EDM Implications for BSM Physics

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University of Massachusetts Amherst

K. Fuyuto, M. Ramsey-Musolf, T. Shen, PLB788(2019)52
J. de Vries, P. Draper, K.Fuyuto, J. Kozaczuk and D. Sutherland, 1809.10143
K. Fuyuto, X-G He, G. Li and M. Ramsey-Musolf, work in Progress

December 8th, 2018
ACFI Workshop

CPV interactions in New Physics

New physics generally contains CP phases.

My talk discusses

- *What kind of CPV interactions are in BSM*
- *EDM constraints on CP phases*

  ✔ Leptoquark

  ✔ Dark Photon

- *Implication for QCD theta term*

Leptoquark

Leptoquark

J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 87, 075004 (2013)
I. Dorsner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Kosnik, Phys. Rept. 641, 1 (2016)

Leptoquark couples to quark and lepton

Scalar LQ : $X = \begin{pmatrix} V \\ Y \end{pmatrix} \quad (\mathbf{3}, \mathbf{2}, 7/6)$

$$\mathcal{L} = -\lambda_u^{ab} \bar{u}^a X^T \epsilon L^b - \lambda_e^{ab} \bar{e}^a X^\dagger Q^b + \text{h.c.}$$

$\lambda_{u,e}$: Complex $\qquad a, b$: Flavor indices

Epsilon tensor : $\epsilon_{12} = 1$

✔ Sources for two CP-violating interactions

Leptoquark

J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
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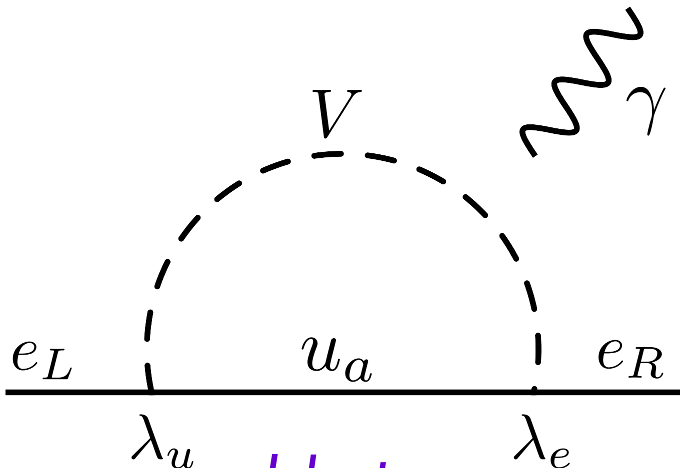
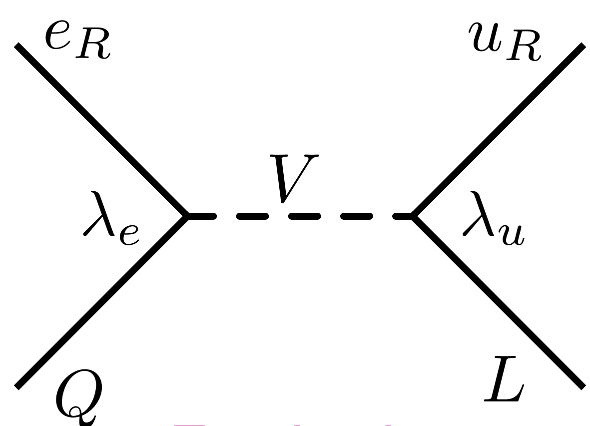
Two CP-violating interactions are induced:

Electron EDM *Semileptonic 4-fermi interaction*

$$\mathcal{L} = -\frac{i}{2} d_e \bar{e} \sigma^{\mu\nu} \gamma_5 e F_{\mu\nu} \; - \frac{1}{\Lambda^2} \left[C^{(1)}_{lequ} \bar{L}^j e_R \epsilon_{jk} \bar{Q}^k u_R + \text{h.c.} \right]$$



1-loop



Tree-level

Leptoquark

J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
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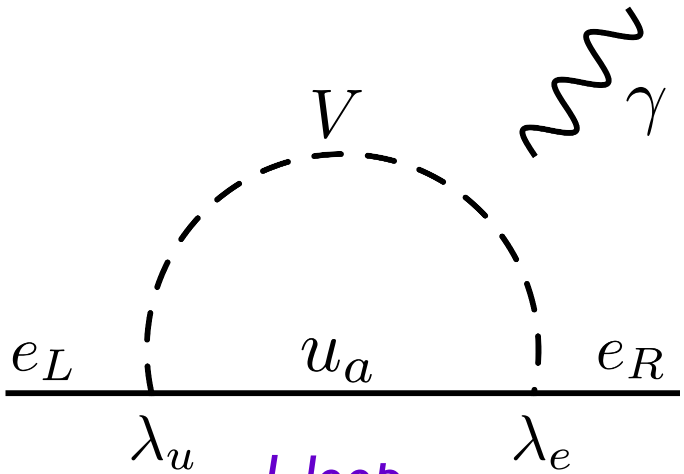

