ cm]\ \bar{\theta}_{\mathrm{QG}} - e\ 18(11)\ w\ \mathrm{MeV} - \underbrace{e(0.60(35)\ \tilde{d}_u + 0.07(4)\ \tilde{d}_d)}_{-e\ 0.07(4)\ \tilde{d}_d}$$

$\tilde{d}_d \gg \tilde{d}_u$

$$d_n^{\mathrm{PQ}} = 0.31(18)\times 10^{-16}[e\ cm]\ \bar{\theta}_{\mathrm{QG}} + e\ 20(12)\ w\ \mathrm{MeV} + \underbrace{e(0.15(9)\ \tilde{d}_u + 0.30(17)\ \tilde{d}_d)}_{+e\ 0.30(17)\ \tilde{d}_d}$$

Ratio from QCD sum rules (small error)

$$\left(\frac{d_p}{d_n}\right)^{\mathrm{PQ}} \simeq -1.5\ (\text{from } \bar{\theta}),\ -0.9\ (\text{from } w),\ -\frac{1}{4}\ (\text{from } \tilde{d}_q)$$

The prediction on the nucleon EDM ratio from QCD sum rules

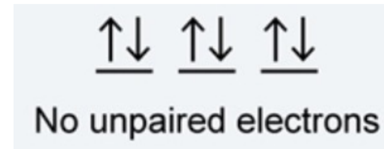
$$\frac{d_p}{d_n} \simeq -1.5 \text{ (from } \bar{\theta}), -0.9 \text{ (from } w), +11(2) \text{ (from } \tilde{d}_q)$$

$$\left(\frac{d_p}{d_n}\right)^{\mathrm{PQ}} \simeq -1.5 \text{ (from } \bar{\theta}), -0.9 \text{ (from } w), -0.25 \text{ (from } \tilde{d}_q)$$

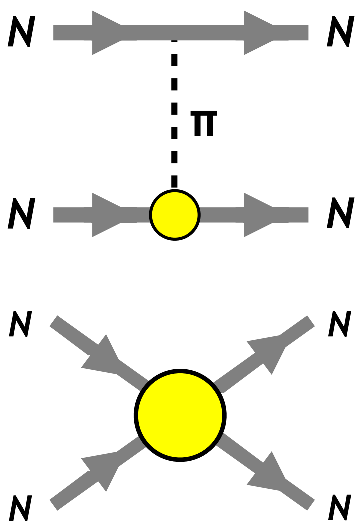
- Unfortunately it is difficult to estimate the theoretical uncertainty of the QCD sum rule approach itself.
- Nevertheless, if the measured ratio d_p/d_n is significantly different from -1, it indicates that the nucleon EDMs might be originated from quark CEDMs.
- Furthermore, we may be able to get a hint on the existence of the QCD axion from the measured nucleon EDM ratio.

EDMs of light nuclei and diamagnetic atoms

In diamagnetic atoms, all electrons are paired.



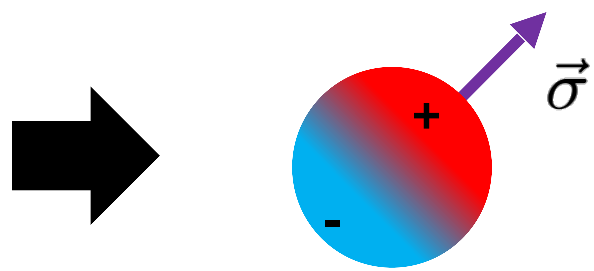
The permanent EDM of a diamagnetic atom or a nucleus is mainly from nucleon EDMs and permanent polarization of the nucleus due to P and CP-odd nuclear forces.



$$\bar{g}_0 \bar{N}\, \vec{\tau} \cdot \vec{\pi}\, N$$
$$+\bar{g}_1 \pi^3 \bar{N} N$$

$$C_1 \bar{N} N\, D_\mu (N^+ S^\mu N)$$
$$+C_2 \bar{N} \vec{\tau} N \cdot D_\mu (N^+ \vec{\tau}\, S^\mu N)$$

P and CP-odd nuclear forces



Polarization of nucleus
→ *Atomic electric dipole moment*

$\bar{g}_1 \pi^3 \bar{N} N$ from hadronic CPV

NDA $\quad \bar{g}_1 \sim 4\pi \frac{(m_u - m_d)}{m_s} \frac{m_*}{\Lambda_\chi} \bar{\theta} + (m_u - m_d)\Lambda_\chi w + 4\pi \Lambda_\chi (\tilde{d}_u - \tilde{d}_d)$

