

Electric Dipole Moments of Charged Leptons with Sterile Fermions

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Rencontre de Physique des Particules 2016

Based on arXiv:1511.03265

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Introduction

- Adding sterile fermions to the SM is an economical extension.
(motivated by neutrino masses and mixings, keV DM, baryon asymmetry of the universe)
- In the extended model, new CP violating phases are introduced in lepton sector (necessary).
→ charged lepton EDMs.

$$\mathcal{L}_{\text{eff}} = -\frac{d_\ell}{2} \bar{\ell} i\sigma^{\mu\nu} \gamma_5 \ell F_{\mu\nu}$$

- Current bounds of charged lepton EDMs

$$|d_e|/e < 8.7 \times 10^{-29} \text{ cm} \quad (\text{ACME})$$

$$|d_\mu|/e < 1.9 \times 10^{-19} \text{ cm} \quad (\text{Muon } g-2)$$

$$|d_\tau|/e < 4.5 \times 10^{-17} \text{ cm} \quad (\text{Belle})$$

Bound of electron EDM is much stronger than muon and tau.

The Model

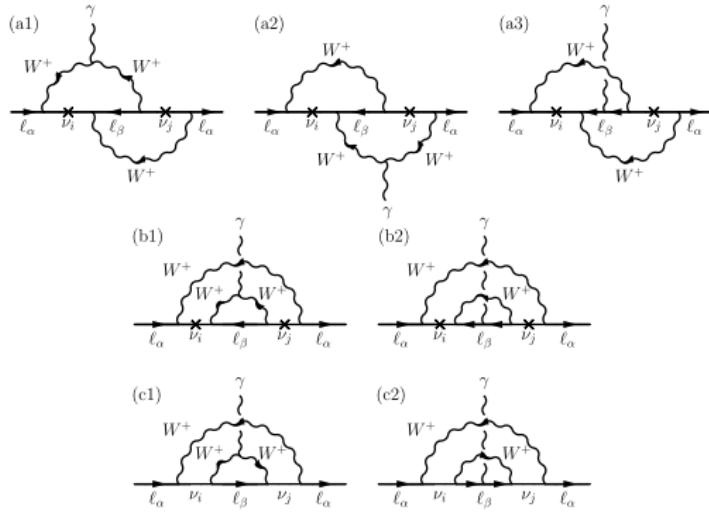
- The SM plus N sterile fermions (We focus on $N = 1, 2$).
- The interactions are given by

$$\mathcal{L} = -\frac{g_2}{\sqrt{2}} U_{\alpha i} W_\mu^- \bar{\ell}_\alpha \gamma^\mu P_L \nu_i - \frac{g_2}{\sqrt{2}} U_{\alpha i} H^- \bar{\ell}_\alpha \left(\frac{m_\alpha}{m_W} P_L - \frac{m_i}{m_W} P_R \right) \nu_i + \text{H.c.}$$

in Feynman-'t Hooft gauge.

- We do not fix neutrino mass generation mechanism.
(Ex. Type-I seesaw, Type-II seesaw, Inverse seesaw, Linear seesaw)
→ the mixing matrix $U_{\alpha i}$ and the neutrino mass m_i are independent.
- Parametrization of U
For $N = 1$ case, 3 Dirac and 3 Majorana phases are included.
For $N = 2$ case, 6 Dirac and 4 Majorana phases are included.

Diagrams contributing to EDM



- Leading contribution comes from two-loop.
- Totally 44 diagrams exist in Feynman-'t Hooft gauge.
- Analytical result is obtained by using FeynCalc.
- EDMs are numerically evaluated.

$$d_\alpha \approx -\frac{g_2^4 e m_\alpha}{4(4\pi)^4 m_W^2} \sum_{\beta} \sum_{i,j} \sqrt{x_i x_j} \left[J_{ij\alpha\beta}^M I_M(x_i, x_j) + J_{ij\alpha\beta}^D I_D(x_i, x_j) \right]$$

where $\alpha, \beta = e, \mu, \tau$ and $i, j = 1 - 4$ or $1 - 5$. ($x_i \equiv m_i^2/m_W^2$)

$$J_{ij\alpha\beta}^M \equiv \text{Im} (U_{\alpha j} U_{\beta j} U_{\beta i}^* U_{\alpha i}^*) , \quad J_{ij\alpha\beta}^D \equiv \text{Im} (U_{\alpha j} U_{\beta i}^* U_{\beta i} U_{\alpha i}^*)$$

