

Electric Dipole moments of charged leptons and lepton flavor violating interactions in the general two Higgs Doublet model

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Abstract

We calculate the electric dipole moment of electron using the experimental result of muon electric dipole moment and upper limit of the $BR(\mu \rightarrow e\gamma)$ in the framework of the general two Higgs doublet model. Our prediction is $10^{-32} e - cm$, which lies in the experimental current limits. Further, we obtain constraints for the Yukawa couplings $\bar{\xi}_{N,\tau e}^D$ and $\bar{\xi}_{N,\tau\mu}^D$. Finally we present an expression which connects the $BR(\tau \rightarrow \mu\gamma)$ and the electric dipole moment of τ -lepton and study the relation between these physical quantities.

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1 Introduction

Lepton Flavor Violating (LFV) interactions are one of the important source of physics beyond the Standard model (SM) and have reached great interest with the improvement of experimental measurements. The processes $\mu \rightarrow e\gamma$ and $\tau \rightarrow \mu\gamma$ are the examples of LFV interactions and the current limits for their branching ratios (BR) are 1.2×10^{-11} [1] and 1.1×10^{-6} [2] respectively. In such decays, the assumption of the non-existence of Cabibbo-Kobayashi-Maskawa (CKM) type matrix in the leptonic sector forbids the charged Flavor Changing (FC) interactions and therefore the physics beyond the SM plays the main role, where the general two Higgs doublet model (2HDM), so called model III, is one of the candidate. In this model, LFV interactions can exist at loop level with the help of the internal neutral higgs bosons h_0 and A_0 . The Yukawa couplings appearing in these loops are free parameters and their strength can be determined by the experimental data. In the literature, there are several studies on LFV interactions in different models. Such interactions are studied in a model independent way in [3], in the framework of model III 2HDM [4], in supersymmetric models [5, 6, 7, 8, 9, 10, 11].

CP violating effects also provide comprehensive information in the determination of free parameters of the various theoretical models. In extensions of the SM, new source of CP-violating phases occur. The exchanges of neutral Higgs bosons in the 2HDM [12] or the charged sector in multi Higgs doublet models (more than two Higgs doublets) [13] induce CP violating effects. In the model III 2HDM, one of the source for the CP violation is the complex Yukawa coupling. Non-zero Electric Dipole Moments (EDM) of the elementary particles are the sign of such violation. These are interesting from the experimental point of view since there are improvements in the experimental limits of charged lepton EDM. EDM of electron, muon and tau have been measured and the present limits are $d_e = 1.8 \pm 1.2 \pm 1.0 \times 10^{-27}$ [14], $d_\mu = (3.7 \pm 3.4) \times 10^{-19}$ [15] and $d_\tau = 3.1 \times 10^{-16}$ [16].

Dipole moments of leptons have been studied in the literature extensively. In [17], it is emphasized that the dominant contribution to the EDM of lighter leptons comes from two loop diagrams that involve one power of the Higgs Yukawa couplings. In this work, the CP-violation is assumed to be mediated by neutral Higgs scalars [18] and the EDM of electron is predicted at the order of the magnitude of $10^{-26} e - cm$. Further EDM of leptons have been analyzed in supersymmetric models [6, 11, 19]. In the recent work [20] EDM of leptons are studied by scaling them with corresponding lepton masses and the EDM of electron is predicted as $10^{-27} e - cm$.

In our work, we study EDM of leptons e, μ, τ and LFV processes $\mu \rightarrow e\gamma, \tau \rightarrow \mu\gamma$ in the

general 2HDM (model III). The source of EDM of a particle is the CP violated interaction and it can come from the complex Yukawa couplings. In the model III, it is possible to get a considerable EDM at one-loop level. Further, LFV processes can exist also at one-loop level with internal mediating neutral particles h_0 and A_0 since there is no CKM type matrix and therefore no charged FC interaction in the leptonic sector according to our assumption.

The paper is organized as follows: In Section 2, we present EDMs of e, μ, τ leptons and the expressions for the decay width of processes $\mu \rightarrow e\gamma$ and $\tau \rightarrow \mu\gamma$ in the framework of the model III. Section 3 is devoted to discussion and our conclusions.

2 Electric dipole moments of charged leptons and LFV interactions in the general two Higgs Doublet model.

The 2HDM type III permits flavor changing neutral currents (FCNC) at tree level and makes CP violating interactions possible with the choice of complex Yukawa couplings. The Yukawa interaction for the leptonic sector in the model III is

$$\mathcal{L}_Y = \eta_{ij}^D \bar{l}_{iL} \phi_1 E_{jR} + \xi_{ij}^D \bar{l}_{iL} \phi_2 E_{jR} + h.c. , \quad (1)$$

where i, j are family indices of leptons, L and R denote chiral projections $L(R) = 1/2(1 \mp \gamma_5)$, ϕ_i for $i = 1, 2$, are the two scalar doublets, l_{iL} and E_{jR} are lepton doublets and singlets respectively. Here ϕ_1 and ϕ_2 are chosen as

$$\phi_1 = \frac{1}{\sqrt{2}} \left[\begin{pmatrix} 0 \\ v + H^0 \end{pmatrix} + \begin{pmatrix} \sqrt{2}\chi^+ \\ i\chi^0 \end{pmatrix} \right] ; \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}H^+ \\ H_1 + iH_2 \end{pmatrix} , \quad (2)$$

and the vacuum expectation values are

$$\langle \phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} ; \langle \phi_2 \rangle = 0 . \quad (3)$$

