기초과학연구원 Institute for Basic Science

The EDM inverse problem: Disentangling 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, Krzysztof Jodlowski, in preparation

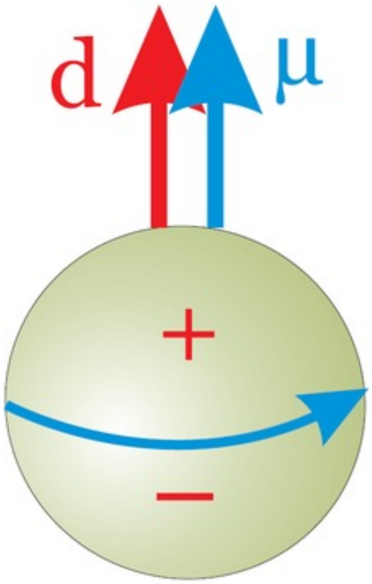
20^{th} Renconstres du Vietnam: The Axion Quest
ICISE, Quy Nhon, Vietnam / Aug 9, 2024

Outline

- CP violation and electric dipole moments (EDMs)
- CP violating (and/or PQ breaking) UV sources
- EDMs of light nuclei, diamagnetic atoms, and paramagnetic molecules / atoms
- Disentangling UV sources by measurements of the EDMs

EM 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.



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

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

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

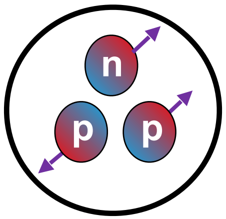
CP violation is an important condition to generate the asymmetry between matter and antimatter.

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

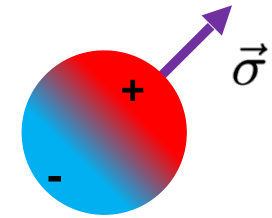
SM prediction : $$Y_{B,\,\mathrm{SM}} \lesssim 10^{-15}$$

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

SM does not provide an enough CP violation, and we need new physics beyond the SM involving additional CP violation.



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

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

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

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

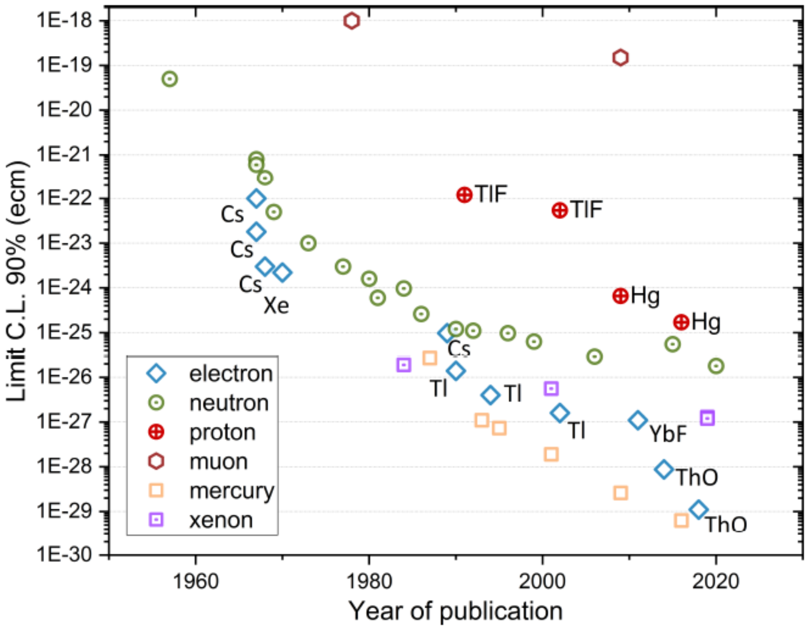
$$d_N \sim \frac{1}{16\pi^2}\frac{f_\pi}{\Lambda_{\mathrm{BSM}}^2}$$
$$d_e \sim \frac{1}{16\pi^2}\frac{m_e}{\Lambda_{\mathrm{BSM}}^2}$$

$\Lambda_{\mathrm{BSM}} \gtrsim O(10{\sim}100)$ TeV

Powerful probe for new physics!

Experimental prospect

2003.00717



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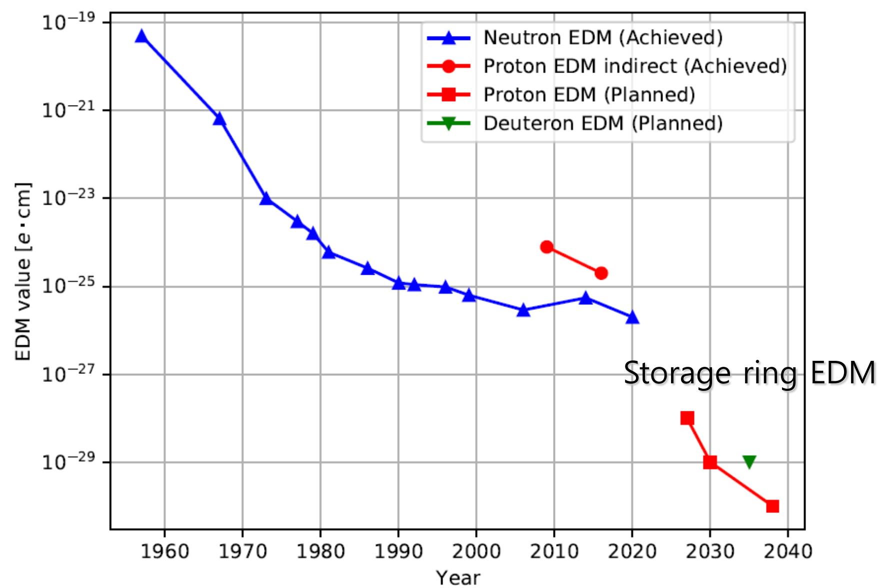


In a decade, the experimental sensitivity on EDMs of electrons, nucleons, atoms, and molecules is going to be improved by several orders of magnitude.

