Uncovering the axion and BSM CP violation with electric dipole moments

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KC, Im, Jodlowski, arXiv: 2308.01090

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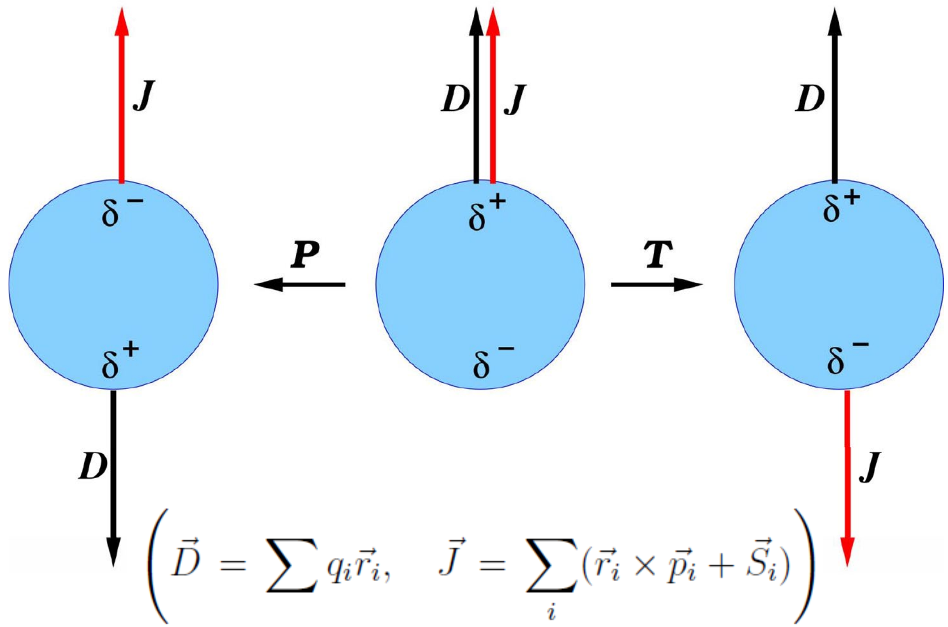
Why Electric Dipole Moments (EDM) are interesting and important?

Nonzero permanent EDM means **P** and **T (=CP)** violation.



$$\left(\vec{D} = \sum q_i \vec{r}_i, \quad \vec{J} = \sum_i (\vec{r}_i \times \vec{p}_i + \vec{S}_i)\right)$$

Historically the violation of these discrete spacetime symmetries have played important role for the progress in fundamental physics.

CP violation is one of the key conditions to generate the asymmetry between matter and antimatter in our universe. Sakharov '67

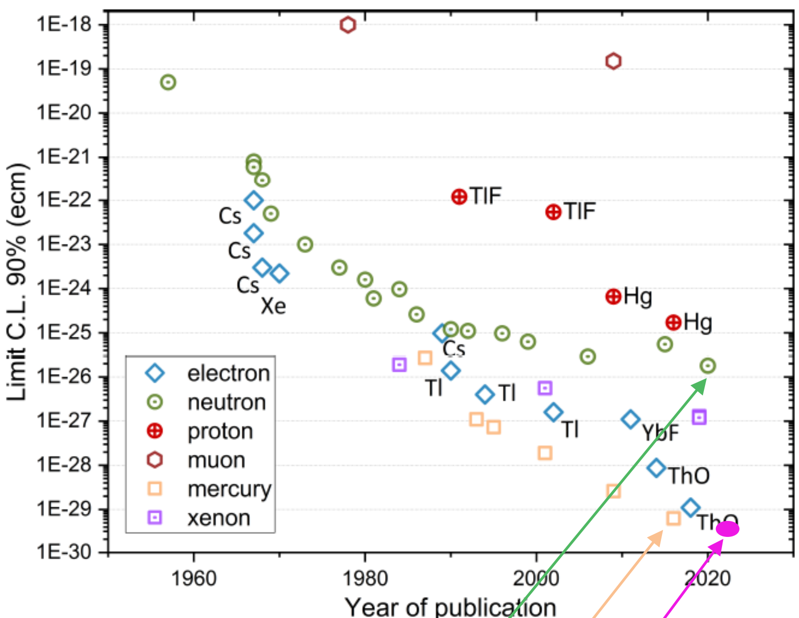
Observed asymmetry: $Y_B = \frac{n_B}{s} \sim 10^{-10}$

Standard Model (SM) prediction: $(Y_B)_{\rm SM} \lesssim 10^{-15}$

SM can provide neither an enough CP violation, nor out of equilibrium.

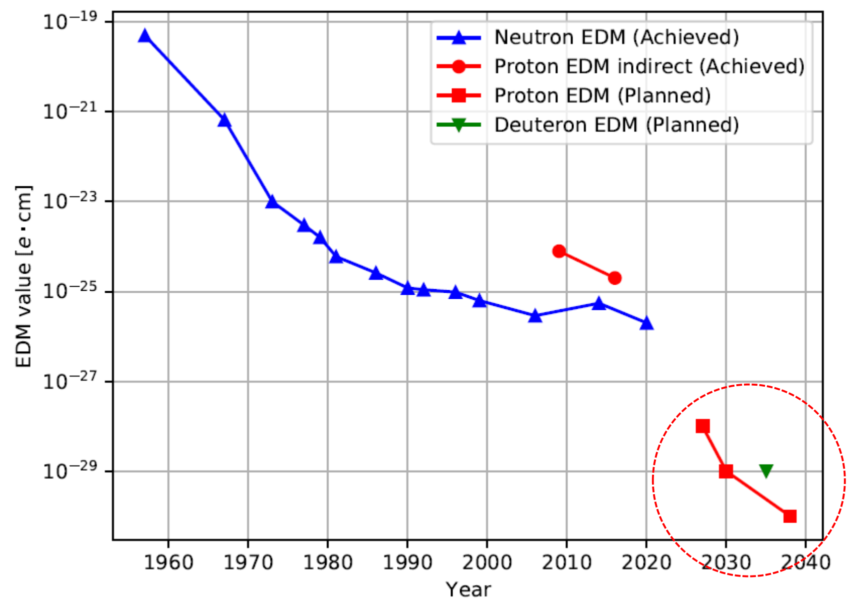
We need "CP-violating new physics beyond the SM (BSM) ", and EDM may provide a hint for those BSM physics.