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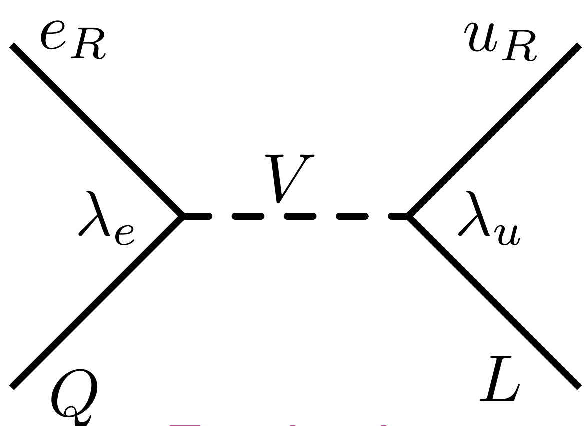

Tree-level

✦ *4-fermi interaction can be larger than electron EDM.*

Leptoquark

J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
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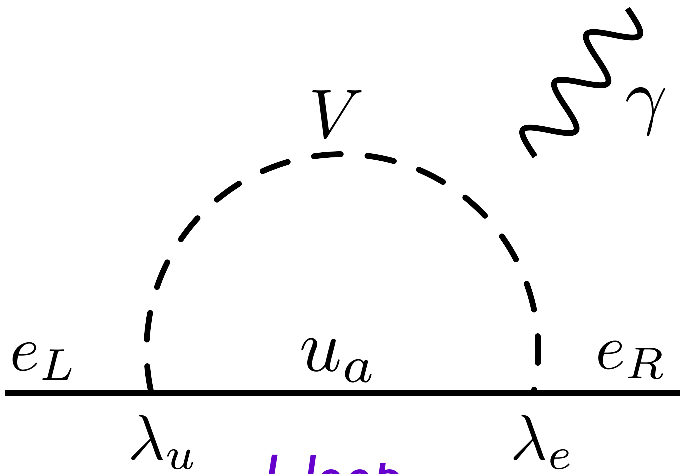

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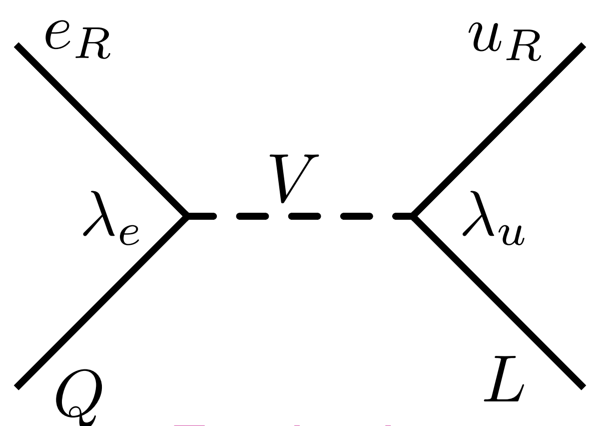

Tree-level

$$\supset \frac{1}{2\Lambda^2}\text{Im}\left(C^{(1)}_{lequ}\right)\bar{e}i\gamma_5 e\;\bar{u}u$$

Leptoquark

J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
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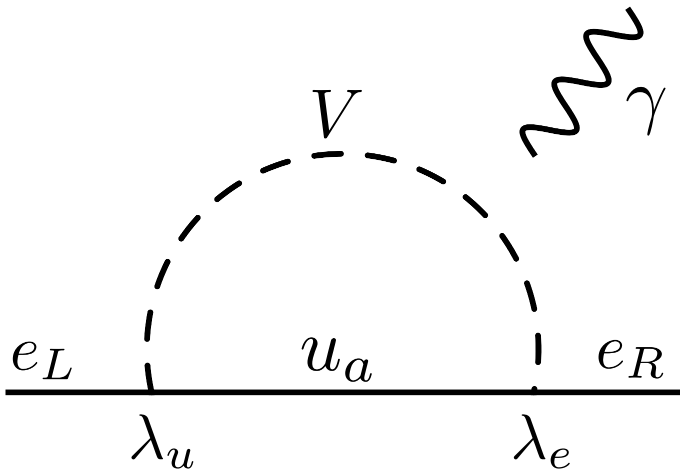
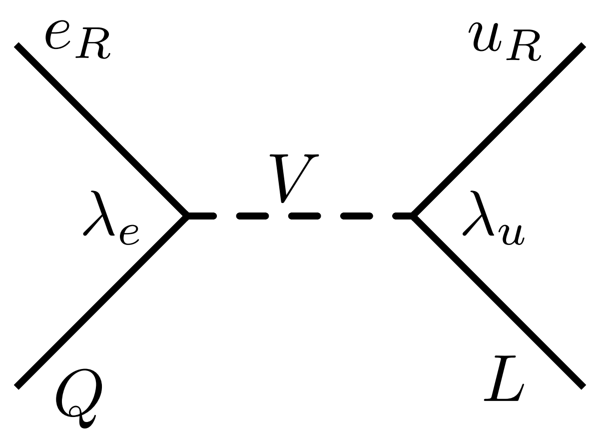