$N = 1$ case

- $I_{M,D}$ can be expanded by x_i, x_j for $i, j = 1, 2, 3$.
 $(x_i \equiv m_i^2/m_W^2 \ll 1, x_4 \ll 1)$
- $\sum_{i=1}^3 \sqrt{x_i} J_{i4\alpha\beta}^M = 0$ for $N = 1$ case

because of $\sum_{i=1}^4 U_{\alpha i}^* m_i U_{\beta i}^* = m_{\alpha\beta} = 0$.

$$d_\alpha \approx -\frac{g_2^4 e m_\alpha}{2(4\pi)^4 m_W^2} \sum_\beta \sum_{i=1}^3 \sqrt{x_i x_4} \left[J_{i4\alpha\beta}^M x_i \frac{\partial I_M}{\partial x_i}(0, x_4) + J_{i4\alpha\beta}^D I_D(0, x_4) \right]$$

The predicted EDM is very suppressed. Ex. $|d_\tau|/e \lesssim 10^{-35}$ cm.

$N = 2$ case

EDMs can potentially be large enough to be detected.

Constraints

- Lepton Flavour Violation

$$\text{Br}(\mu \rightarrow e\gamma) \leq 5.7 \times 10^{-13}$$

$$\text{Br}(\mu \rightarrow e\bar{e}e) \leq 1.0 \times 10^{-12}$$

- Direct collider production

$$pp \rightarrow W^{\pm*} \rightarrow \ell^\pm \nu_i \rightarrow \ell^\pm \ell^\pm jj \text{ at LHC}$$

$$e^+e^- \rightarrow \nu_i \nu_j^* \rightarrow \nu_i e^\pm W^\mp \text{ at ILC}$$

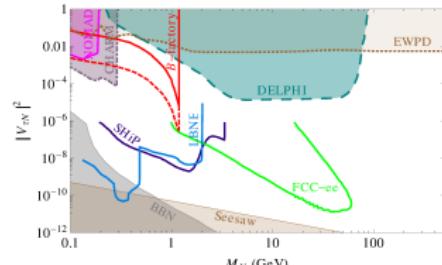
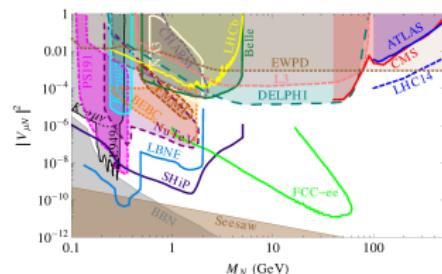
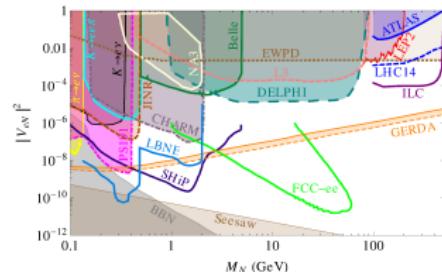
- Electroweak precision data

