Electric Dipole Moments of Charged Leptons with Sterile Fermions

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Electric Dipole Moments (EDMs) and Neutrino Models

EDM is a CP (Charge and Parity) violating observable which is also relevant to the origin of the baryon asymmetry in the universe. The fact that CP is violating in the quark sector in the Standard Model (SM) is well-known. However it is not enough to explain the observed baryon asymmetry in the universe. Observing EDMs may be related with the existence of new physics beyond the SM. The current experimental upper bounds:

$$|d_e|/e \leq 8.7\times10^{-29}\ \mathrm{cm}\quad (\mathrm{ACME})$$
$$|d_\mu|/e \leq 1.9\times10^{-19}\ \mathrm{cm}\quad (\mathrm{Muon}\ g-2)$$
$$|d_\tau|/e \leq 4.5\times10^{-17}\ \mathrm{cm}\quad (\mathrm{Belle})$$

We consider the models extended with some sterile fermions which are motivatied to explain the non-zero neutrino masses and large mixing angles.

[1] First, we consider a toy model with N sterile fermions.

- This model can be regarded as an effective model of Type-I seesaw, Inverse Seesaw and Linear Seesaw models.
- No correlation is assumed between sterile fermion masses and mixings. Sterile fermion masses and mixings are treated as free parameters. $\to$ EDMs are computed.

[2] Second, we apply our computation to a specific model which is the minimal Inverse Seesaw model.

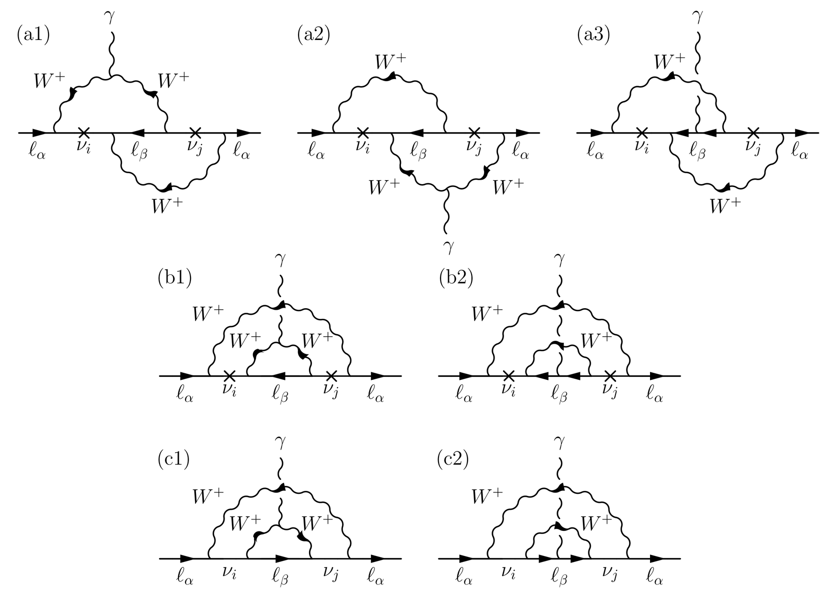
- In Inverse Seesaw models, N right-handed neutrinos and M singlet fermions are generally introduced to the SM.
- The model with $N=2$ and $M=2$ is the minimal realization to reproduce the neutrino oscillation data.

The mass matrix of the (2,2) minimal inverse seesaw model are given by

$$M=\begin{pmatrix} 0&0&0&d_{11}&d_{12}&0&0\\ 0&0&0&d_{21}&d_{22}&0&0\\ 0&0&0&d_{31}&d_{32}&0&0\\ d_{11}&d_{21}&d_{31}&0&0&n_1&0\\ d_{12}&d_{22}&d_{32}&0&0&0&n_2\\ 0&0&0&n_1&0&\mu_{11}&\mu_{12}\\ 0&0&0&0&n_2&\mu_{12}&\mu_{22}\end{pmatrix}\begin{matrix}\nu_{L1}\\ \nu_{L2}\\ \nu_{L3}\\ N_1^c\\ N_2^c\\ s_1\\ s_2\end{matrix}$$

$$\to\quad \text{diagonalize}\quad U^TMU=\mathrm{diag}(m_1,\cdots,m_7)$$

EDM Computations with Sterile Fermions



The leading contribution to the charged lepton EDMs is given at two-loop level.