Electron-nucleon interaction

$$-\frac{G_F}{\sqrt{2}} C_S \bar{e} i \gamma_5 e \; \bar{N} N$$



Constrained by EDM measurements in paramagnetic systems

✔ *Polar molecule systems*

Analytic formula

- *Electron EDM*

$$d_e = -\frac{e m_{u_a} N_C}{32\pi^2 m_V^2} \mathrm{Im}\left(\lambda_u^{a1}\lambda_e^{1a}\right)\left[\frac{2}{3} I_2\left(\frac{m_{u_a}^2}{m_V^2}\right) + \frac{5}{3} J_2\left(\frac{m_{u_a}^2}{m_V^2}\right)\right]$$

m_V : *LQ mass* I_2, J_2 : *Loop function*

- *Electron-nucleon interaction*

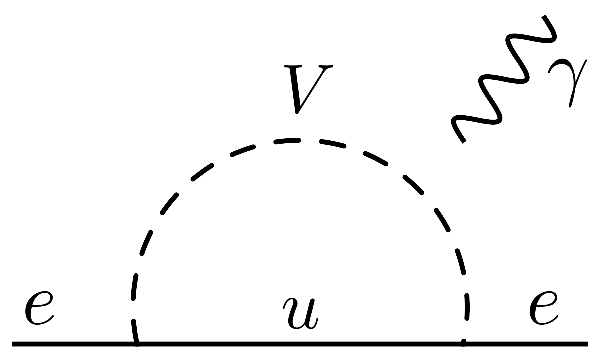
$$C_S \simeq g_S \frac{v^2}{2m_V^2} \mathrm{Im}\left(\lambda_u^{11}\lambda_e^{11}\right)$$

$g_S = 6.3$

J. Engel, M. J. Ramsey-Musolf and U. van Kolck, Prog. Part. Nucl. Phys. 71, 21 (2013)

✔ *Up-quark contribution*

$$C_S,\ d_e \propto \mathrm{Im}\left(\lambda_u^{11}\lambda_e^{11}\right)$$



Analytic formula

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J. Engel, M. J. Ramsey-Musolf and
U. van Kolck, Prog. Part. Nucl. Phys. 71, 21 (2013)

✔ *Up-quark contribution*

C_S dominates the systems!

$$\frac{d_e}{\alpha_j C_S} \sim O(10^{-2})$$

Current limit on d_e and C_S

Effective EDM : $d_j \equiv d_e + \alpha_j C_S$

$$\alpha_{\mathrm{ThO(HfF^+)}} = 1.5(0.9) \times 10^{-20}\ e\ \mathrm{cm}$$

Current experimental values :

ThO : $d_{\mathrm{ThO}} = (4.3 \pm 4.0) \times 10^{-30}\ e\ \mathrm{cm}$

V. Andreev et al. [ACME Collaboration], Nature 562(2018)7727

Sole source: $|d_e| < 1.1 \times 10^{-29}\ e\ \mathrm{cm}$

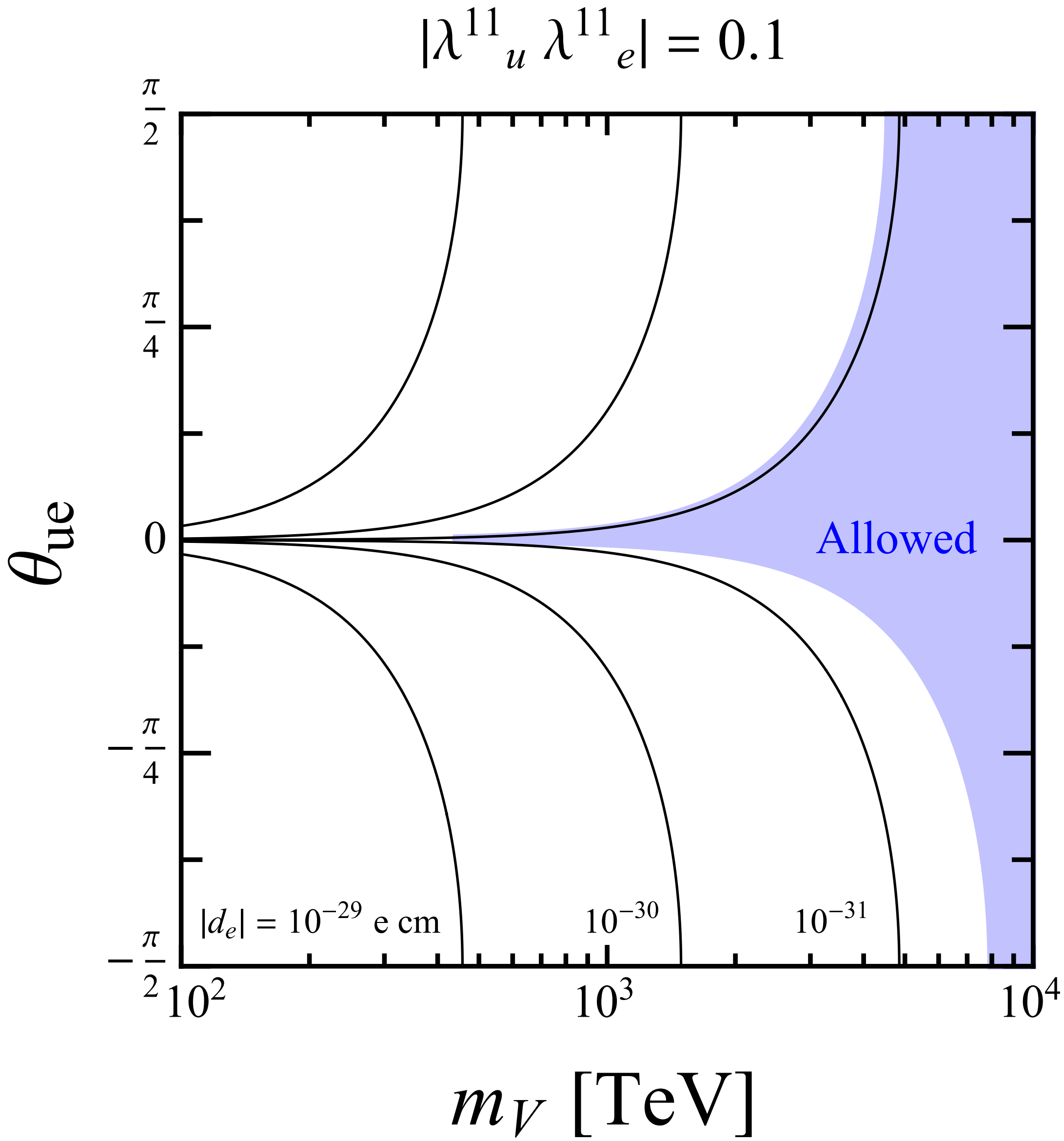
HfF⁺ : $d_{\mathrm{HfF^+}} = (0.9 \pm 7.9) \times 10^{-29}\ e\ \mathrm{cm}$

