Impact of the electroweak Weinberg operator on the electric dipole moment of electron

Kiyoto Ogawa (Nagoya.univ)
Collaborators: T.Banno, J.Hisano, T.Kitahara, N.Osamura

JHEP02(2025)082 [arXiv:2408.02375]
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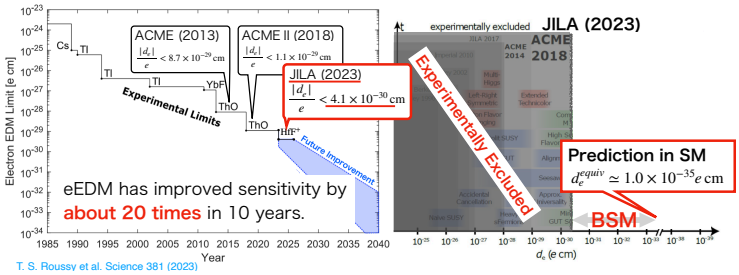
1. Introduction

Electric Dipole Moment (EDM) $\mathcal{L} = -d\frac{i}{2}\bar{\psi}\sigma_{\mu\nu}F^{\mu\nu}\gamma_5\psi$

Parity(P) & Time reversal(T=CP) symmetries are violated

Especially, eEDM has improved sensitivity drastically!



T. S. Roussy et al. Science 381 (2023)
R. Alarcon et al. "Electric dipole moments and the search for new physics" in Snowmass,(2021),(2022)
https://cfp.physics.northwestern.edu/gabrielse-group/acme-electron-edm.html
Y. Ema, T. Gao, M. Pospelov,Phys.Rev.Lett. 129 (2022) 23, 231801 M. Pospelov, A. Ritz, Phys.Rev.D 89 (2014) 5, 056006

eEDM is attractive observable to probe BSM!

2. Set Up in our work

- **order estimate on eEDM (n-loop)**

$$\frac{d_e}{e} \approx \left(\frac{\lambda^2}{16\pi^2}\right)^n \frac{m_e}{\Lambda^2}\sin\phi_{CP} \quad \begin{bmatrix} n: \text{loop order} & \Lambda: \text{BSM scale} \\ \lambda: \text{coupling constants} & \sin\phi_{CP}: \text{CP phase} \end{bmatrix}$$

- **constraints to BSM scale**

Current

$$\frac{|d_e|}{e} < 4.1\times10^{-30}\,\text{cm} \quad \begin{pmatrix}\lambda \simeq g\ (\text{SU(2)}_L\ \text{gauge coupling}) \\ \sin\phi_{CP} = O(1)\end{pmatrix}$$

$\Lambda \gtrsim 80$ TeV (n = 1)
$\Lambda \gtrsim 4$ TeV (n = 2)
$\Lambda \gtrsim 200$ GeV (n = 3)

Future Experiments

$\frac{|d_e|}{e} < O(10^{-31})\,\text{cm} \Rightarrow \Lambda \gtrsim 1$ TeV (n = 3)

$\frac{|d_e|}{e} < O(10^{-32})\,\text{cm} \Rightarrow \Lambda \gtrsim 3$ TeV (n = 3)

sensitive to TeV scale at 3-loop level

➡ Motivation in our work!

We consider the case that induce eEDM at 3-loop level

TeV / SM

$SU(2)_L$ multiplets : ψ_A, ψ_B (fermion), S (scalar)

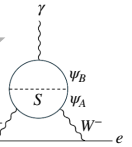
CP violating Yukawa interaction $\mathcal{L} \supset -\bar{\psi}_B g_{\bar{B}AS}\psi_A S - \bar{\psi}_A g_{\bar{A}\bar{B}\bar{S}}\bar{\psi}_B S^*$

$g_{BAS} = X_{BAS}(s + \gamma_5 a)$ (s, a : complex number)
$g_{\bar{A}\bar{B}\bar{S}} = X_{\bar{A}\bar{B}\bar{S}}(s^* - \gamma_5 a^*)$ ($X_{BAS}, X_{\bar{A}\bar{B}\bar{S}}$: coefficients that depend on representation)

~~CP~~

EFT approach

eEDM



2-loop

Electroweak-Weinberg Operator

T. Abe, J. Hisano, and R. Nagai, JHEP 03 (2018) 175

$\mathcal{L}_W = -\frac{g^3}{3}C_W f^{abc}W^a_{\mu\nu}W^{b\nu}_{\ \rho}\tilde{W}^{c\rho\mu}$ $\tilde{W}^a_{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}W^a_{\rho\sigma}$

1-loop

eEDM

F. Boudjema et.al.Phys. Rev. D43(1991) 2223–2232

3-loop contribution is Leading Order(LO)!