W boson decay, Z invisible decay,
Lepton flavor universality of meson
decays,

Non-unitarity of the mixing matrix $U_{\alpha i}$

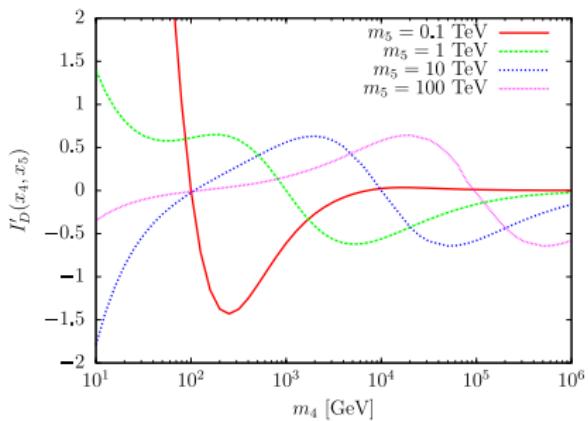
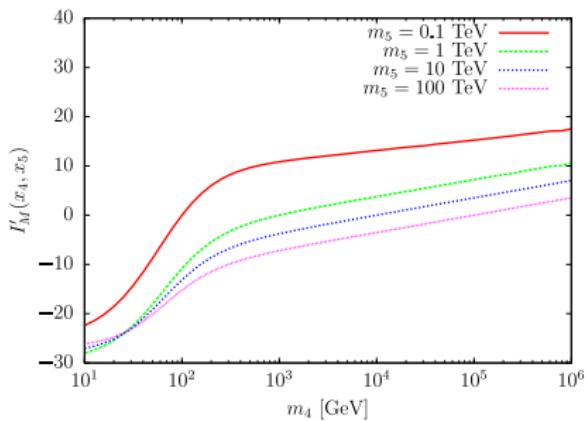
- Perturbative unitarity bound

$$\frac{\Gamma_{\nu_i}}{m_i} < \frac{1}{2}$$



Numerical Analysis

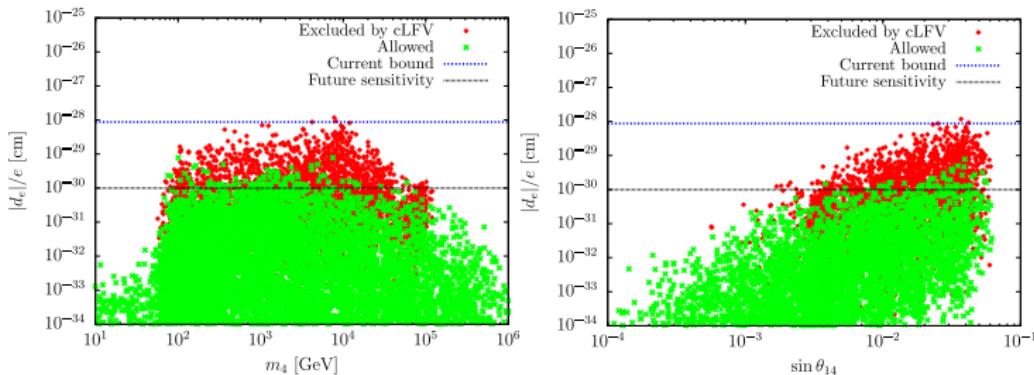
Loop functions I_M , I_D



- When $x_i, x_j \gg 1$, $I_M(x_i, x_j) \gg I_D(x_i, x_j)$
- Since I_M increases with $\log(x_i/x_j)$, I_M is dominant.
- $I_D \gg I_M$ if $x_i, x_j \ll 1$, but the predicted EDMs are too small.