W. B. Cairncross et al., PRL. 119, no. 15, 153001 (2017)

Sole source: $|d_e| < 1.3 \times 10^{-28}\ e\ \mathrm{cm}$

Result

$$\mathrm{Im}\left(\lambda_u^{11}\lambda_e^{11}\right) = \left|\lambda_u^{11}\lambda_e^{11}\right| \sin\theta_{ue}$$



Blue region:

Allowed at 90% C.L.

Black lines:

Predictions of d_e

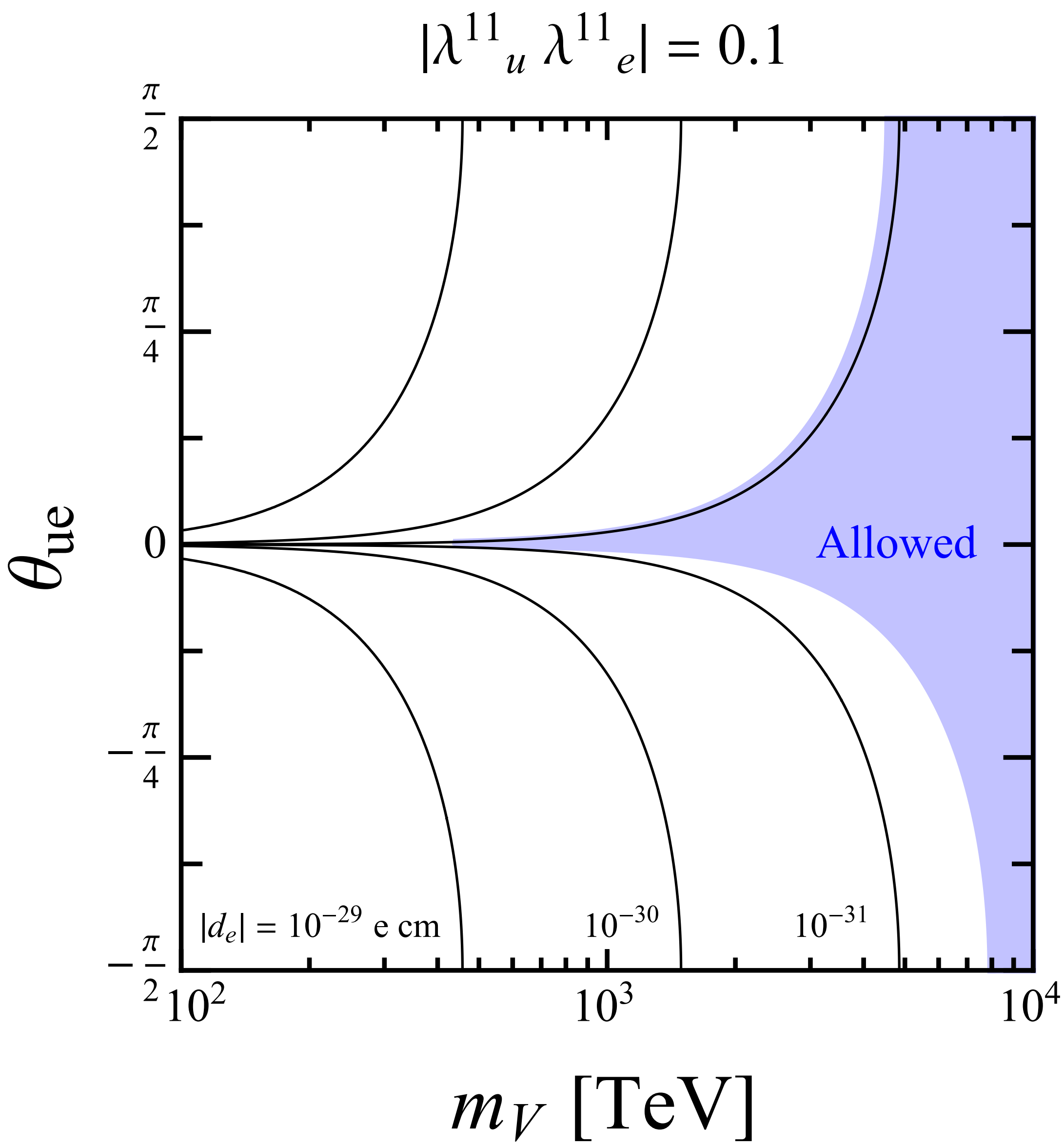
$$|d_e| = 10^{-29,30,31}\ e\ \mathrm{cm}$$