Agrees more or less

χPT & QCD sum rules;
(Osamura, Gubler, Yamanaka '22)

$$\bar{g}_1 = (3.4 \pm 2.4)\times 10^{-3}\bar{\theta} \pm (2.2 \pm 1.6)\times 10^{-3}\,\mathrm{GeV}^2 w$$

$$+(28 \pm 12)\,\mathrm{GeV}\,(\tilde{d}_u - \tilde{d}_d)$$

χPT & baryon spectrum;
(de Vries, Mereghetti, Walker-Loud '15)

χPT & QCD sum rules;
(de Vries et al '21)

Light nuclei

Bsaisou, Meissner, Nogga, Wirzba '14

$$d_D = 0.94(1)(d_n + d_p) + 0.18(2)\bar{g}_1\, e\,\mathrm{fm}$$

$$d_{\mathrm{He}} = 0.9 d_n - 0.03(1) d_p + \left[0.11(1)\bar{g}_0 + 0.14(2)\bar{g}_1 - (0.04(2)C_1 - 0.09(2)C_2)\,\mathrm{fm}^{-3}\right] e\,\mathrm{fm}$$

Diamagnetic atoms with heavy nuclei

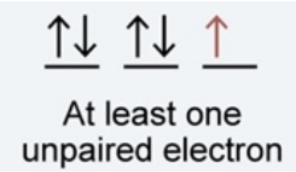
e.g.) Engel, Ramsey-Musolf, Kolck '13
Fleig, Jung '18

$$d_{\mathrm{Hg}} = -2.1(5)\cdot 10^{-4}\left[1.9(1)d_n + 0.20(6)d_p + \left(0.13^{+0.5}_{-0.07}\,\bar{g}_0 + 0.25^{+0.89}_{-0.63}\,\bar{g}_1\right) e\,\mathrm{fm}\right]$$

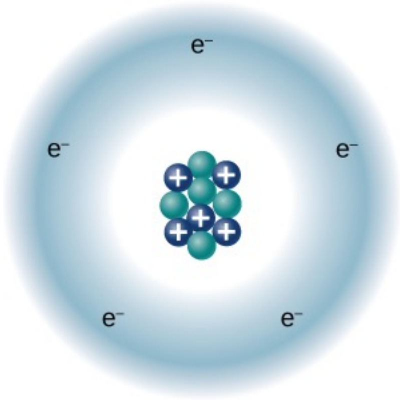
$$d_{\mathrm{Ra}} = 7.7\times 10^{-4}\left[(2.5\pm 7.5)\bar{g}_0 - (65\pm 40)\bar{g}_1 - (1.1(3.3)C_1 - 3.2(2.1)C_2)\,\mathrm{fm}^{-3}\right] e\,\mathrm{fm}$$

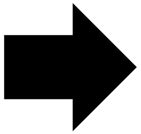
EDMs of paramagnetic molecules and atoms

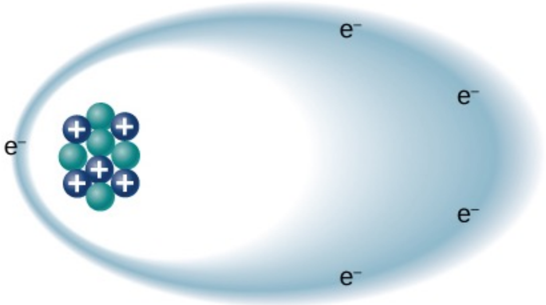
In paramagnetic systems, there is at least one unpaired electron.



The permanent EDM of a paramagnetic system is mainly from electron EDM and permanent polarization of the system due to P and CP-odd electron-nucleon interactions.







P and CP-odd electron-nucleon interactions

unpolarized

$$C_S\, \bar{e}\, i\gamma^5 e \bar{N} N$$

polarized

Polar molecules

e.g.) Fleig, Jung '18

$$\omega_{\mathrm{HfF}^+} = 3.49(14) \cdot 10^{28}\, d_e [\mathrm{mrad/s}][e\,\mathrm{cm}]^{-1} + 3.20(13) \cdot 10^{8}\, C_S [\mathrm{mrad/s}]$$

$$\omega_{\mathrm{ThO}} = 1.206(49) \cdot 10^{29}\, d_e [\mathrm{mrad/s}][e\,\mathrm{cm}]^{-1} + 1.816(73) \cdot 10^{9}\, C_S [\mathrm{mrad/s}]$$

$$\omega_{\mathrm{YbF}} = 1.96(15) \cdot 10^{28}\, d_e [\mathrm{mrad/s}][e\,\mathrm{cm}]^{-1} + 1.76(20) \cdot 10^{8}\, C_S [\mathrm{mrad/s}]$$