EDMs have a bright prospect for significant experimental progress.



arXiv:2003.00717

d_e from HfF^+



arXiv:2203.08103

Storage ring EDM

$d_n < 1.8 \times 10^{-26}$ e cm

$d_e < 4.1\times 10^{-30}$ e cm

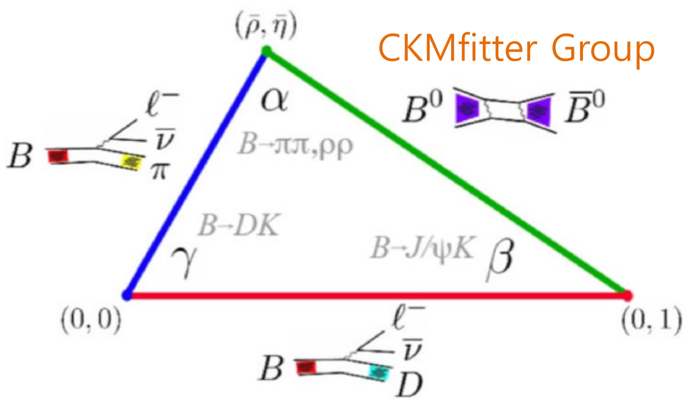
$d_{Hg} < 7.4\times 10^{-30}$ e cm

Abel et al '20
Roussy et al '22
Graner et al '16

SM prediction for EDMs

CP violation in the weak interactions: $\delta_{\rm KM} = \arg \cdot \det([y_u y_u^\dagger, y_d y_d^\dagger])$

CP violation in the strong interactions: $\bar{\theta} = \theta_{\rm QCD} + \arg \cdot \det(y_u y_d)$



$\Rightarrow$ $\sin\delta_{\rm KM} = \mathcal{O}(1)$

$$\frac{d_n}{e\cdot {\rm cm}} = -(1.5\pm 0.7)\times 10^{-16}\sin\bar\theta \;+\; \mathcal{O}(10^{-31}-10^{-32})\times\sin\delta_{\rm KM}$$

$$\frac{d_p}{e\cdot {\rm cm}} = (1.1\pm 1.0)\times 10^{-16}\sin\bar\theta \;+\; \mathcal{O}(10^{-31}-10^{-32})\times\sin\delta_{\rm KM}$$

De Vries et al '01　　Mannel, Uraltsev '12

$\Rightarrow$ $|\bar\theta| \lesssim 10^{-10}$

(Strong CP problem: Why $\bar\theta$ is so small compared to $\delta_{\rm KM}$?)

SM prediction

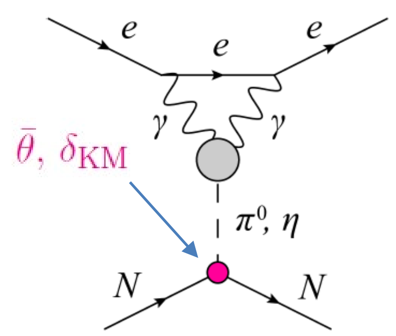
$$\frac{d_e}{e \cdot \mathrm{cm}} = -(2.2 - 8.6) \times 10^{-28} \sin\bar{\theta} \; + \; \mathcal{O}(10^{-44}) \times \sin\delta_{\mathrm{KM}} \lesssim \mathcal{O}(10^{-37})$$

KC, Hong '91; Ghosh, Sato '18 Pospelov, Ritz '14

$$\frac{d_e^{\mathrm{equiv}}}{e \cdot \mathrm{cm}} \simeq 4.5 \times 10^{-22} \sin\bar{\theta} \; + \; 10^{-35} \sin\delta_{\mathrm{KM}} \; \lesssim \; \mathcal{O}(10^{-31})$$

Flambaum et al '19 Ema et al '22

Electron EDM-equivalent parameterizing the effect of the electron-nucleon point interaction $\bar{e}\gamma_5 e\bar{N}N$ for the paramagnetic molecule ThO.



EDMs from δ_{KM} are all well below the current experimental bounds, while the hadronic EDMs from $\bar{\theta}$ can have any value below the current bounds.

There can also be CP-violations (CPV) beyond the SM (BSM), which may induce EDMs at any value below the current bounds.

Therefore, if some hadronic EDM is experimentally discovered in near future, it might be due to either BSM CPV or $\bar{\theta}$.

To discriminate between these two possibilities, we need

(i) quantitative understanding of the contribution from $\bar{\theta}$ in theory side,

(ii) measurement of multiple EDMs in experiment side.

This issue has ben discussed before, but in a limited context involving only a few EDMs or rather specific BSM models.

Lebedev et al '04; Dekens et al '14, de Vries et al '21

EDMs may also depend on how the strong CP problem is solved.

Any solution of the strong CP problem involves a specific structure in the theory, with which

a) $\bar{\theta}$ is calculable,

b) the calculated value of $\bar{\theta}$ is small enough, i.e. $|\bar{\theta}| < 10^{-10}$.

Two different scenarios:

i) $\bar{\theta}$ is determined by low energy physics well below the weak scale:

Peccei-Quinn (axion) solution: Low energy QCD around 1 GeV

ii) $\bar{\theta}$ is determined by physics at high scales well above the weak scale:

Spontaneous CP (or P) violation at high scale, which is carefully designed to have $|\bar{\theta}| < 10^{-10}$

Both scenarios can involve BSM CPV, in addition to the SM CPV by $\delta_{\rm KM} = \mathcal{O}(1)$.

In the 1st scenario, $\bar{\theta}$ is determined at low energy scale well below the scale where BSM CPV begins to operate.