Current limit

$$|d_e| \lesssim 10^{-31}\ e\ \mathrm{cm}$$

Result

$$\mathrm{Im}\left(\lambda_u^{11}\lambda_e^{11}\right) = \left|\lambda_u^{11}\lambda_e^{11}\right| \sin\theta_{ue}$$



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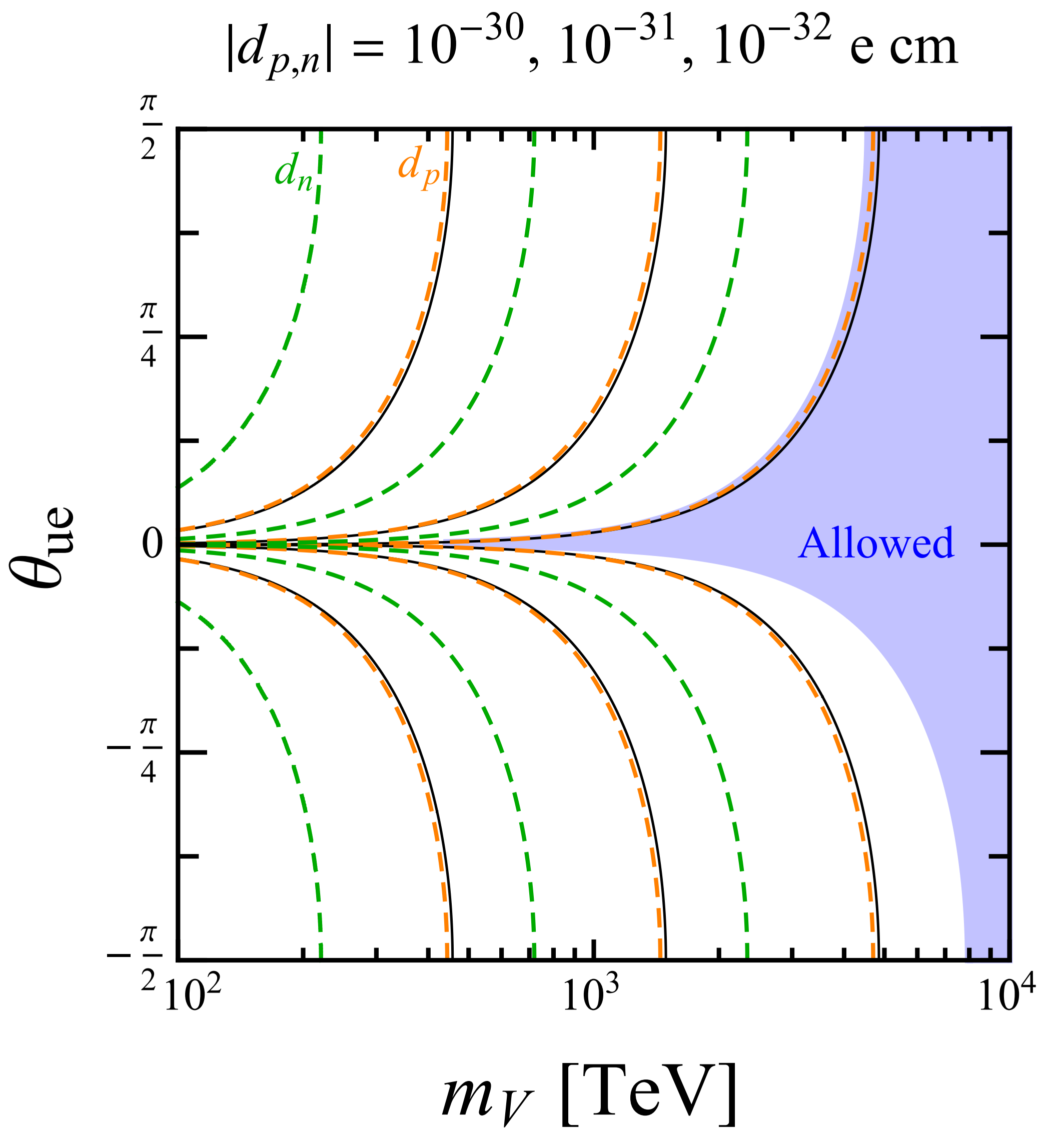
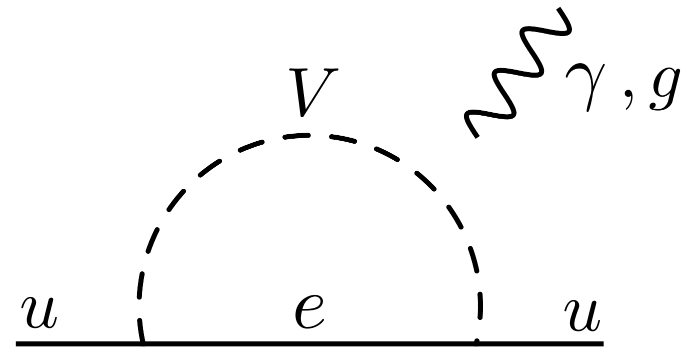
$$|d_e| = 10^{-29,30,31}\ e\ \mathrm{cm}$$