EDM inverse problem

Paramagnetic atoms/molecules	d_e, C_S $(\bar{e}e\bar{N}N)$
Light nuclei and diamagnetic atoms	$d_n, d_p, \bar{g}_0, \bar{g}_1, C_1, C_2$ $(\pi\bar{N}N)$ $(\bar{N}N\bar{N}N)$

Total 8 independent observables

$$X_{\text{CPV source}} \in \{d_e, C_{\bar{e}e\bar{d}d}, \bar{\theta}, w, \tilde{d}_u, \tilde{d}_d, d_u, d_d\}$$

8 potentially important UV CP-violating sources

Determining d_e and C_S with paramagnetic systems

Using HfF^+ and ThO, $$\begin{pmatrix} \omega_{\mathrm{HfF^+}} \\ \omega_{\mathrm{ThO}} \end{pmatrix} [\mathrm{mrad/s}]^{-1} = \mathcal{M}_{\mathrm{HT}} \begin{pmatrix} d_e\,[e\,\mathrm{cm}]^{-1} \\ C_S \end{pmatrix}$$

$$\mathcal{M}_{\mathrm{HT}} = \begin{pmatrix} 3.49(14)\cdot 10^{28} & 3.20(13)\cdot 10^{8} \\ 1.206(49)\cdot 10^{29} & 1.816(73)\cdot 10^{9} \end{pmatrix} \qquad \mathrm{Det}(\mathcal{M}_{\mathrm{HT}}) = 2.5(4)\cdot 10^{37}$$

Invertible

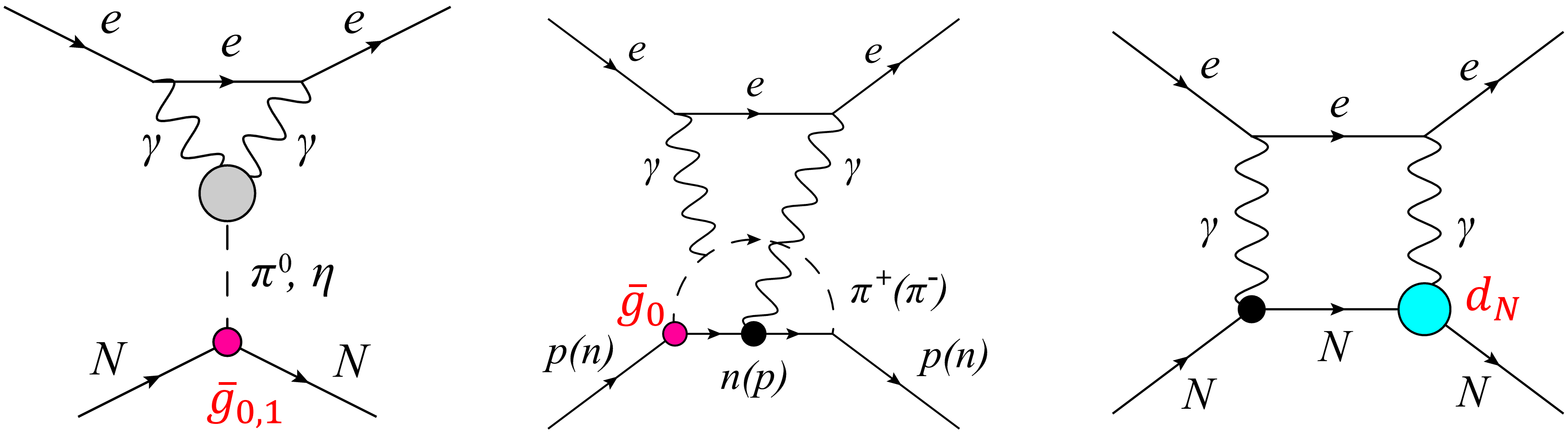
Measurements of two different paramagnetic EDMs can successfully determine d_e and C_S.

However, if a non-zero C_S is discovered, C_s can be either from $C_{\bar{e}e\bar{d}d}$ or hadronic sources.

$$C_S = C_S(C_{\bar{e}e\bar{d}d}, \bar{g}_0, \bar{g}_1, d_n, d_p)$$

C_S from hadronic sources

V Flambaum, M Pospelov, A Ritz, Y Stadnik '19



$$C_S = C_S(\bar{g}_0, \bar{g}_1, d_n, d_p)$$

If a non-zero C_S originates from these hadronic sources, there must be correspondingly sizable EDMs of light nuclei and diamagnetic systems, while it's not the case if C_S is from $C_{\bar{e}e\bar{d}d}$.