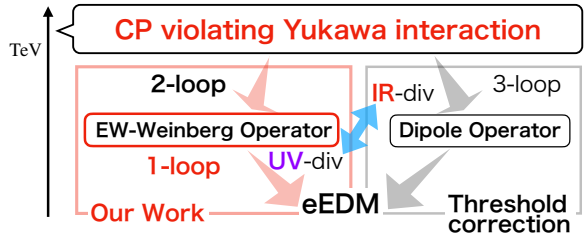
- The neutral component of the $SU(2)_L$ multiplets is DM candidate. (Minimal DM)
- quintuplet fermion, septet scalar are favored (DM stability)

M. Cirelli and A. Strumia, New J. Phys. 11(2009) 105005

Our Work : Evaluate eEDM in EFT approach

➡ Can this model de probed in the future experiment?

3.eEDM induced by EW-Weinberg operator



UV & IR-div must be removed by the consistent regularization.

dimensional regularization(DR)

- **Lagrangian 4-dim → d-dim** $\mathcal{L}^{(d)} = \mathcal{L}^{(4)} + \mathcal{L}^{(d-4)}$ Evanescent operator
- Treatment for γ_5 & Levi-Chivita symbol
  Bollini-Méndez-Holeman-Veltman(BMHV) Scheme

G. 't Hooft and M. J. G. Veltman, Nucl. Phys. B 44 (1972) 189–213.

- **γ_5 & Levi-Chivita symbol are defined as 4-dimensional**

$\gamma_5 = -\frac{i}{4!}\bar{\epsilon}^{\mu\nu\rho\sigma}\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma$ $\hat{\epsilon}^{\mu\nu\rho\sigma} = 0$

- **give up anticommutation property**

$\{\bar{\gamma}^\mu, \gamma_5\} = 0,\ [\hat{\gamma}^\mu, \gamma_5] = 0$

※ bars and hats conventionally represent 4 and (d − 4)-dim.

EW-Weinberg Operator in d-dim

$\mathcal{L}^d_W = -\frac{g^3}{3}C^{(4)}_W f^{abc}\bar{W}^a_{\mu\nu}\bar{W}^{b\nu}_{\ \rho}\tilde{\bar{W}}^{c\rho\mu} - \frac{g^3}{3}C^{(d-4)}_W f^{abc}\hat{W}^a_{\mu\hat{\nu}}\hat{W}^{b\hat{\nu}}_{\ \ \rho}\tilde{\hat{W}}^{c\rho\mu}$

eEDM

Result1 $\frac{d_e}{e} = \frac{\alpha_2^2}{6}m_e C^{(4)}_W + \frac{\alpha_2^2}{9}m_e C^{(d-4)}_W$

We separately evaluate the 4- & (d-4)-dim contributions.

We do not understand about $C^{(d-4)}_W$.

➡ **In our study, we analyze 4-dim result.**

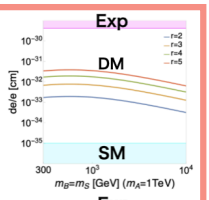
4.Numerical analysis

$(A, B, S) = (r, 1, r)$ $\text{Im}(sa^*) = 0.25$

- **EW-Weinberg contribution is the window between the experimental constraints and SM.**

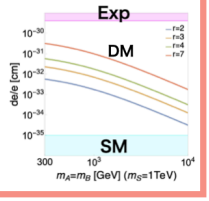
Result2

This scenario can be tested in future eEDM!



- In Minimal Dark Matter model, higher representation is favored.

Minimal DM might be tested in 203X.



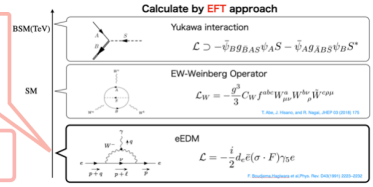
5.Conclusion

TeV scale physics which induces eEDM by 3-loop level is attractive!

- **Our Work**

We consider eEDM induced by Yukawa interaction of $SU(2)_L$ multiplets.

Result1 **We separately evaluate the 4- & (d-4)-dim contributions.**

$\frac{d_e}{e} = \frac{\alpha_2^2}{6}m_e C^{(4)}_W + \frac{\alpha_2^2}{9}m_e C^{(d-4)}_W$

Result2 **This scenario can be tested in future eEDM!!**