LQ Model : d_e < C_S

Result



Up-quark EDM and cEDM



Green : Neutron

Orange : Proton

$d_{p,n} \sim 10^{-32}$ e cm

* *Comparable to SM values*

Nonzero $d_{p,n}$ point to different CPV sources.

QCD theta term

QCD theta term

QCD theta term : $\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$

From neutron EDM limit : $\theta \lesssim 10^{-10}$

"Strong CP problem"

1. UV Solution   *Ex) Nelson-Barr models*   A.E. Nelson, PLB136 (1984) 387, S. M. A. Barr, PRD30(1984)1805. S. M. Barr, PRD30(1984)1805

$\theta = 0$ *at UV, but* $\theta \neq 0 \ (\approx 10^{-10})$ *at some scale.*

2. IR Solution   *Ex) Peccei-Quinn Symmetry*

$\theta \to a/f_a$ *a :Axion*   R. Peccei and H. R. Quinn, Phys.Rev.Lett. 38 (1977) 1440
R. Peccei and H. R. Quinn, Phys.Rev. D16 (1977) 1791{1797.

Dimension 6 operators

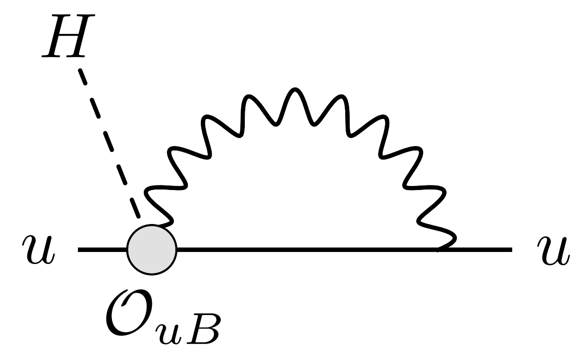
New Physics : Dimension 6 operators

For example, $\mathcal{O}_{uB} = \bar{Q}\sigma^{\mu\nu} u_R \tilde{H} B_{\mu\nu}$

They give large threshold corrections to theta term.