Then the low energy mechanism to fix $\bar{\theta}$ at small value can be significantly affected by BSM CPV at the same scale.

On the other hand, in the 2nd scenario, $\bar{\theta}$ is determined at high energy scale around which BSM CPV might also be generated. In such case, the underlying physics responsible for $|\bar{\theta}| < 10^{-10}$ is decoupled from low energy world.

Then, in the context of low energy EFT, $\bar{\theta}$ and BSM CPV can be regarded to be independent from each other.

This difference between two scenarios may lead to a significant difference in the resulting pattern of experimentally measurable EDMs.

Motivated by this possibility, we examine to what extent EDMs can provide information on the underlying BSM CPV, and also on the mechanism solving the strong CP problem, in particular on the PQ (axion) solution.

EFT approach for EDMs from BSM CP violations

BSM model at E > 1 TeV

Integrate out all massive BSM particles and consider the resulting SMEFT

$$\begin{aligned}\mathcal{L}_{\rm CPV}(\mu=\Lambda) =& c_{\widetilde{G}} f^{abc} G^{a\mu}_{\alpha} G^{b\delta}_{\mu} \widetilde{G}^{c\alpha}_{\delta} + c_{\widetilde{W}} \epsilon^{abc} W^{a\mu}_{\alpha} W^{b\delta}_{\mu} \widetilde{W}^{c\alpha}_{\delta} \\ &+ |H|^2 \left(c_{H\widetilde{G}} G^{a}_{\mu\nu} \widetilde{G}^{a\mu\nu} + c_{H\widetilde{W}} W^{a}_{\mu\nu} \widetilde{W}^{a\mu\nu} + c_{H\widetilde{B}} B_{\mu\nu} \widetilde{B}^{\mu\nu} \right) \\ &+ c_{H\widetilde{W}B} H^\dagger \tau^a H \widetilde{W}^a_{\mu\nu} B^{\mu\nu}\end{aligned}$$

Integrate out all massive SM particles and scale down the theory to near the QCD scale

$$\Delta\mathcal{L}_{\rm BSM-CPV} = \sum_i \lambda_i \mathcal{O}_i$$

$$\left(\mathcal{O}_i = \bar{q}\gamma_5 \sigma\cdot G q,\ GG\tilde{G},\ \bar{q}\gamma_5\sigma\cdot F q,\ \bar{q}\gamma_5 q \bar{q} q, \ldots \right)$$

(light quark and gluon CEDMs, EDMs, 4-fermion operators)

Use the relevant QCD, nuclear & atomic physics results

Experimentally measurable nucleon, atomic, molecular EDMs

PQ (axion) solution of the strong CP problem

The axion solution to the strong CP problem is based on a global U(1) symmetry:

$$U(1)_{\rm PQ}: \quad a(x) \;\to\; a(x) + \text{constant}$$

Peccei, Quinn

which is dominantly broken by the QCD anomaly:

Effective lagrangian at E ~ 1 GeV:

PQ-breaking by the QCD anomaly

Additional interactions

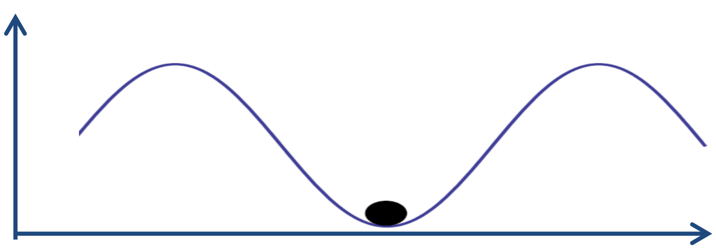
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} + \frac{1}{2}\partial_\mu a \partial^\mu a + \boxed{\frac{1}{32\pi^2}\frac{a}{f_a}G^{a\mu\nu}\tilde{G}^a_{\mu\nu}} + \Delta\mathcal{L}$$

Additional axion potential

$$\Rightarrow \quad V_{\rm QCD}(a) \simeq -\frac{f_\pi^2 m_\pi^2}{(m_u+m_d)}\sqrt{m_u^2 + m_d^2 + 2m_u m_d \cos(a/f_a)}$$

$$\delta V(a)$$

Shift of the axion VEV



$$\langle a \rangle = 0$$

$$\Rightarrow \quad \bar{\theta} \equiv \frac{\langle a \rangle}{f_a} = 0 + \ldots$$

Full axion potential: $V(a) = V_{\rm QCD}(a) + \delta V(a)$

Low energy PQ-breaking by $aG\tilde{G}$ around the QCD scale, combined with the conventional CP-conserving QCD

$$\Rightarrow \quad V_{\rm QCD}(a) \simeq -\frac{f_\pi^2 m_\pi^2}{(m_u + m_d)}\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos(a/f_a)}$$

Two possible origins for additional axion potential $\delta V(a)$ which can give nonzero axion VEV:

i) Low energy PQ-breaking by $aG\tilde{G}$, combined with CP-violating (but PQ and flavor-conserving) effective interactions of gluons and light quarks around the QCD scale

ii) High scale PQ-breaking other than $aG\tilde{G}$, e.g. quantum gravity effects such as string/brane instantons or gravitational wormholes

PQ quality problem

In modern viewpoint, PQ-breaking by quantum gravity is considered to be inevitable, so $\bar{\theta}$ in the PQ (axion) solution is determined not only by low energy physics around the QCD scale, but also by high scale physics, even Planck-scale physics, which is not decoupled due to the existence of the axion:

Black hole evaporation? Gravitational Euclidean wormholes?
String world-sheet or brane instantons?, …

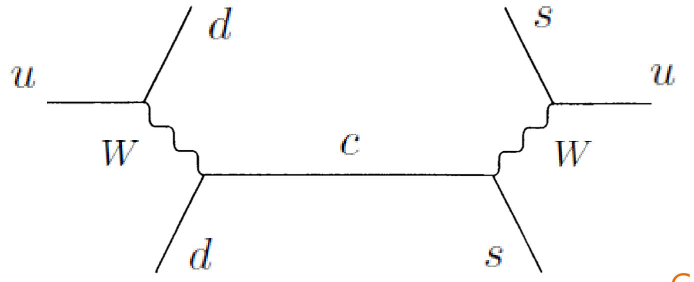
There have been many theoretical studies on this PQ quality problem, focusing mostly on "how to protect the PQ symmetry from quantum gravity to have $|\bar{\theta}_{\rm UV}| < 10^{-10}$":

Accidental symmetry?, Higher dimensional gauge symmetry?, …

On the other hand, there has been no discussion about "how to discriminate between $\bar{\theta}_{\rm UV}$ and $\bar{\theta}_{\rm BSM}$ with experimental data, or more generically how to identify the origin of the axion VEV with experimental data".