CP violating UV sources

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

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

EWSB and integrating out heavy SM fields

Around the QCD scale ~ 1 GeV

Gluon Chromo-EDM (Weinberg operator)

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

Quark Chromo-EDMs (CEDMs)

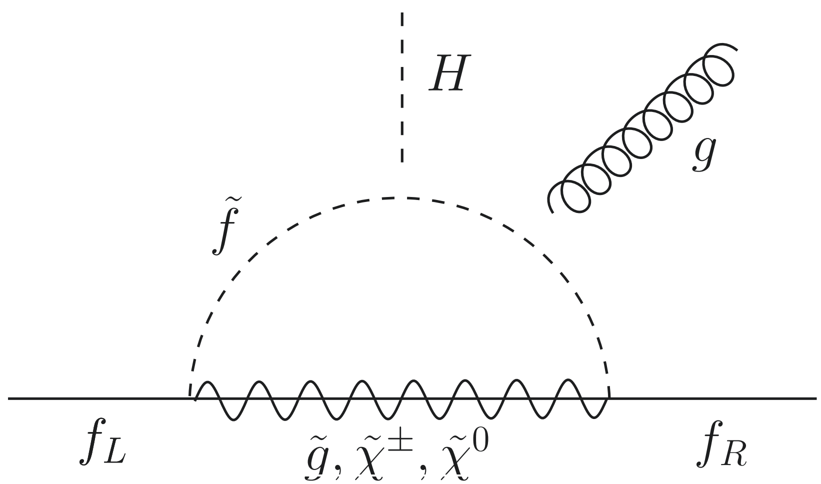
$$+ \bar{q}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}q + \bar{e}\sigma^{\mu\nu}i\gamma_5 F_{\mu\nu}e + \bar{q}q\bar{q}q + \bar{e}e\bar{q}q$$

Quark EDMs — Electron EDM — 4-Fermi operators

Potentially dominant CPV operators around the QCD scale ~ 1 GeV

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

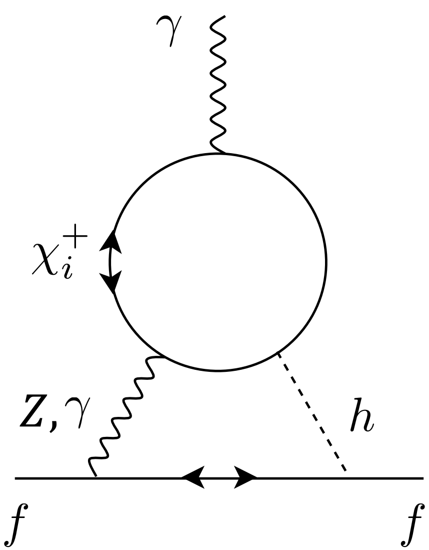
BSM example :
MSSM with a universal SUSY breaking scale

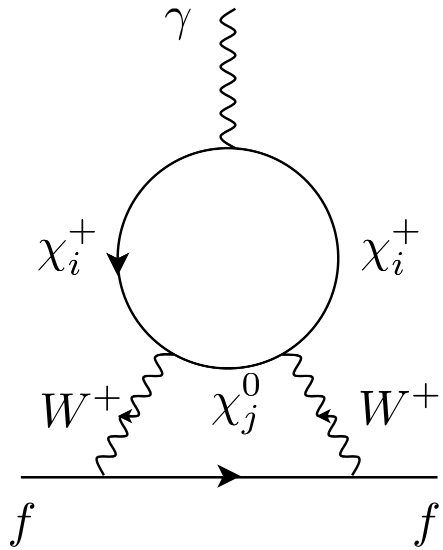


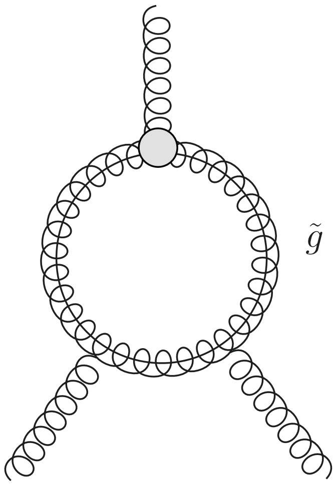
$$\bar{q}\sigma^{\mu\nu} i\gamma_5 G_{\mu\nu} q$$