$$i\mathscr{M}=d_\ell\,\varepsilon_\mu^*(q)\overline{u}(p_2)i\sigma^{\mu\nu}q_\nu\gamma_5u(p_1).$$

The formula of the EDMs is formally given by

$$d_\ell=-\frac{g_2^4em_\ell}{4(4\pi)^4m_W^2}\sum_{\ell'}\sum_{i,j}\left[J^M_{ij\ell\ell'}I_M(x_i,x_j)+J^D_{ij\ell\ell'}I_D(x_i,x_j)\right],$$

where $x_i=m_i^2/m_W^2$, $J^M_{ij\ell\ell'}$ and $J^D_{ij\ell\ell'}$ are the phase factors defined by

$$J^M_{ij\ell\ell'}\equiv\mathrm{Im}\left(U_{\ell j}U_{\ell' j}U^*_{\ell' i}U^*_{\ell i}\right),\quad J^D_{ij\ell\ell'}\equiv\mathrm{Im}\left(U_{\ell j}U^*_{\ell' j}U_{\ell' i}U^*_{\ell i}\right).$$

There are a lot of diagrams we should compute.

- The number of diagrams depend on the gauge fixing. If the Feynman gauge is chosen, roughly 100 of diagrams must be computed since the propagator of the W boson includes the Goldstone boson contribution (longitudinal mode).
- The loop functions $I_{M/D}(x_i,x_j)$ can be computed analytically with FeynCalc. This is the most difficult part of the EDM compututation.
- The diagrams (a), (b) give a non-zero contribution only if the sterile fermions in the loops are Majorana fermions (Majorana contributions).
- On the other hand, the contribution of the diagrams (c) always exists which corresponds to Dirac contributions.
- The phase factors $J^M_{ij\ell\ell'}$ and $J^D_{ij\ell\ell'}$ are anti-symmetric in terms of $i\leftrightarrow j$. The loop functions I_M and I_D are also anti-symmetric. Therefore the EDMs itself are symmetric under $i\leftrightarrow j$.
- At least 2 sterile fermions are required to obtain the electron EDM comparable to the current experimental bound or future sensitivity. (Future sensitivity: $|d_e|/e\sim10^{-30}$ cm)

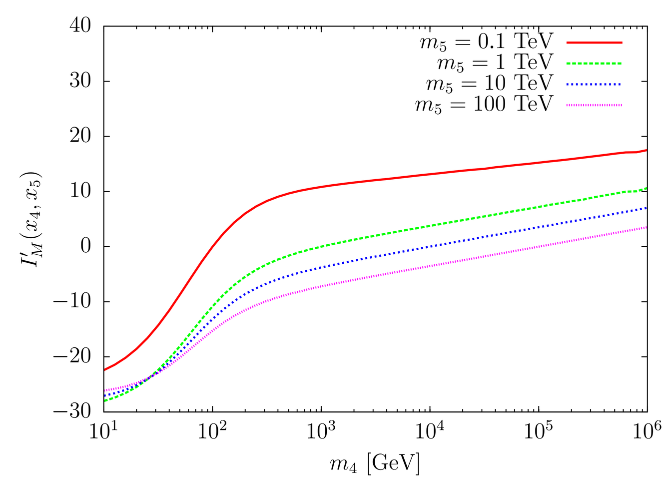
Constraints and Numerical Results in the Effective Model with 2 Sterile Fermions