Disentangling hadronic sources with light nuclei and diamagnetic atoms

$$d_A = d_A(d_n, d_p, \bar{g}_0, \bar{g}_1, C_1, C_2)$$

6 independent observables

⬇

$$X_{\mathrm{CPV\ source}} \in \{\bar{\theta}, w, \tilde{d}_u, \tilde{d}_d, d_u, d_d\}$$

6 potentially important hadronic UV sources

However, the 4-nucleon contact interactions C_1 and C_2 can be shown to be sizable only from the gluon CEDM (Weinberg operator) by chiral symmetry properties: $C_1 = C_1(w)$ and $C_2 = C_2(w)$ are not independent effectively

In principle, we cannot fully disentangle hadronic UV sources more than 5.

A motivated class of BSM scenarios is that CP violation from new physics is mediated to the SM sector dominantly by color and Higgs interactions.

Barbieri, Pomarol, Rattazi, Strumia '04
Cirigliano et al '19
K Choi, SHI, K Jodlowski '23

Ex) MSSM with a universal SUSY breaking scale, Split SUSY with a light gluino, 2 HDMs, Vector-like quarks, etc

Also assuming $\tilde{d}_d \sim \frac{m_d}{m_u} \tan\beta \, \tilde{d}_u \gg \tilde{d}_u$,

$$X_{\text{CPV source}} \in \{\bar{\theta}, w, \tilde{d}_d\}$$

Using three systems, e.g. (d_n, d_D, d_{He}),

$$\begin{pmatrix} d_n \\ d_D \\ d_{\mathrm{He}} \end{pmatrix} [e\,\mathrm{cm}]^{-1} = \mathcal{M}_{\mathrm{nDHe}} \begin{pmatrix} \bar{\theta} \\ w\,[\mathrm{GeV}]^2 \\ \tilde{d}_d\,[\mathrm{GeV}] \end{pmatrix}$$

$5.9(34) \cdot 10^{-15}$

with QCD axion

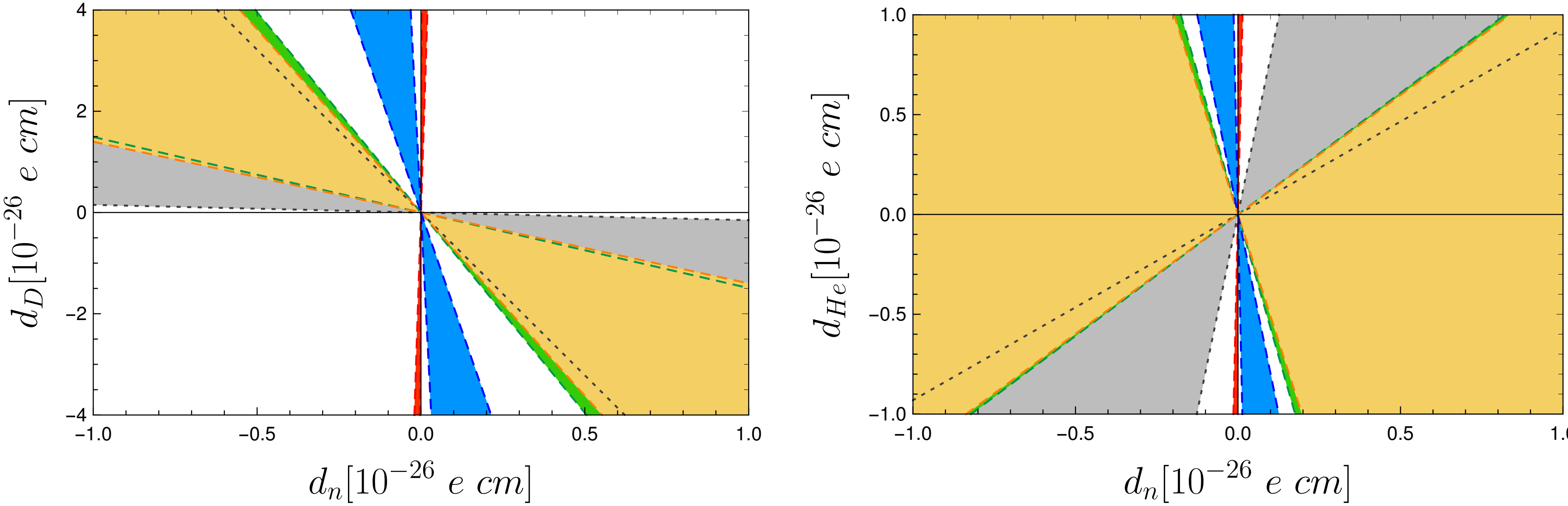
$$\mathcal{M}_{\mathrm{nDHe}} = \begin{pmatrix} 3.1(18) \cdot 10^{-17} & 4.0(24) \cdot 10^{-16} & 6(6) \cdot 10^{-16} \\ -8(4) \cdot 10^{-17} & -6.2(25) \cdot 10^{-16} & -6.8(25) \cdot 10^{-13} \\ 1.5(5) \cdot 10^{-16} & 0.9(31) \cdot 10^{-16} & -5.4(20) \cdot 10^{-13} \end{pmatrix}$$