Quark CEDMs domination

BSM example : Split supersymmetry







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

$$f^{abc}G^a G^b \widetilde{G}^c$$

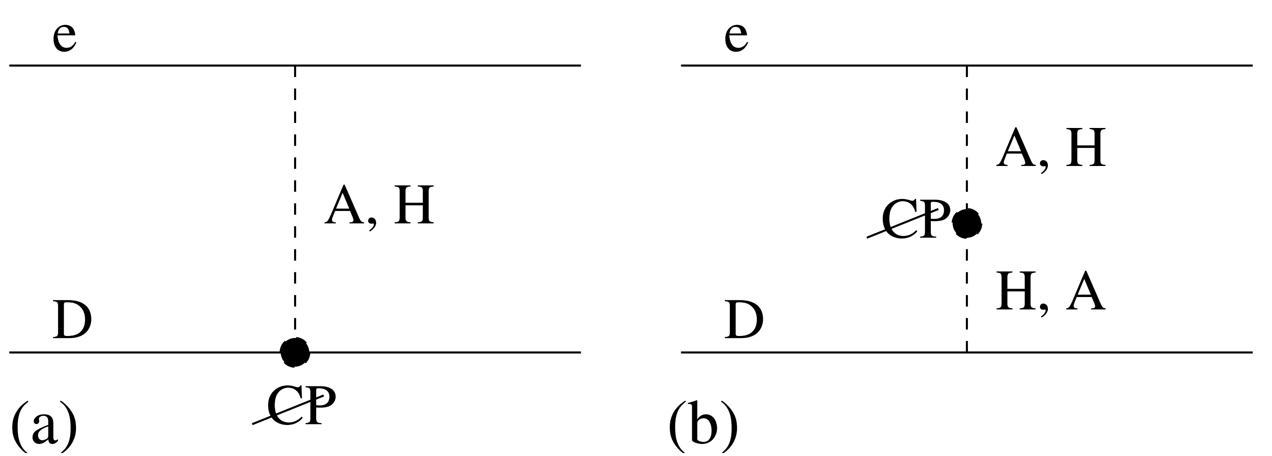
Quark and Electron EDMs

Gluon CEDM

Giudice and Romanino '05

Hisano, Kobayashi, Kuramoto, Kuwahara '15

BSM example :
Split supersymmetry with large tan β

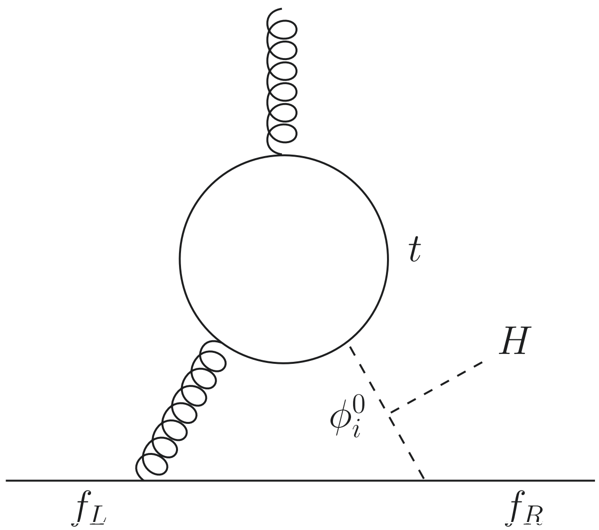


$$\bar{e}_L e_R \bar{d}_R d_L$$

Semi-leptonic 4-Fermi operator

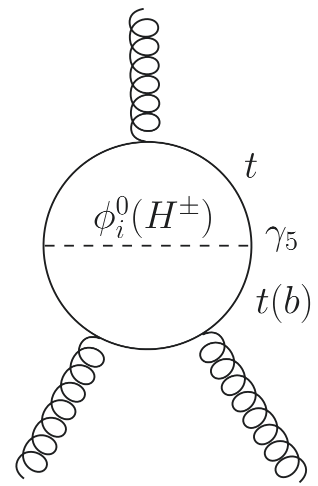
Lebedev and Pospelov ‘02

BSM example : 2 Higgs-doublet models



$\bar{q}\sigma^{\mu\nu} i\gamma_5 G_{\mu\nu} q$

Quark CEDMs



$f^{abc} G^a G^b \widetilde{G}^c$

Gluon CEDM

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

BSM example: QCD axion

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

K. Choi's talk

PQ breaking from quantum gravity

$$\bar{\theta}_{\rm UV} \sim \frac{f_a^{4+n}}{M_{\rm Pl}^n f_\pi^2 m_\pi^2} \sin\delta_{\rm QG1} + \frac{m_{3/2} M_{\rm Pl}^3}{f_\pi^2 m_\pi^2} e^{-S_{\rm ins}} \sin\delta_{\rm QG2}$$

PQ breaking from hadronic BSM CP violation

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

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

Hadronic BSM CP violation induces a non-zero $\bar{\theta}$ as well as directly contributing to nuclear and atomic EDMs, while the quantum gravity effects appear only through $\bar{\theta}$.

Potentially dominant CPV operators around the QCD scale ~ 1 GeV

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

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, including the PQ quality issue and comprehensive coverage of the leading operators.

CP-violating observables at nuclear level

$$\mathcal{L}_{\rm dipole} = -\frac{i}{2}d_n\bar{n}\sigma^{\mu\nu}F_{\mu\nu}\gamma_5 n - \frac{i}{2}d_p\bar{p}\sigma^{\mu\nu}F_{\mu\nu}\gamma_5 p - \frac{i}{2}d_e\,\bar{e}\,\sigma^{\mu\nu}F_{\mu\nu}\gamma_5 e$$

$$\mathcal{L}_{\pi N} = \bar{g}_0\bar{N}\vec{\tau}\cdot\vec{\pi}N + \bar{g}_1\pi_3\bar{N}N \qquad N = \begin{pmatrix} p \\ n \end{pmatrix}$$

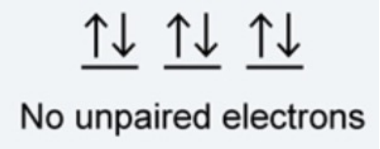
$\vec{\tau}$ =isospin Pauli matrices

$$\mathcal{L}_{4N} = C_1\bar{N}ND_\mu(N^\dagger S^\mu N) + C_2\bar{N}\vec{\tau}N\cdot D_\mu(N^\dagger\vec{\tau}S^\mu N)$$