$$\Delta\theta \sim \frac{1}{16\pi^2\Lambda^2} C_{uB}\Lambda^2 \gg 10^{-10}$$

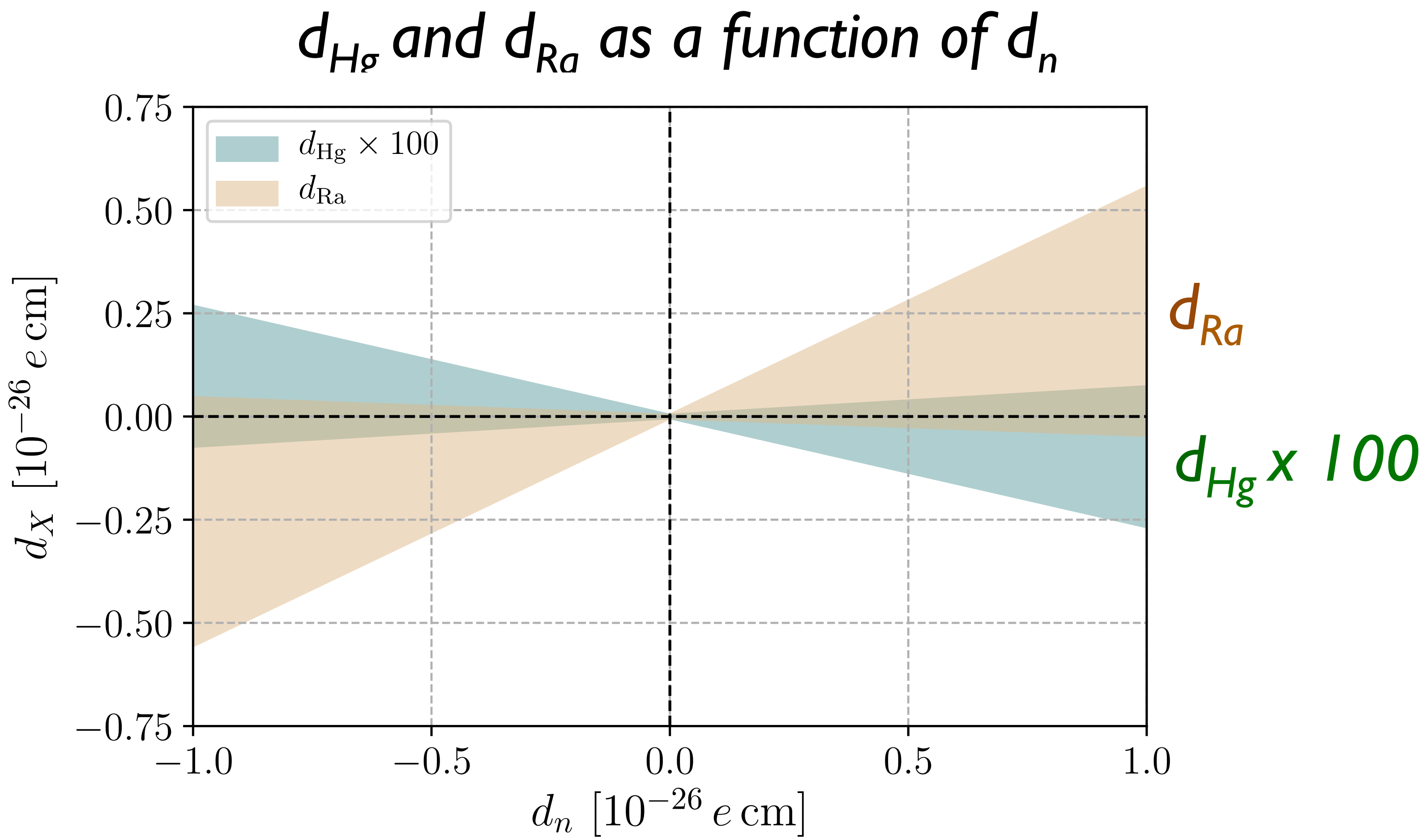
Quadratic divergence



If experiments, EDMs or colliders, see any sing of dim 6 operators, it might point to IR solution.