CP-violating (but PQ & flavor-conserving) effective interactions of gluons and light quarks around the QCD scale:

* SM flavor-conserving CPV around the QCD scale:



Georgi, Randall '86

$$\Rightarrow \quad \Delta\mathcal{L}_{\rm SM-CPV} \sim \frac{G_F^2 J}{m_c^2}\left[\bar{u}_L\gamma^\mu d_L \cdot \bar{d}_L\gamma_\mu\right] \not{D} \left[\gamma_\nu s_L \cdot \bar{s}_L \gamma^\nu u_L\right] \quad (J \simeq 3\times 10^{-5})$$

* Model-dependent BSM flavor-conserving CPV around the QCD scale

$$\Delta\mathcal{L}_{\rm BSM-CPV} = \sum_i \lambda_i \mathcal{O}_i \quad \left(\mathcal{O}_i = GG\tilde{G},\, \bar{q}\gamma_5\sigma\cdot Gq,\, \bar{q}q\bar{q}\gamma_5 q,\, ...\right)$$

(gluon chromo-EDM, quark chromo-EDM, four-quark operators, ...)

$$\delta V = \delta V_{\rm SM} + \delta V_{\rm BSM} + \delta V_{\rm UV}$$

$$\delta V_{\rm SM} \sim 10^{-19} f_\pi^2 m_\pi^2 \sin\delta_{\rm KM} \sin(a/f_a)$$

Axion potential induced by $aG\tilde{G}$ & SM CPV:

$$\delta V_{\rm BSM} \sim \sum_i \lambda_i \int d^4x \left\langle \frac{g_s^2}{32\pi^2} G\tilde{G}(x) \mathcal{O}_i(0) \right\rangle \sin(a/f_a)$$

Axion potential induced by $aG\tilde{G}$ & BSM CPV:

$$\delta V_{\rm UV} = \Lambda_{\rm UV}^4 e^{-S_{\rm ins}} \cos(a/f_a + \delta_{\rm UV})$$

Axion potential induced by high scale PQ-breaking, e.g. string/brane instantons or other quantum gravity effects

$$\Rightarrow \quad \bar\theta = \frac{\langle a \rangle}{f_a} = \bar\theta_{\rm SM} + \bar\theta_{\rm BSM} + \bar\theta_{\rm UV}$$

$$\bar\theta_{\rm SM} \sim 10^{-19}$$

(too small to be interesting)

$$\bar\theta_{\rm BSM} \sim \frac{\sum_i \lambda_i \int d^4x \left\langle \frac{1}{32\pi^2} G\tilde{G}, \mathcal{O}_i \right\rangle}{f_\pi^2 m_\pi^2}$$

Axion VEV induced by $aG\tilde{G}$ & BSM CPV, which can have any value below 10^{-10}

$$\bar\theta_{\rm UV} \sim \frac{e^{-S_{\rm ins}} \Lambda_{\rm UV}^4 \sin\delta_{\rm UV}}{f_\pi^2 m_\pi^2}$$

Axion VEV induced by high scale PQ-breaking, which also can have any value below 10^{-10}

EDM might be able to discriminate between $\bar{\theta}_{\rm UV}$ and $\bar{\theta}_{\rm BSM}$:

$$\Delta\mathcal{L}_{\rm BSM-CPV} = \sum_i \lambda_i \mathcal{O}_i \qquad \delta V_{\rm UV} = \Lambda_{\rm UV}^4 e^{-S_{\rm ins}} \cos(a/f_a + \delta_{\rm UV})$$

$\oplus\ aG\tilde{G}$

$$\bar{\theta} = \bar{\theta}_{\rm BSM} + \bar{\theta}_{\rm UV} = \sum_i \lambda_i \frac{\partial\bar{\theta}}{\partial\lambda_i} + \bar{\theta}_{\rm UV}$$

EDMs

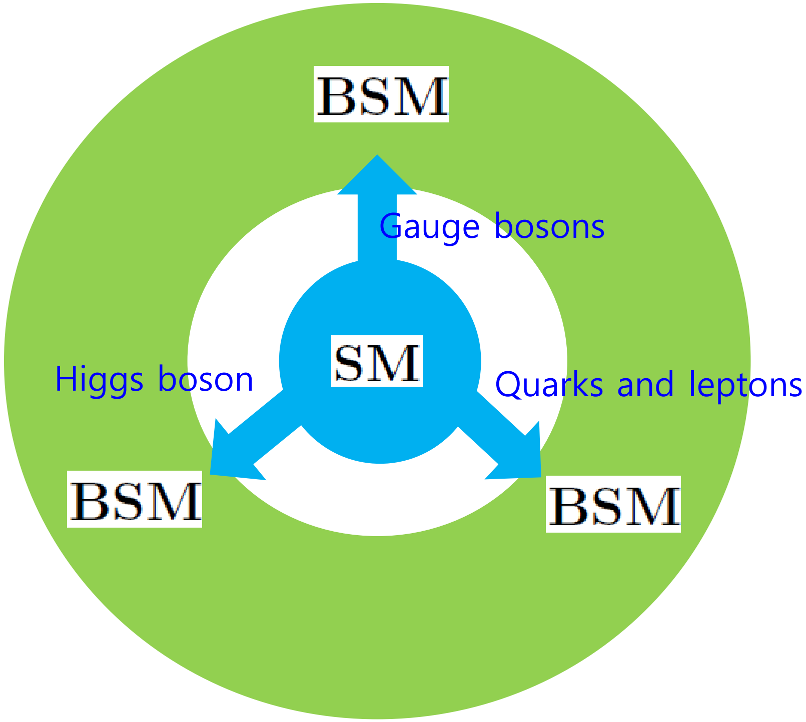
$$d_I = \sum_i \lambda_i \frac{\partial d_I}{\partial\lambda_i} + \bar{\theta}_{\rm UV} \frac{\partial d_I}{\partial\bar{\theta}} \quad (I = n, p, D, He, Ra, Xe, Hg, ...)$$