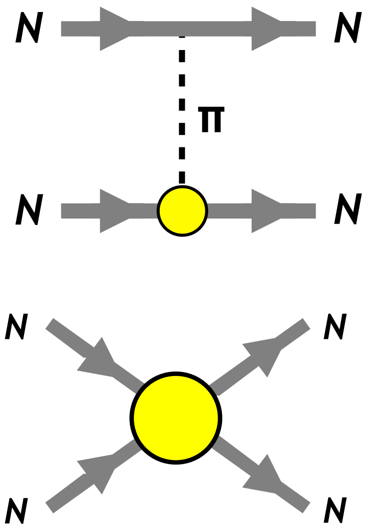
$$\mathcal{L}_{eN} = -\frac{G_F}{\sqrt{2}}(\bar{e}i\gamma_5 e)\bar{N}(C_S^{(0)} + C_S^{(1)}\tau_3)N + \frac{8G_F}{\sqrt{2}}(\bar{e}\sigma^{\mu\nu}e)\bar{N}(C_T^{(0)} + C_T^{(1)}\tau_3)S_\mu v_\nu N$$
$$-\frac{G_F}{\sqrt{2}}(\bar{e}e)\frac{\partial^\mu}{m_N}\left[\bar{N}(C_P^{(0)} + C_P^{(1)}\tau_3)S_\mu N\right]$$

EDMs of light nuclei and diamagnetic atoms

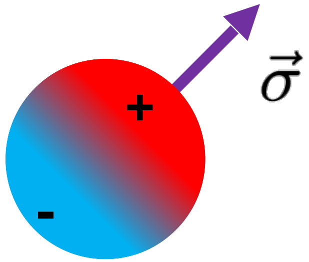
In diamagnetic systems, all electrons are paired.



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



P and CP-odd nuclear forces



Polarization of nucleus
→ *Atomic electric dipole moment*

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

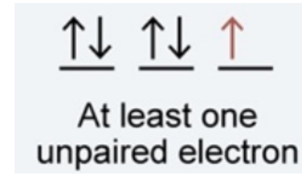
e.g.) Engel, Ramsey-Musolf, Kolck '13
Fleig, Jung '18

$$d_{\mathrm{Hg}} = -2.1(5)\cdot 10^{-4}\left[1.9(1)d_n + 0.20(6)d_p + \left(0.13^{+0.5}_{-0.07}\,\bar{g}_0 + 0.25^{+0.89}_{-0.63}\,\bar{g}_1\right) e\,\mathrm{fm}\right] -0.012(12)d_e + \left[-0.028(6)C_S + 6\cdot 10^{-3}C_P + 1.7C_T\right]\times 10^{-7} e\,\mathrm{fm}$$

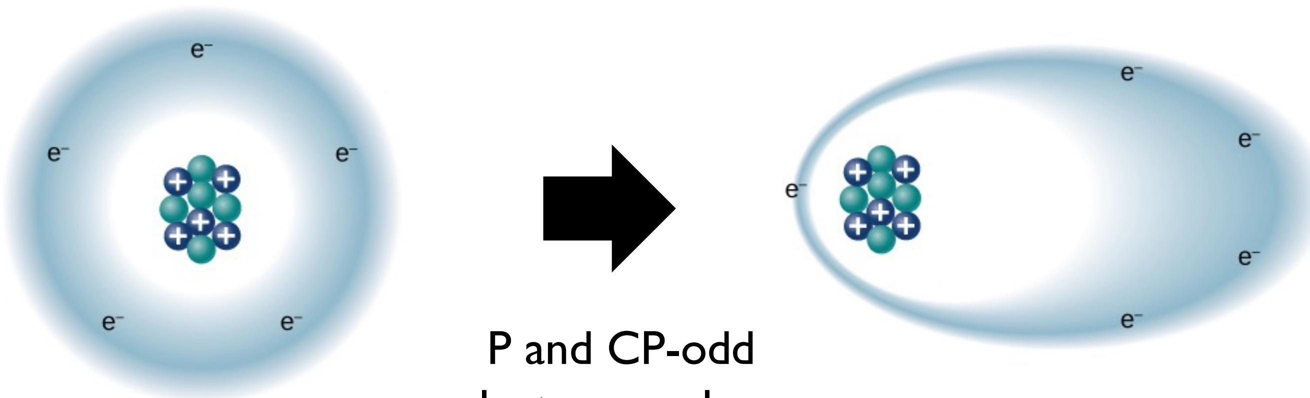
$$d_{\mathrm{Ra}} = 7.7\times 10^{-4}\left[(2.5\pm 7.5)\bar{g}_0 - (65\pm 40)\bar{g}_1 - (1.1(3.3)C_1 - 3.2(2.1)C_2)\,\mathrm{fm}^{-3}\right] e\,\mathrm{fm} -0.054(2)d_e + \left[0.029C_S - 6.4\cdot 10^{-3}C_P - 1.8C_T\right]\cdot 10^{-6} e\,\mathrm{fm}$$

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.