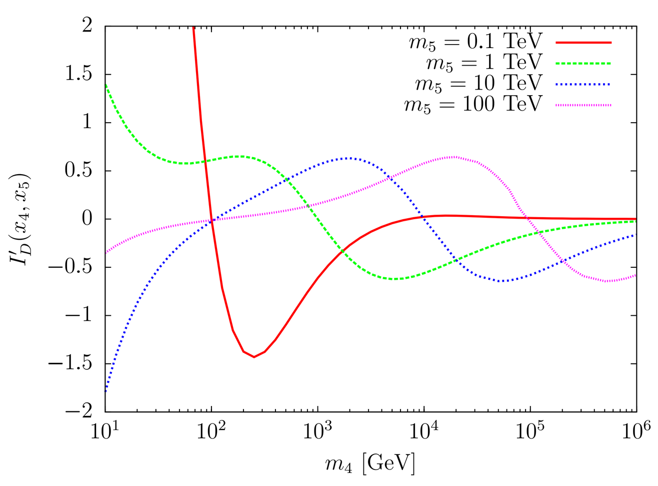
[1] Constraints

- Lepton flavour violating processes ($\mu\to e\gamma$, $\mu\to e\bar{e}e$)
  The current upper bounds: $\mathrm{Br}(\mu\to e\gamma)\leq5.7\times10^{-13}$, $\mathrm{Br}(\mu\to e\bar{e}e)\leq1.0\times10^{-12}$.
- Direct collider production of sterile fermions at colliders
  $e^+e^-\to\nu_i\nu_j^*\to\nu_ie^\pm W^\mp$ at the LEP and $pp\to W^{\pm *}\to\ell^\pm\nu_i\to\ell^\pm\ell^\pm jj$ at the LHC.
- Electroweak precision data
  Non-unitarity of the PMNS matrix U_{PMNS}, deviation of the W and Z decay width.
- Perturbative unitarity bound: $\dfrac{\Gamma_{\nu_i}}{m_i}\lesssim\dfrac{1}{2}$ where $\Gamma_{\nu_i}=\dfrac{g_2^2m_i^3}{16\pi m_W^2}\sum_\ell|U_{\ell i}|^2$.

In particular, the constraints of lepton flavour violation and pertubative unitarity are relevant with the EDMs.

[2] Numerical Results

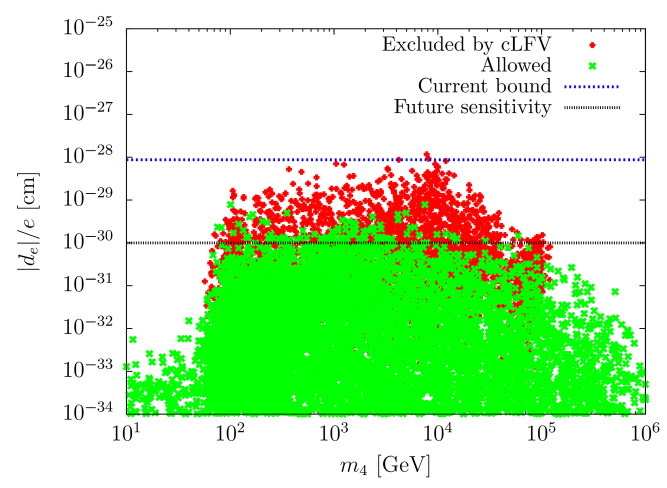


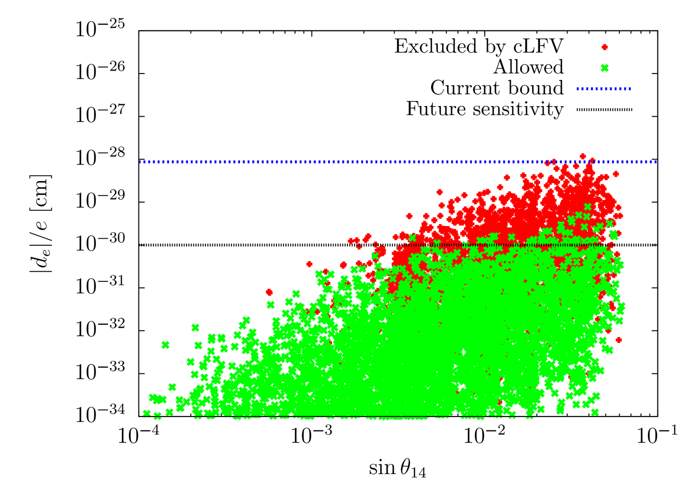


One can see that I_M is dominant in the most of the region and thus Majorana nature of the sterile fermions is important to induce a large EDM. Note that $I'_{M/D}(x_i,x_j)=\sqrt{x_i x_j}I_{M/D}(x_i,x_j)$.

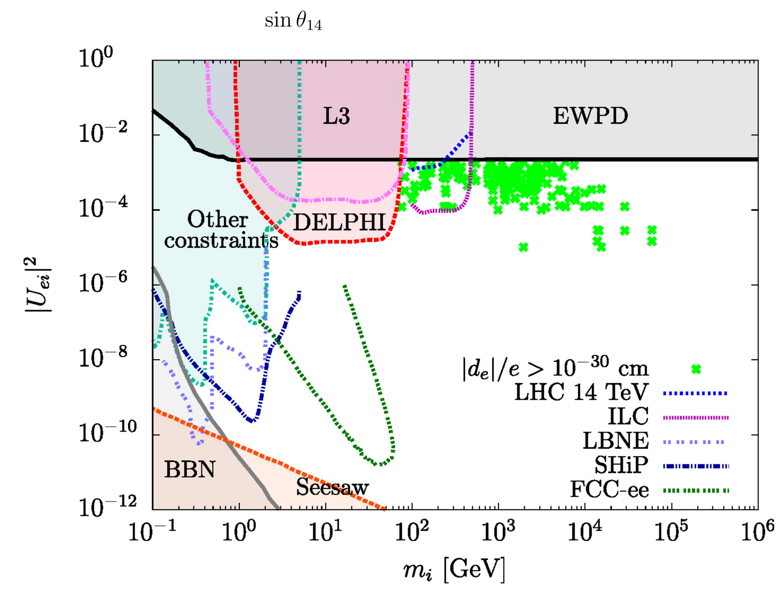
We explore the following ranges of the parameters.