✔ See EDM predictions in pure theta scenario

Predictions of pure theta scenario

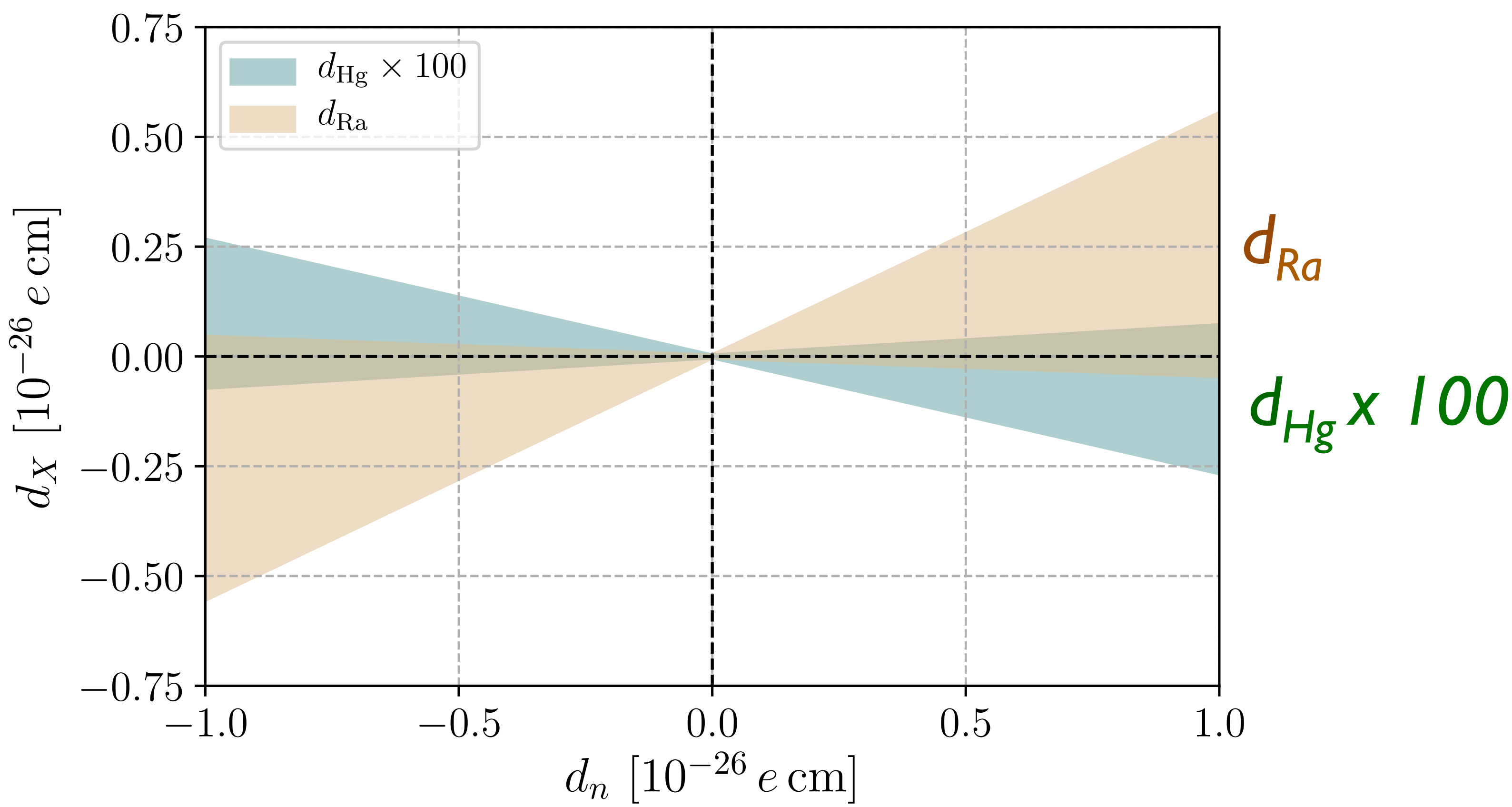


✔ *Inside of color regions is prediction in pure theta scenario.*

** Theoretical uncertainties give a spread of region.*

Predictions of pure theta scenario

d_{Hg} and d_{Ra} as a function of d_n

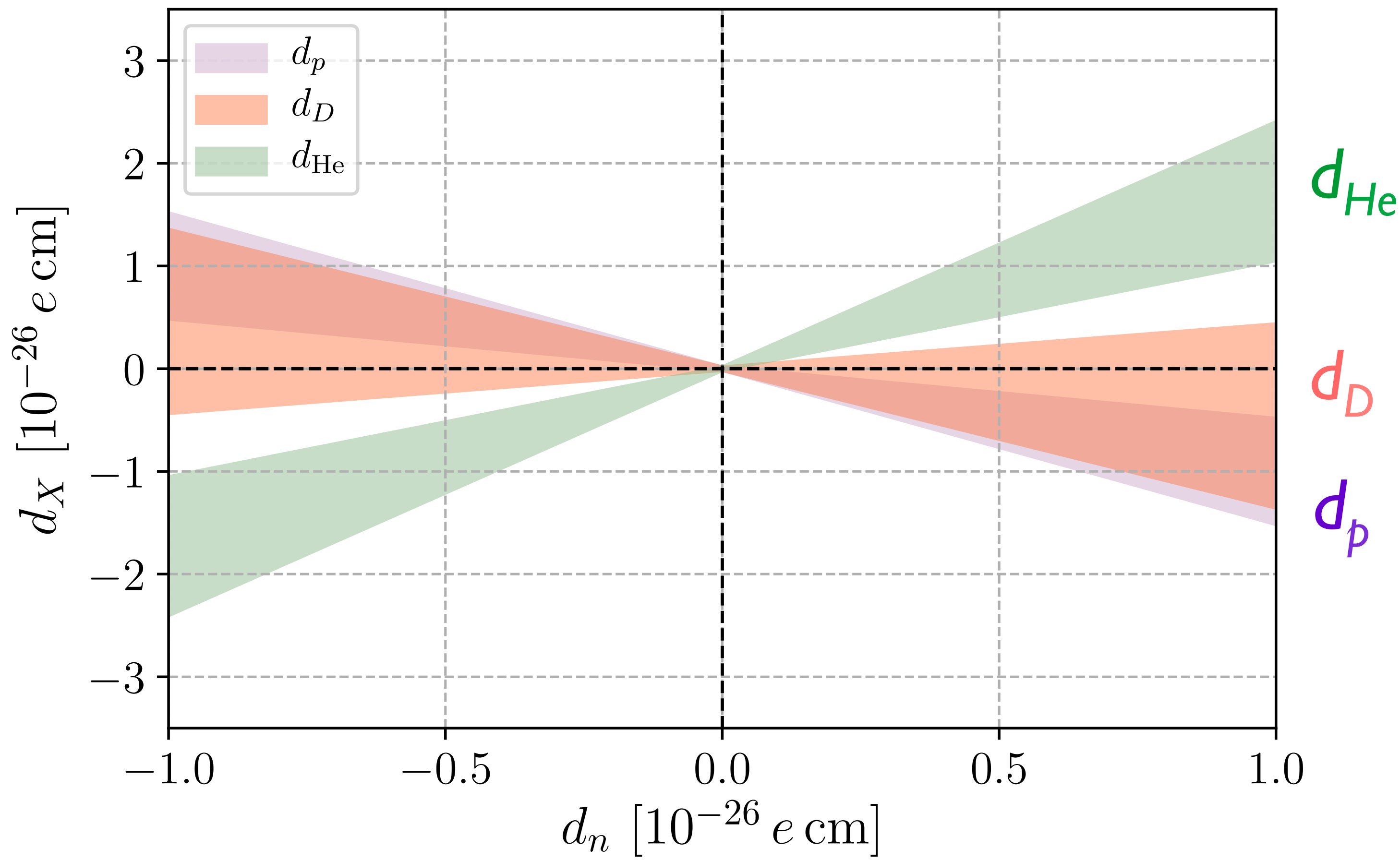


✔ *Inside of color regions is prediction in pure theta scenario.*

Outside of color regions point to other BSM CP sources.

Predictions of pure theta scenario

d_p, d_D and d_{He} as a function of d_n



EDM measurements would give implication for strong CP problem.

Conclusion

✔ *Leptoquark : Electron EDM and e-N interaction*

$d_e \ll C_S$ *C_S is dominant source.*

* *Sole-source limit is not available.*

✔ *Dark Photon : Dimension 5 operators*

$\frac{\tilde{\beta}}{\Lambda} \mathrm{Tr} \left[W_{\mu\nu} \Sigma \right] \tilde{X}_{\mu\nu}$ *Examined by EDMs.*

* *Induced by light degree of freedom*

✔ *QCD theta term : Unique EDM predictions*

Looking for various EDMs is necessary.

* *Implication for solution to strong CP problem*