unpolarized

P and CP-odd electron-nucleon interactions

polarized

Polar molecules

e.g.) Fleig, Jung '18

$$\omega_{\mathrm{HfF}^+} = 3.49(14)\cdot 10^{28}\, d_e[\mathrm{mrad/s}][e\,\mathrm{cm}]^{-1} + 3.20(13)\cdot 10^{8}\, C_S[\mathrm{mrad/s}]$$
$$\omega_{\mathrm{ThO}} = 1.206(49)\cdot 10^{29}\, d_e[\mathrm{mrad/s}][e\,\mathrm{cm}]^{-1} + 1.816(73)\cdot 10^{9}\, C_S[\mathrm{mrad/s}]$$
$$\omega_{\mathrm{YbF}} = 1.96(15)\cdot 10^{28}\, d_e[\mathrm{mrad/s}][e\,\mathrm{cm}]^{-1} + 1.76(20)\cdot 10^{8}\, C_S[\mathrm{mrad/s}]$$

$$C_S \equiv C_S^{(0)} + \frac{Z-N}{Z+N} C_S^{(1)} \qquad \frac{Z-N}{Z+N} = 0.20 \pm 0.03$$

almost system-independent

Paramagnetic atoms

e.g.) Fleig, Skripnikov '20
Degenkolb et al '24
Shitara et al '21

$$d_{\mathrm{Tl}} = -558(28) d_e + \left(-0.68 C_S + 1.5\cdot 10^{-6} C_P + 0.5\cdot 10^{-3} C_T\right)\cdot 10^{-4} e\,\mathrm{fm}$$
$$d_{\mathrm{Cs}} = 123(4) d_e + \left(0.78 C_S + 2.2\cdot 10^{-5} C_P + 0.92\cdot 10^{-2} C_T\right)\cdot 10^{-5} e\,\mathrm{fm}$$
$$d_{\mathrm{Fr}} = 799(24) d_e + 1.05(3) C_S \cdot 10^{-4} e\,\mathrm{fm}$$

Measurable quantities at nuclear level

Paramagnetic systems

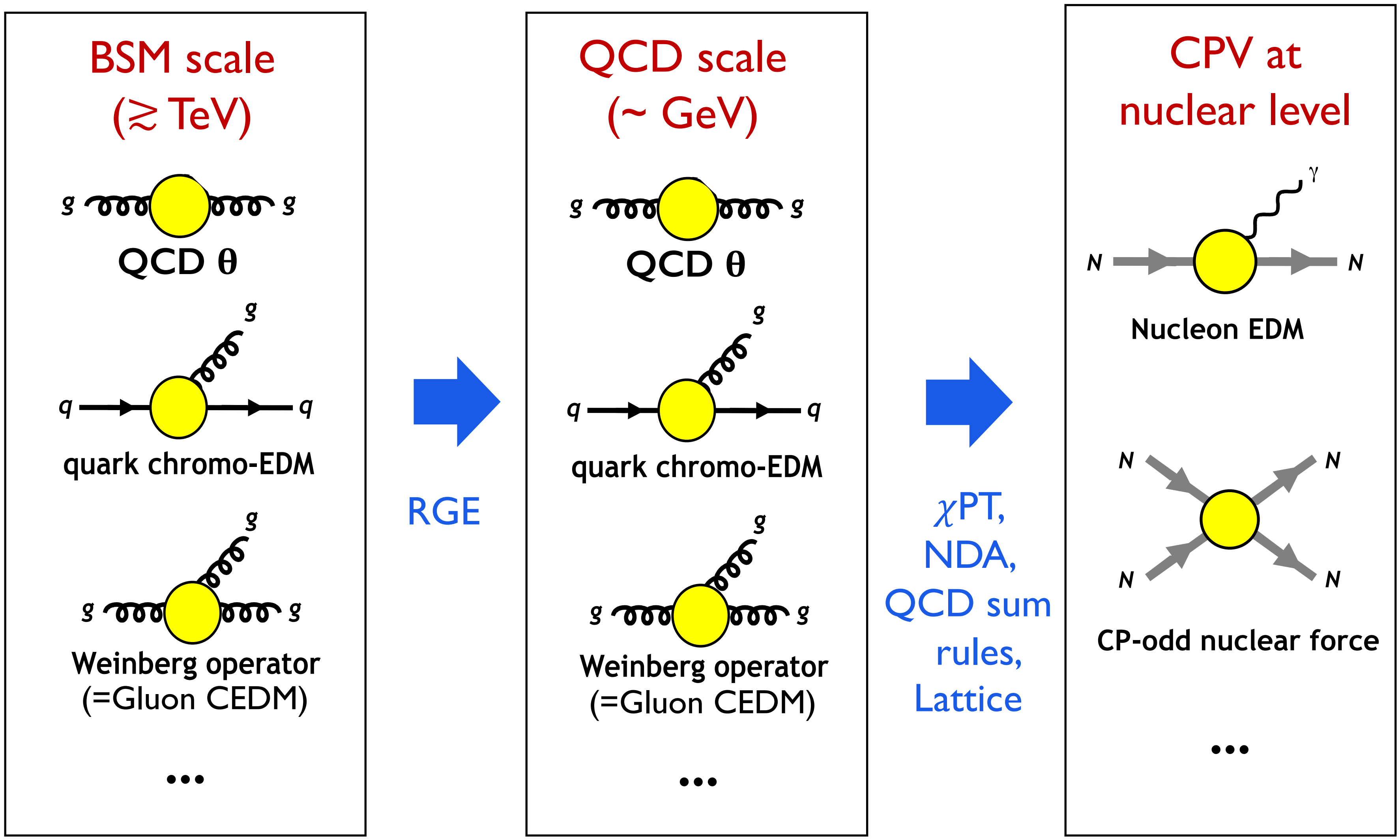
$$d_e, C_S \quad (\mathrm{ee}NN)$$

Light nuclei and diamagnetic systems

$$d_n, d_p, \bar{g}_0, \bar{g}_1, C_1, C_2$$

$$(\pi NN) \qquad (NNNN)$$

From BSM scale to nuclear CPV observables



Estimation of the nucleon EDMs

Naïve dimensional analysis (NDA) (at $\mu = 225$ MeV)