$$1\ \mathrm{GeV}\leq m_i\leq10^6\ \mathrm{GeV},\quad \text{mixing anlges between light neutrinos and sterile states}\leq0.1.$$

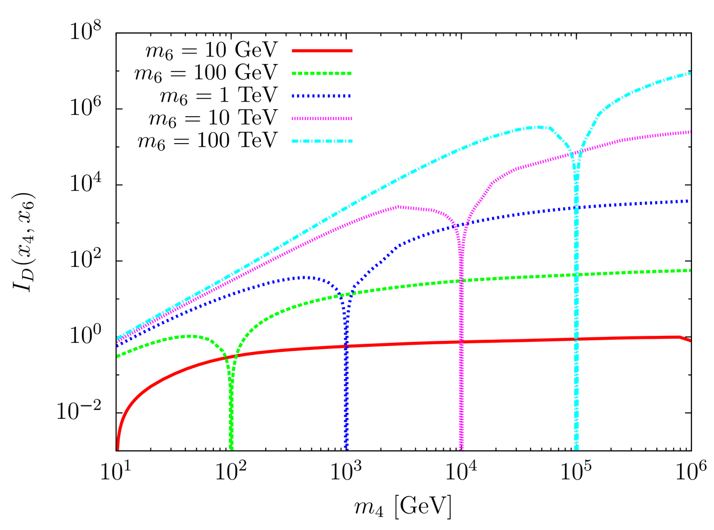


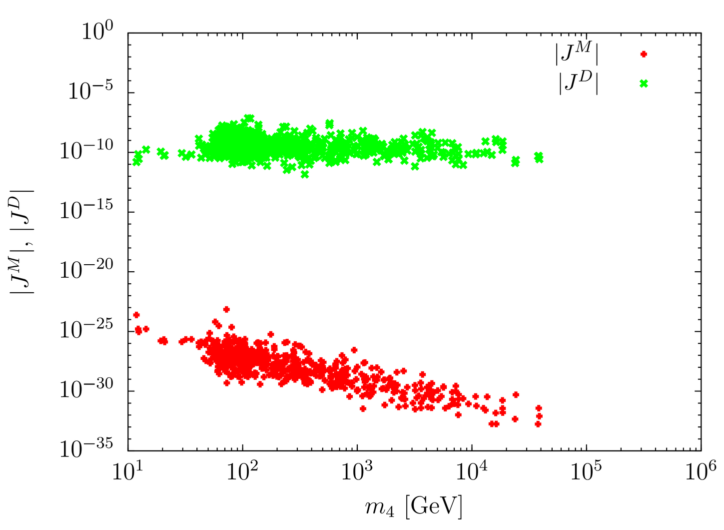


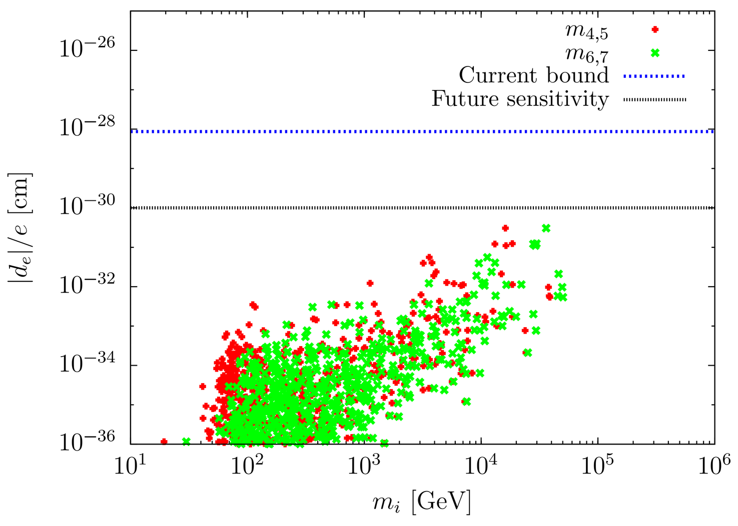
- One order of magnitude lower than the current experimental bound. But the predicted electron EDM can reach to the future sensitivity (update of ACME Collaboration).
- The sterile fermions masses should be in the range of 10^2 GeV $\lesssim m_i\lesssim10^5$ GeV to obtain electron EDM comparable with the future sensitivity.
- For the other charged leptons, the predicted EDMs are roughly given by $\dfrac{|d_e|}{m_e}\sim\dfrac{|d_\mu|}{m_\mu}\sim\dfrac{|d_\tau|}{m_\tau}$. These are very smaller than the current bounds and future sensitivities unfortunately.