In the presence of axion, BSM CPV affects EDMs both directly and through the induced axion VEV, while high scale PQ breaking by quantum gravity affects EDMs only through the induced axion VEV.

Our primary question is “to what extent can we extract information on BSM CPV and the PQ mechanism from EDM portfolio?”

Addressing this question for generic BSM CPV involves too many free parameters. Therefore we focus on somewhat specific form of BSM CPV to simplify the problem.

BSM physics might be classified by how it communicates with the SM:



Certain class of BSM physics communicate with the SM mainly through the SM gauge bosons, particularly gluons, or through the Higgs boson, while being relatively sequestered from the SM quark and leptons:

Multi-Higgs doublets, Split-SUSY with light gluinos, Vector-like quarks, …

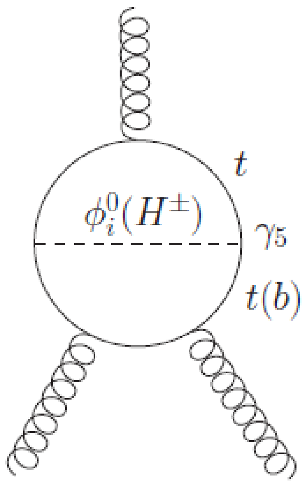
Here we focus on such BSM models in which BSM CPV is transmitted to the low energy world in the form of the gluon and quark chromo-EDMs around the EW scale, over a large portion of the parameter space:

$$\mathcal{L}_{\mathrm{BSM-CPV}}(\mu = M_W) = \frac{1}{3} w f^{abc} G^{a\mu}_{\alpha} G^{b\delta}_{\mu} \widetilde{G}^{c\alpha}_{\delta} - \frac{i}{2} \sum_q \tilde{d}_q g_s \bar{q} \sigma^{\mu\nu} G_{\mu\nu} \gamma_5 q$$

Gluon CEDM
(Weinberg operator)

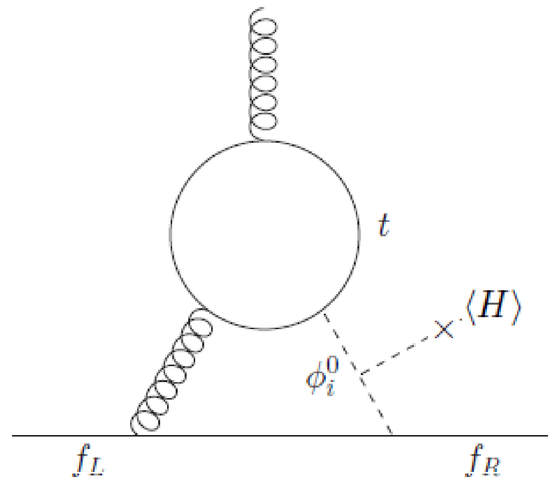
Quark CEDMs

Models of multi-Higgs doublets



$$\frac{1}{3} w f^{abc} G^{a\mu}_{\alpha} G^{b\delta}_{\mu} \widetilde{G}^{c\alpha}_{\delta}$$

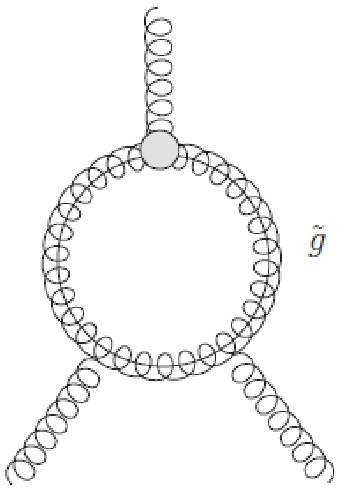
Gluon CEDM
(Weinberg operator)



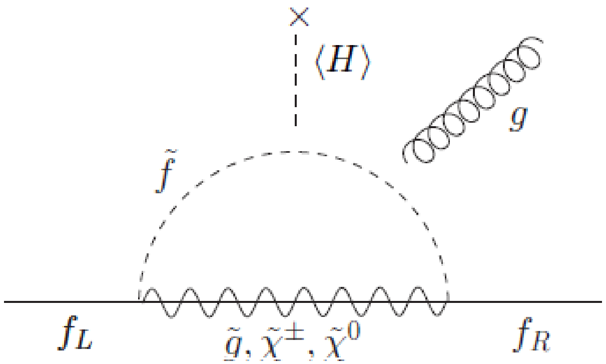
$$\frac{i}{2} \sum_q \tilde{d}_q g_s \bar{q} \sigma^{\mu\nu} G_{\mu\nu} \gamma_5 q$$

Quark CEDM

SUSY models



Gluon CEDM
(Weinberg operator)