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

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

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

Agrees more or less

QCD sum rules (at $\mu = 1$ GeV)

Pospelov, Ritz '99
Hisano, Lee, Nagata, Shimizu '12
Hisano, Kobayashi, Kuramoto, Kuwahara '15
Yamanaka, Hiyama '20

$$d_p = -0.46\times10^{-16}[e\,cm]\,\bar{\theta} - e\,18\,w\,\mathrm{MeV} + \underbrace{e(-0.17\,\tilde{d}_u + 0.12\,\tilde{d}_d + 0.0098\,\tilde{d}_s)}_{+e(1.1\ \mathrm{MeV})K_2}$$

$$\tilde{d}_q \equiv m_q K_2$$

$$d_n = 0.31\times10^{-16}[e\,cm]\,\bar{\theta} + e\,20\,w\,\mathrm{MeV} + \underbrace{e(-0.13\,\tilde{d}_u + 0.16\,\tilde{d}_d - 0.0066\,\tilde{d}_s)}_{-e(0.15\ \mathrm{MeV})K_2}$$

$\Rightarrow$ $d_p(\bar{\theta}, w) \approx -d_n(\bar{\theta}, w)$ while $d_p(\tilde{d}_q) \approx -7 d_n(\tilde{d}_q)$

If there exists the QCD axion (i.e. dynamical $\bar{\theta}$),

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

NDA

QCD sum rule (Pospelov, Ritz '00)

$$d_p^{PQ} = -0.46\times 10^{-16}[e\ cm]\ \bar{\theta}_{\rm UV} - e\ 18\ w\ {\rm MeV} - \underbrace{e(0.58\ \tilde{d}_u + 0.073\ \tilde{d}_d)}_{-e(1.7\ {\rm MeV})K_2}$$

$$\tilde{d}_q \equiv m_q K_2$$

$$d_n^{PQ} = 0.31\times 10^{-16}[e\ cm]\ \bar{\theta}_{\rm UV} + e\ 20\ w\ {\rm MeV} + \underbrace{e(0.15\ \tilde{d}_u + 0.29\ \tilde{d}_d)}_{+e(1.7\ {\rm MeV})K_2}$$

➡ $d_p^{PQ} \approx -d_n^{PQ}$ regardless of the 3 hadronic CPV sources

$$\boxed{\bar{g}_1 \bar{N} \pi_3 N}$$

NDA $\quad \bar{g}_1 \sim 4\pi \frac{(m_u - m_d) m_*}{\Lambda_\chi^2} \bar{\theta} + (m_u - m_d)\Lambda_\chi w + \Lambda_\chi (\tilde{d}_u - \tilde{d}_d)$

χPT & QCD sum rules;
agrees with NDA
(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;
larger than $4\pi\times$NDA
(de Vries, Mereghetti, Walker-Loud '15)

χPT & QCD sum rules;
enhanced by $\frac{\sigma_{\pi N}}{\bar{m}} \sim 4\pi$
(de Vries et al '21)

Disentangling d_e and C_S with paramagnetic systems

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

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

$$\mathrm{Det}(\mathcal{M}_{\mathrm{HT}}) = 2.5(4)\cdot 10^{37}$$

Invertible!

$$\Rightarrow \begin{pmatrix}d_e\,[e\,\mathrm{cm}]^{-1}\\ C_S\end{pmatrix} = \begin{pmatrix}7.3(13)\cdot 10^{-29} & -1.29(23)\cdot 10^{-29}\\ -4.9(9)\cdot 10^{-9} & 1.41(25)\cdot 10^{-9}\end{pmatrix}\begin{pmatrix}\omega_{\mathrm{HfF}^+}\\ \omega_{\mathrm{ThO}}\end{pmatrix}[\mathrm{mrad/s}]^{-1}$$

$$\begin{pmatrix}\omega_{\mathrm{HfF}^+}\\ \omega_{\mathrm{ThO}}\end{pmatrix} = \begin{pmatrix}0.0459(933)\\ 0.510(683)\end{pmatrix}[\mathrm{mrad/s}] \Rightarrow \begin{pmatrix}d_e\\ C_S\end{pmatrix} = \begin{pmatrix}-0.3(11)\times 10^{-29}[e\,\mathrm{cm}]\\ 0.5(11)\times 10^{-9}\end{pmatrix}$$

Current experimental data

Roussy et al ’23
ACME, Andreev et al ‘18

Still consistent with $d_e = C_S = 0$

If $d_e = 10^{-30}$ e cm and $C_S \approx 0$

$$\begin{pmatrix}\omega_{\mathrm{HfF}^+}\\ \omega_{\mathrm{ThO}}\end{pmatrix} = \begin{pmatrix}0.0349(14)\\ 0.1206(49)\end{pmatrix}[\mathrm{mrad/s}] \Rightarrow \begin{pmatrix}d_e\\ C_S\end{pmatrix} = \begin{pmatrix}1.0(6)\cdot 10^{-30}[e\,\mathrm{cm}]\\ 0(5)\cdot 10^{-11}\end{pmatrix}$$