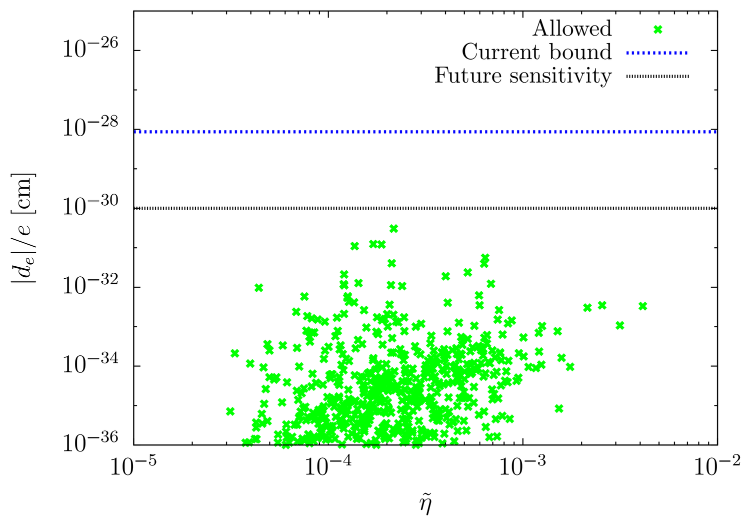


EDMs in the (2,2) Minimal Inverse Seesaw Model









Since the pairs of the mass eigenstates (ν_4, ν_5) and (ν_6, ν_7) are degenerate, the EDM formula can be simplified as

$$d_e\approx-\frac{g_2^4em_e}{2(4\pi)^2m_W^2}J^DI_D(x_4,x_6),\quad\text{where}\quad J^D=\sum_\beta\left[J^D_{46e\beta}+J^D_{47e\beta}+J^D_{56e\beta}+J^D_{57e\beta}\right].$$

$\tilde{\eta}=1-|\det(\tilde{U}_{\mathrm{PMNS}})|$ is the parameter which represents the deviation from the unitarity of the mixing matrix U_{ij}.

- The loop functions can be larger for heavier sterile neutrino masses. However they are theoretically and experimentally bounded from above for heavy sterile neutrino masses.
- The phase factors show $|J^M|\ll|J^D|$ as expected. This is because the sterile neutrinos make pseudo-Dirac states in Inverse Seesaw models.
- The electron EDM can be a few factor below the future sensitivity at most when the sterile neutrino masses are above electroweak scale.

Summary and Discussion

- We computed EDMs in the effective model with 2 sterile fermions and a more specific (2,2) Inverse Seesaw model which is the minimal model consistent with the neutrino oscillation data.
- In the effective models, Majorana nature of the sterile fermions is important to induce a large EDM. At least 2 sterile fermions are needed. The sterile fermion masses should be above electroweak scale to induce a large EDM.
- In the Inverse Seesaw model, since the sterile neutrinos are pseudo-Dirac states, the predicted electron EDM is somewhat weakened. However, it can be slightly below the future sensitivity.
- If we introduce more sterile fermions, a factor larger EDM is expected. But since the constraint of $\mu\to e\gamma$ also becomes stronger, only factor 2 enhancement would be expected at most.
- In Inverse Seesaw models, the EDMs may be correlated with the resonant leptogenesis since the sterile fermion states are naturally degenerate. However since the lightest sterile state should satisfy the out-of equiribrium condition for leptogenesis, the mixing matrix must be very small to generate sufficient baryon asymmetry. $\to$ no correlation.