Numerical Analysis

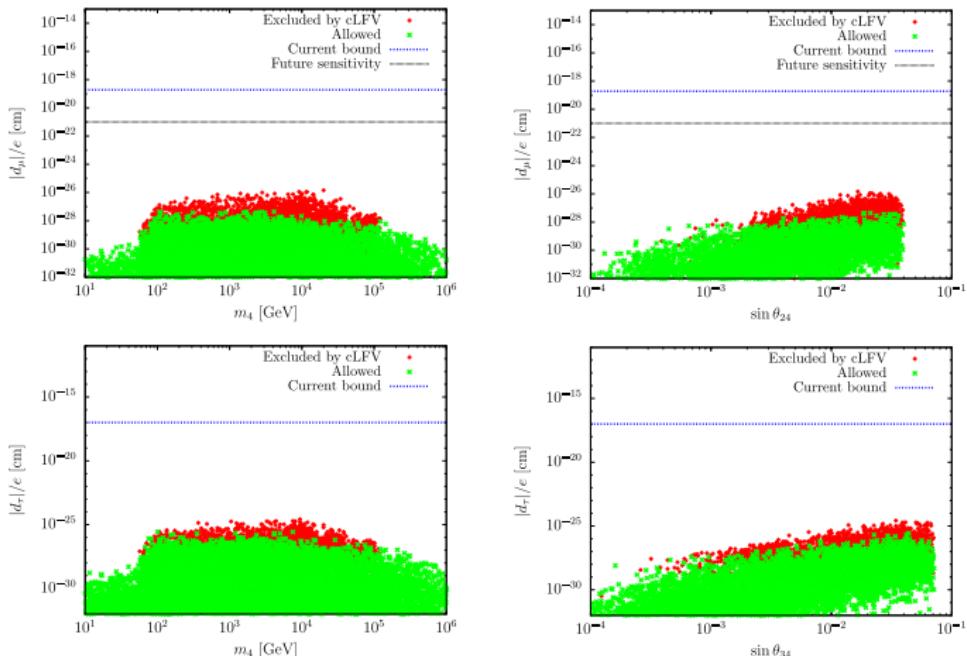
Electron EDM



- Large sterile fermion mass is cut by perturbative unitarity bound.
- Upper region is constrained by cLFV.
- Below $\mathcal{O}(100)$ GeV region is constrained by electroweak precision data.
- All the green points are lower than current bound. But can reach to future prospect (ACME).

Numerical Analysis

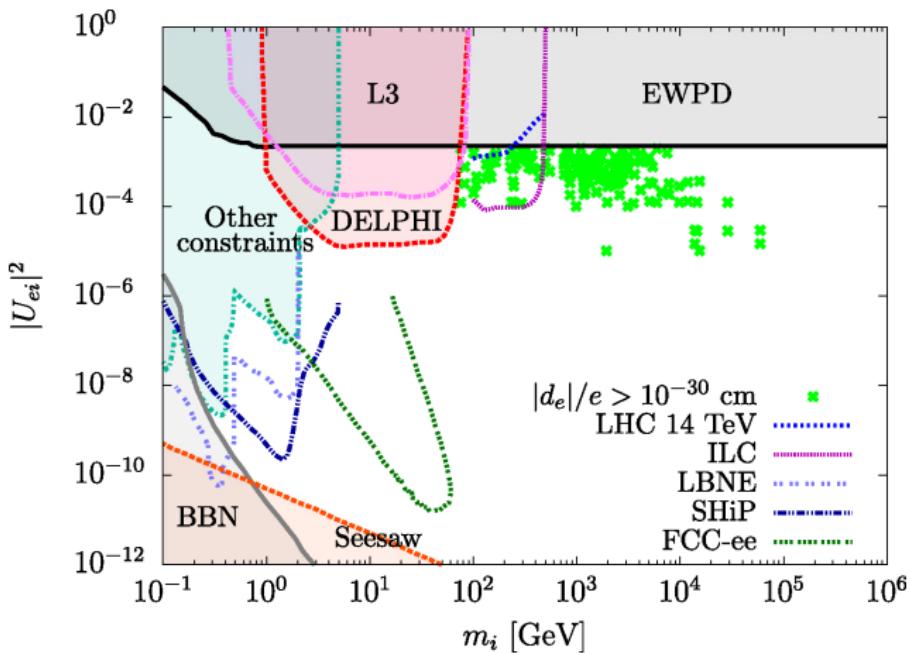
Muon and tau EDM



- Predicted values are much below the future prospects.

Numerical Analysis

In $m_i - |U_{ei}|^2$ plane for electron



- Colored region is already excluded.
- Green points: $|d_e|/e \gtrsim 10^{-30}$ cm.
- Some parameter space can be tested by ILC.

Summary

- 1 We computed charged lepton EDMs at two-loop level.
- 2 At least 2 sterile fermions are needed to get sizable electron EDM which is testable by future experiments.
- 3 Majorana nature of neutrino is important to get a large EDM of charged leptons ($I_M \gg I_D$).
- 4 Sterile fermion masses should be 100 GeV – 10 TeV in order to get a comparable electron EDM with future prospect.