$$\mathrm{Det}(\mathcal{M}_{\mathrm{nDHe}}) = -4.5(35) \cdot 10^{-44}$$

Invertible

Predicted ratios d_D/d_n and d_{He}/d_n

K Choi, SHI, K Jodlowski '23



Gray: $\bar{\theta}$ Blue: $\tilde{d}_q$ (with QCD axion)

Brown: w Red: $\tilde{d}_q$ (without QCD axion)

The precision measurements of $\mathrm{n}, \mathrm{D}, \mathrm{He}$ EDMs may tell us which is the origin of the EDMs among $\bar{\theta}, w, \tilde{d}_d$ as well as indicating whether there exists QCD axion or not.

Considering the UV sources (d_u, d_d) (e.g. typical split SUSY) instead of $\tilde{d}_q$,

$$X_{\text{CPV source}} \in \{\bar{\theta}, w, d_u, d_d\}$$

Using the nucleons and light nuclei (d_n, d_p, d_D, d_{He}), and the lattice results for $d_N(d_u, d_d)$, R Gupta et al '18, Alexandrou et al '20

$$\begin{pmatrix} d_n \\ d_p \\ d_D \\ d_{\text{He}} \end{pmatrix} [e\,\text{cm}]^{-1} = \mathcal{M}_{\text{npDHe}} \begin{pmatrix} \bar{\theta} \\ w\,[\text{GeV}]^2 \\ d_u\,[\text{GeV}] \\ d_d\,[\text{GeV}] \end{pmatrix}$$

$$\mathcal{M}_{\text{npDHe}} = \begin{pmatrix} 3.1(18)\cdot 10^{-17} & 4.0(24)\cdot 10^{-16} & -1.78(9)\cdot 10^{-15} & 7.1(4)\cdot 10^{-15} \\ -4.7(26)\cdot 10^{-17} & -3.6(21)\cdot 10^{-16} & 7.1(4)\cdot 10^{-15} & -1.78(9)\cdot 10^{-15} \\ -8(4)\cdot 10^{-17} & -6.2(25)\cdot 10^{-16} & 5.02(26)\cdot 10^{-15} & 5.02(26)\cdot 10^{-15} \\ 1.5(5)\cdot 10^{-16} & 0.9(31)\cdot 10^{-16} & -1.82(9)\cdot 10^{-15} & 6.47(32)\cdot 10^{-15} \end{pmatrix}$$

$$\text{Det}(\mathcal{M}_{\text{npDHe}}) = -4.7(34)\cdot 10^{-60}$$ Invertible

Most generally for 5 different UV sources, e.g.

$$X_{\rm CPV} \in \{\bar{\theta}, w, \tilde{d}_d, d_u, d_d\}$$

We need EDM data on another light nucleus or a diamagnetic system.

Unfortunately (to our knowledge) no other theoretical computation of another light nucleus for the moment (except ^3H which shares the structure of *He* and so doesn't help),
And heavy diamagnetic atoms are subject to large theoretical uncertainties, not currently allowing to disentangle 5 UV sources.

$$d_{\rm Hg} = -2.1(5)\cdot 10^{-4}\left[1.9(1)d_n + 0.20(6)d_p + \left(0.13^{+0.5}_{-0.07}\,\bar{g}_0 + 0.25^{+0.89}_{-0.63}\,\bar{g}_1\right) e\,{\rm fm}\right]$$

$$d_{\rm Ra} = 7.7\times 10^{-4}\left[(2.5\pm 7.5)\bar{g}_0 - (65\pm 40)\bar{g}_1 - ((1.1\pm 3.3)C_1 - 3.2(21)C_2)\,{\rm fm}^{-3}\right] e\,{\rm fm}$$

Improving these uncertainties to be below 20% may render the system invertible.