Theoretical predictions

with experimental errors below 10% level

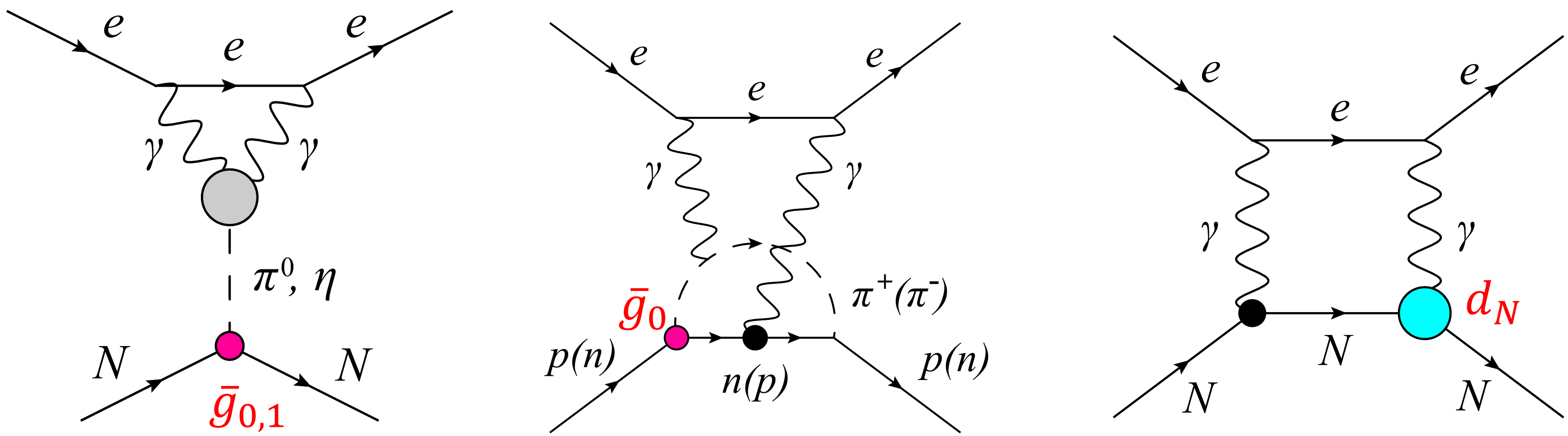
Measurements of two different paramagnetic EDMs may successfully disentangle d_e and C_S.

If a non-zero C_S is discovered, C_S can be either from C_{eeqq} or hadronic sources.

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

C_S from hadronic sources

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



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

If a non-zero C_S originates from the hadronic sources, there must be large diamagnetic EDMs as well, while not if C_S is from C_{eeqq}.

Disentangling hadronic sources with light nuclei and diamagnetic systems

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

6 independent observables

$$A = p, n, D, He, Hg, Ra, \ldots$$

while there are 8 potentially leading CPV UV sources → cannot be fully disentangled.

$$X_{\text{CPV}} \in \left\{ \bar{\theta}, w, \tilde{d}_u, \tilde{d}_d, d_u, d_d, C^{(1)}_{quqd}, C^{(8)}_{quqd} \right\}$$

Moreover, by chiral symmetry properties, the 4-nucleon interactions C_1 and C_2 can be sizable only for the gluon CEDM (Weinberg operator)
→ C_1 and C_2 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 $\tilde{d}_d \sim \frac{m_d}{m_u} \tan\beta \, \tilde{d}_u \gg \tilde{d}_u$,

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

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

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

Also using the NDA value for $C_1 = C_2 = w/f_\pi$,

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

cf) Yamanaka, Oka '22

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

$\longrightarrow -9(4)\cdot 10^{-16}$ $(C_2 = w/f_\pi \to -w/f_\pi)$

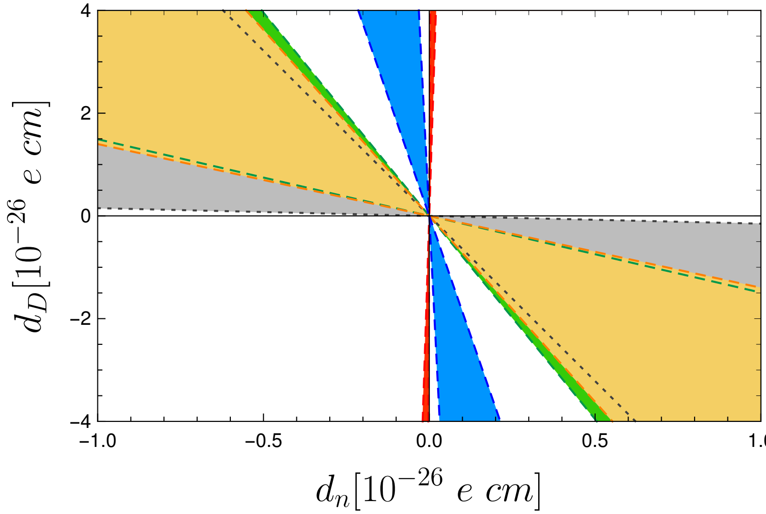
The different magnitudes of the neutron EDM are predicted from the quark CEDM depending on the existence of QCD axion.

$$\mathrm{Det}(\mathcal{M}_{\rm nDHe}) = -3.9(35)\cdot 10^{-44} \to -6(4)\cdot 10^{-44}$$

Invertible!