Quark CEDM

Vector-like quarks

$$\boxed{m_\psi \psi \psi^c + y_s S \psi \psi^c + \text{h.c.}}$$

KC, Kim, Im, Mo ,16

$\psi + \psi^c$: vector-like quark

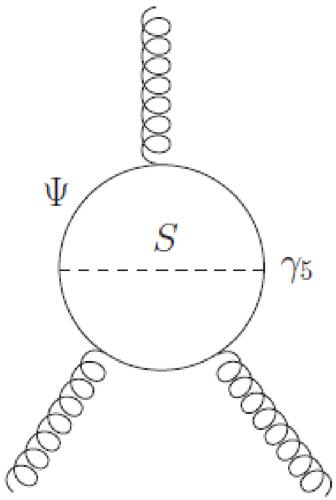
S : singlet real scalar

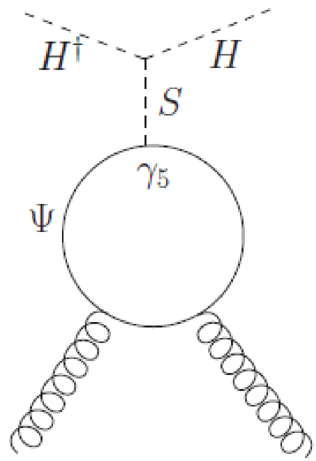
⬇ m_ψ, y_S : complex

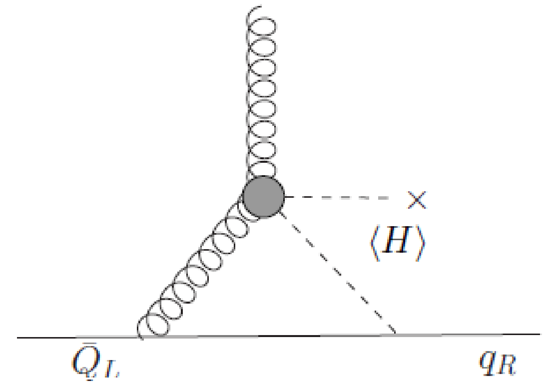
$$|m_\psi| \bar{\Psi}\Psi + |y_S| \cos\alpha \, S\bar{\Psi}\Psi + i|y_S| \sin\alpha \, S\bar{\Psi}\gamma^5\Psi$$

$$\Psi = \begin{pmatrix} \psi \\ \psi^{c*} \end{pmatrix} \qquad \alpha = \arg(m_\psi) - \arg(y_S)$$

s-h mixing







Gluon CEDM
(Weinberg operator)

Quark CEDM

Relative importance of CEDM depends on the size of s-h mixing.

1-loop RG evolution from the BSM scale ~ TeV to 1 GeV

$$C_1(\mu) = \frac{d_q(\mu)}{m_q Q_q}, \quad C_2(\mu) = \frac{\tilde{d}_q(\mu)}{m_q}, \quad C_3(\mu) = \frac{w(\mu)}{g_s}$$

$$\frac{d\mathbf{C}}{d\ln\mu} = \frac{g_s^2}{16\pi^2}\gamma\,\mathbf{C},$$

$$\gamma \equiv \begin{pmatrix} \gamma_e & \gamma_{eq} & 0 \\ 0 & \gamma_q & \gamma_{Gq} \\ 0 & 0 & \gamma_G \end{pmatrix} = \begin{pmatrix} 8C_F & 8C_F & 0 \\ 0 & 16C_F - 4N_c & -2N_c \\ 0 & 0 & N_c + 2n_f + \beta_0 \end{pmatrix}$$

$$C_F = (N_c^2 - 1)/2N_c = 4/3 \qquad \beta_0 \equiv (33 - 2n_f)/3$$

Applying the hadronic matrix elements obtained from the QCD sum rule and chiral perturbation theory for the CEDMs and EDMs renormalized at 1 GeV:

$$d_p(\bar\theta, \tilde d_q, d_q, w) = -0.46 \times 10^{-16}\bar\theta\, e\,\mathrm{cm} + e\left(-0.17\tilde d_u + 0.12\tilde d_d + 0.0098\tilde d_s\right) + 0.36 d_u - 0.09 d_d - 18 w\, e\,\mathrm{MeV},$$

$$d_n(\bar\theta, \tilde d_q, d_q, w) = 0.31 \times 10^{-16}\bar\theta\, e\,\mathrm{cm} + e\left(-0.13\tilde d_u + 0.16\tilde d_d - 0.0066\tilde d_s\right) - 0.09 d_u + 0.36 d_d + 20 w\, e\,\mathrm{MeV}.$$

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

In case with a QCD axion,

$$\bar\theta_{\mathrm{PQ}} \equiv \frac{\langle a\rangle}{f_a} = \bar\theta_{\mathrm{UV}} + \bar\theta_{\mathrm{BSM}} \qquad \bar\theta_{\mathrm{BSM}} = \frac{m_0^2}{2}\sum_{q=u,d,s}\frac{\tilde d_q}{m_q} + \mathcal{O}(4\pi f_\pi^2 w) \qquad \left(m_0^2 \simeq 0.8\,\mathrm{GeV}^2\right)$$

$$d_p^{\mathrm{PQ}}(\bar\theta_{\mathrm{UV}}, \tilde d_q, d_q, w) = -0.46 \times 10^{-16}\bar\theta_{\mathrm{UV}}\, e\,\mathrm{cm} - e\left(0.58\tilde d_u + 0.073\tilde d_d\right) + 0.36 d_u - 0.089 d_d - 18 w\, e\,\mathrm{MeV},$$

$$d_n^{\mathrm{PQ}}(\bar\theta_{\mathrm{UV}}, \tilde d_q, d_q, w) = 0.31 \times 10^{-16}\bar\theta_{\mathrm{UV}}\, e\,\mathrm{cm} + e\left(0.15\tilde d_u + 0.29\tilde d_d\right) - 0.089 d_u + 0.36 d_d + 20 w\, e\,\mathrm{MeV},$$

Examine the following **4 simple scenarios** to see if the nucleon EDMs and some nuclear or atomic EDMs, which have a good prospect to be measured in future experiments, can discriminate between the following 4 scenarios:

- $\bar{\theta}$ domination (with or without axion)

  (Axion VEV dominantly induced by the UV-originated PQ-breaking)

- Gluon CEDM domination at the EW scale (with or without axion)

  (Axion VEV dominantly induced by the gluon CEDM)