Conclusions

- Nuclear, atomic, and molecular permanent EDMs are powerful probes for BSM above TeV scale.
- A key question is the feasibility of identifying the UV source of CP violation via EDM measurements: "The EDM inverse problem"
- In particular, we examine whether the source of the QCD axion VEV can be identified from future EDM data.
- We find that the BSM CPV dominated by gluon or quark CEDMs with/without QCD axion can be experimentally distinguished from the θ-dominant CPV by characteristic nuclear and atomic EDM ratios.
- Generally future EDM data and improvement of theoretical computation of EDMs may disentangle $d_e, C_{\bar{e}e\bar{d}d}$, and 5 hadronic UV sources like $(\bar{\theta}, w, d_u, d_d, \tilde{d}_d)$.

Back-up: NDA estimations

$$d_N \sim e \frac{m_*}{\Lambda_\chi^2}\, \bar{\theta} + e \frac{\Lambda_\chi}{4\pi} w + e\, \tilde{d}_q + d_q$$

$$\Lambda_\chi = 4\pi f_\pi$$

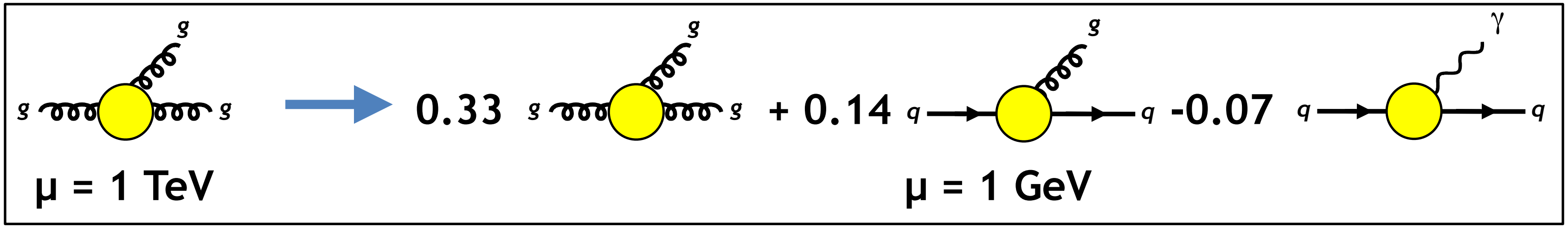
$$m_* \equiv \left(tr M_q^{-1}\right)^{-1} \simeq \frac{m_u m_d}{m_u + m_d}$$

$$\bar{g}_0 \sim 4\pi \frac{m_*}{\Lambda_\chi}\, \bar{\theta} + (m_u + m_d)\Lambda_\chi w + 4\pi\, \Lambda_\chi (\tilde{d}_u + \tilde{d}_d)$$

$$\bar{g}_1 \sim 4\pi \frac{(m_u - m_d)}{m_s} \frac{m_*}{\Lambda_\chi}\, \bar{\theta} + (m_u - m_d)\Lambda_\chi w + 4\pi\, \Lambda_\chi (\tilde{d}_u - \tilde{d}_d)$$

$$C_1 \sim C_2 \sim \frac{4\pi}{\Lambda_\chi} w$$

RGE effect



(Adapted from Nodoka Yamanaka)

$$\Delta\tilde{d}_q(1\ \text{GeV}) \simeq -r\, m_q\, w(1\ \text{GeV})$$

$$r = 0.41\ (\Lambda_{\text{BSM}} = 1\ \text{TeV}),\ 0.54\ (\Lambda_{\text{BSM}} = 10\ \text{TeV})$$

The radiatively induced quark-CEDM from the gluon CEDM is important (even dominant) for $\bar{g}_1$, while not for d_N :

NDA

$$\bar{g}_1 \sim 4\pi \frac{(m_u - m_d)}{m_s}\frac{m_*}{\Lambda_\chi}\bar{\theta} + (m_u - m_d)\Lambda_\chi w + 4\pi\,\Lambda_\chi\,(\tilde{d}_u - \tilde{d}_d)$$

$$d_N \sim \frac{e m_*}{\Lambda_\chi^2}\bar{\theta} + \frac{e\Lambda_\chi}{4\pi} w + e\,\tilde{d}_q$$