$(C_2 = w/f_\pi \to -w/f_\pi)$

K Choi, SHI, K Jodlowski ‘23



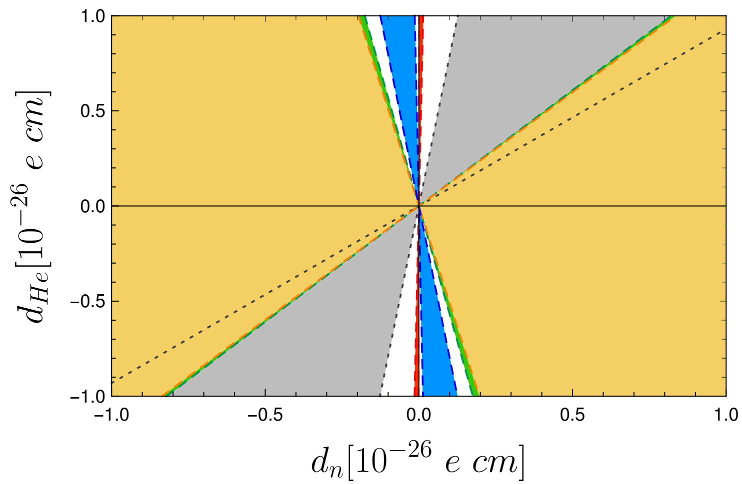
Gray: $\bar{\theta}$

Brown: w

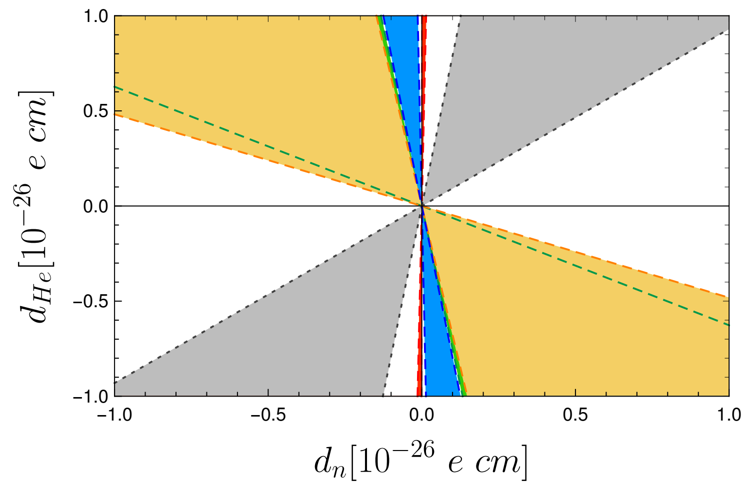
Blue: $\tilde{d}_q$ (with QCD axion)

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

$c_1 = c_2 = w/f_\pi$



$c_1 = -c_2 = w/f_\pi$



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

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

Using the nucleons and light nuclei (d_n, d_p, d_D, d_{He}), and the lattice results for $d_N(d_u, d_d)$,

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

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

$c_1 = c_2 = w/f_\pi$

$\longrightarrow -9(4)\cdot 10^{-16}$

$(C_2 = w/f_\pi \to -w/f_\pi)$

$$\mathrm{Det}(\mathcal{M}_{\rm npDHe}) = -(4\pm 4)\times 10^{-60} \longrightarrow -(7\pm 5)\times 10^{-60}$$

marginally 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.
- An important question is about the feasibility of experimental determination of the origin of the CP violation by EDM measurements: "The EDM inverse problem"
- In particular we examine whether the origin of the QCD axion VEV can be determined by 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 profiles.
- Generally future EDM data and improvement of theoretical computation of EDMs may disentangle d_e, C_{eeqq}, w, and 4 other UV CPV sources (e.g. $\bar{\theta}, d_u, d_d, \tilde{d}_q$).

Back-up: NDA estimations

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

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

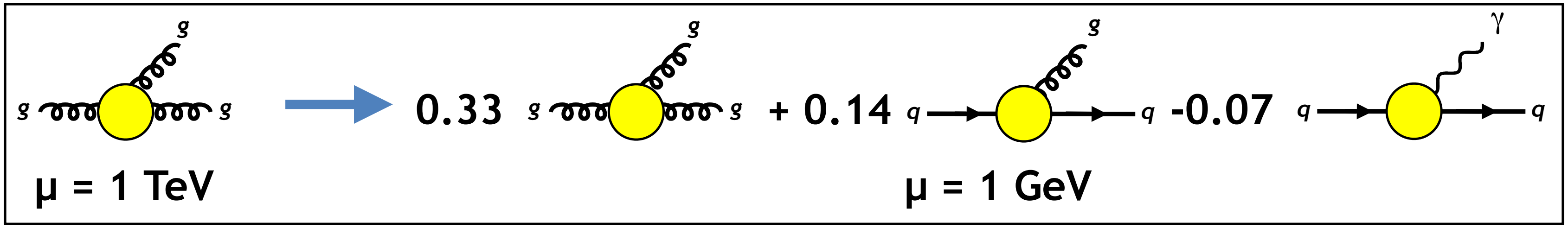
$$m_* \equiv \left(trM_q^{-1}\right)^{-1} \simeq \frac{m_u m_d}{m_u + m_d}$$

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

$$\bar{g}_1 \sim \frac{4\pi(m_u - m_d)m_*}{\Lambda_\chi^2}\,\bar{\theta} + (m_u - m_d)\Lambda_\chi w + \Lambda_\chi(\tilde{d}_u - \tilde{d}_d)$$

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

RGE effect



(Adapted from Nodoka Yamanaka)

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

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

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

NDA

$$\bar{g}_1 \sim 4\pi \frac{(m_u - m_d)m_*}{\Lambda_\chi^2}\,\bar{\theta} + (m_u - m_d)\Lambda_\chi w + \Lambda_\chi\,(\tilde{d}_u - \tilde{d}_d)$$

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