- Quark CEDM domination at the EW scale with axion

  (Axion VEV dominantly induced by the quark CEDM)

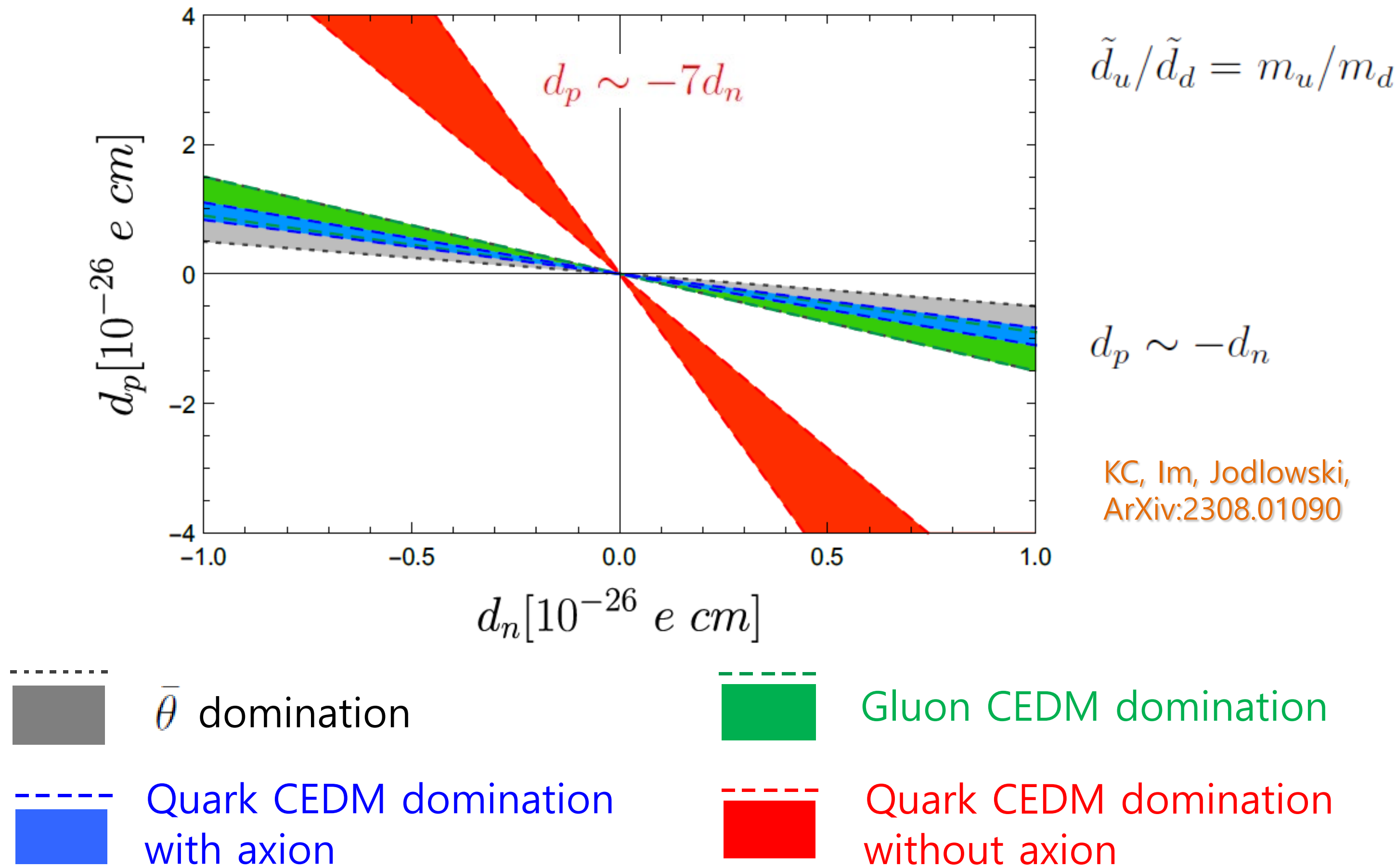
- Quark CEDM domination at the EW scale without axion

$\bar{\theta}$ is fixed by both low energy physics and non-decoupled high scale physics

$\bar{\theta}$ is fixed by decoupled high scale physics

With this study, we might be able to get an insight on "to what extent EDMs can provide information on BSM CPV and also on the QCD axion".

Nucleon EDMs



With d_p/d_n , one can clearly distinguish "quark CEDM domination without axion" from other cases, while the other three cases are not distinguishable from each other.

CPV pion-nucleon couplings provide additional nuclear physics parameters generated by the underlying $\bar{\theta}$ parameter and BSM CPV:

$$\bar{g}_0 \bar{N} \frac{\vec{\sigma}}{2} \cdot \vec{\pi} N + \bar{g}_1 \pi_3 \bar{N} N$$

Some nuclear and atomic EDMs are particularly sensitive to these CPV pion-nucleon couplings. Some are sensitive only to the isospin-violating coupling, while others are equally sensitive to the both couplings:

$$\begin{aligned}
d_D &= 0.94(1)(d_n + d_p) + 0.18(2)\bar{g}_1\, e\,\mathrm{fm}, \\
d_{He} &= 0.9 d_n - 0.05 d_p + [0.10(3)\bar{g}_0 + 0.14(3)\bar{g}_1]\; e\,\mathrm{fm}, \\
d_{Ra} &= 7.7 \times 10^{-4}\, [(2.5 \pm 7.5)\bar{g}_0 - (65 \pm 40)\bar{g}_1]\; e\,\mathrm{fm}, \\
d_{Xe} &= 1.3 \times 10^{-5} d_n - 10^{-5}\, [1.6\bar{g}_0 + 1.7\bar{g}_1]\; e\,\mathrm{fm},
\end{aligned}$$

CPV pion-nucleon couplings induced by $\bar{\theta}$ and the gluon and quark CEDMs.

QCD sum rule, ChPT, Lattice

Chupp et al '19
de Vries et al '21
Osamura et al '22

$$\bar{g}_0(\bar{\theta}) = (15.7 \pm 1.7) \times 10^{-3}\bar{\theta},$$

$$\bar{g}_1(\bar{\theta}) = -(3.4 \pm 2.4) \times 10^{-3}\bar{\theta}$$

$$\bar{g}_0(\tilde{d}_q) \simeq (2.2 \pm 0.7)\mathrm{GeV}\,(\tilde{d}_u + \tilde{d}_d)$$

$$\bar{g}_1(\tilde{d}_q) \simeq (38 \pm 13)\mathrm{GeV}\,(\tilde{d}_u - \tilde{d}_d)$$

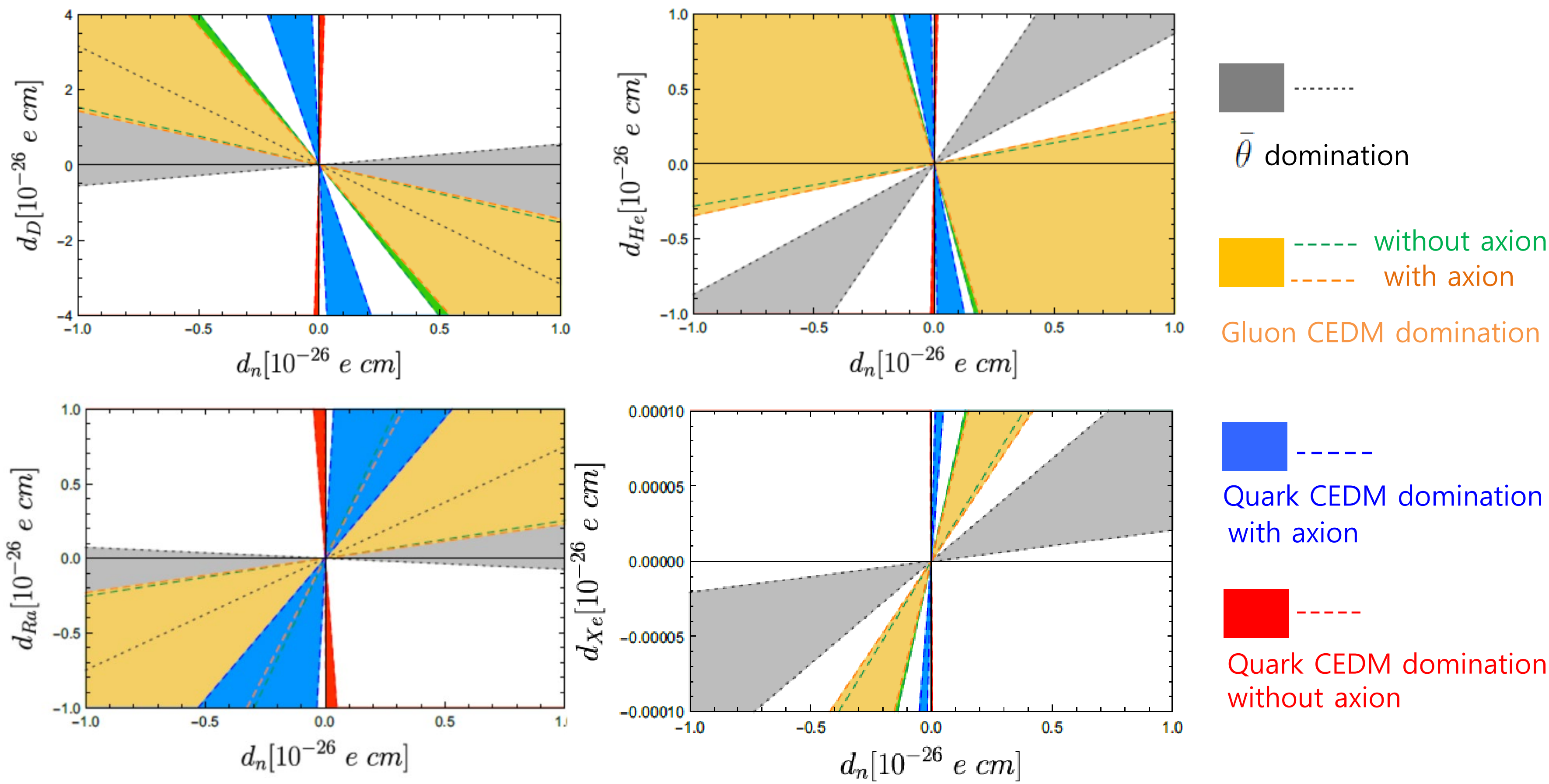
$$\bar{g}_0(\omega) \simeq 10^{-2}\omega\,\mathrm{GeV}^2$$

$$\bar{g}_1(w) \simeq \pm(2.6 \pm 1.5) \times 10^{-3} w\,\mathrm{GeV}^2$$

Larger than the naïve estimation by about one order of magnitude, which is mainly due to the accidentally large value of

$$\sigma_{\pi N} = \frac{(m_u + m_d)}{4m_N}\langle N|(\bar{u}u + \bar{d}d)|N\rangle \simeq 60\,\mathrm{MeV}$$

Diamagnetic atomic EDMs



In case with axion, $\bar{\theta}$ -domination corresponds to the $\bar{\theta}_{\rm UV}$ -domination which can be discriminated from other scenarios having $|\bar{\theta}_{\rm BSM}| \gg |\bar{\theta}_{\rm UV}|$.

Conclusion

EDMs may provide not only the information on BSM CP violation, but also additional information on the QCD axion including its existence and the origin of the axion VEV (PQ quality).

As simple examples, with the nucleon and some nuclear or atomic EDMs, the following 4 scenarios can be discriminated from each other:

1) $\bar{\theta}$ domination
2) Gluon CEDM domination (with or without axion)
3) quark CEDM domination without axion
4) quark CEDM domination with axion

Extending this analysis to more general situation appears to be challenging and it requires a further improvement of the involved QCD, nuclear and atomic physics calculations for EDMs.

Thank you for your attention.