With this choice, the SM particles can be collected in the first doublet and the new particles in the second one. The part which produce FCNC at tree level is

$$\mathcal{L}_{Y,FC} = \xi_{ij}^D \bar{l}_{iL} \phi_2 E_{jR} + h.c. . \quad (4)$$

Here the Yukawa matrices ξ_{ij}^D have in general complex entries. Note that in the following we replace ξ^D with ξ_N^D where "N" denotes the word "neutral". The complex Yukawa couplings are the source of CP violation and EDM of particles are created by the CP violated interactions. The effective EDM interaction for a lepton is defined as

$$\mathcal{L}_{EDM} = id_l \bar{l} \gamma_5 \sigma_{\mu\nu} l F^{\mu\nu} , \quad (5)$$

where $F_{\mu\nu}$ is the electromagnetic field tensor and "d_l" is EDM of the lepton. Here, "d_l" is a real number by hermiticity. Concentrating only on neutral currents in the model III, the neutral Higgs bosons h_0, A_0 can induce CP violating interactions which can create EDM at loop level. Note that, we take H_1 and H_2 in eq. (2) as the mass eigenstates h_0 and A_0 respectively since no mixing between CP-even neutral Higgs bosons h_0 and the SM one, H_0 , occurs at tree level. Due to possible small mixing at loop level we also study the mixing effects on the physical parameters in the Discussion part.

Now, we give the necessary 1-loop diagrams due to neutral Higgs particles in Fig. 1. Since, in the on-shell renormalization scheme, the self energy $\Sigma(p)$ can be written as

$$\Sigma(p) = (\hat{p} - m_l) \bar{\Sigma}(p) (\hat{p} - m_l) , \quad (6)$$

diagrams *a, b* in Fig. 1 vanish when l -lepton is on-shell. However the vertex diagram *c* in Fig. 1 gives non-zero contribution. The most general Lorentz-invariant form of the coupling of a charged lepton to a photon of 4-momentum q_ν can be written as

$$\begin{aligned} \Gamma_\mu &= G_1(q^2) \gamma_\mu + G_2(q^2) \sigma_{\mu\nu} q^\nu \\ &+ G_3(q^2) \sigma_{\mu\nu} \gamma_5 q^\nu \end{aligned} \quad (7)$$

where q_ν is photon 4-vector and q^2 dependent form factors $G_1(q^2)$ and $G_2(q^2)$ are proportional to the charge and anomalous magnetic moment of l -lepton respectively. Non-zero value of $G_3(q^2)$ is responsible for the CP violation and it is proportional to EDM of l -lepton. By extracting this part of the vertex, l -lepton EDM "d_l" ($l = e, \mu, \tau$) (see eq.(5)) can be calculated as a sum of contributions coming from neutral Higgs bosons h_0 and A_0 ,

$$d_l = -\frac{iG_F}{\sqrt{2}} \frac{e}{32\pi^2} \frac{Q_\tau}{m_\tau} ((\bar{\xi}_{N,l\tau}^{D*})^2 - (\bar{\xi}_{N,\tau l}^D)^2) (F_1(y_{h_0}) - F_1(y_{A_0})) , \quad (8)$$

for $l = e, \mu$ and

$$\begin{aligned} d_\tau &= -\frac{iG_F}{\sqrt{2}} \frac{e}{32\pi^2} \left\{ \frac{Q_\tau}{m_\tau} ((\bar{\xi}_{N,\tau\tau}^{D*})^2 - (\bar{\xi}_{N,\tau\tau}^D)^2) (F_2(r_{h_0}) - F_2(r_{A_0})) \right. \\ &\left. - Q_\mu \frac{m_\mu}{m_\tau^2} ((\bar{\xi}_{N,\mu\tau}^{D*})^2 - (\bar{\xi}_{N,\tau\mu}^D)^2) (r_{h_0} \ln(z_{h_0}) - r_{A_0} \ln(z_{A_0})) \right\} , \end{aligned} \quad (9)$$

where the functions $F_1(w)$, $F_2(w)$ and $F_3(w)$ are

$$\begin{aligned} F_1(w) &= \frac{w(3 - 4w + w^2 + 2 \ln w)}{(-1 + w)^3} , \\ F_2(w) &= w \ln w + \frac{2(-2 + w)w \ln \frac{1}{2}(\sqrt{w} - \sqrt{w-4})}{\sqrt{w(w-4)}} . \end{aligned} \quad (10)$$

Here $y_H = \frac{m_\tau^2}{m_H^2}$, $r_H = \frac{1}{y_H}$ and $z_H = \frac{m_\mu^2}{m_H^2}$, Q_τ and Q_μ are charges of τ and μ leptons respectively. In eqs. (8) and (9) $\bar{\xi}_{N,ij}^D$ is defined as $\xi_{N,ij}^D = \sqrt{\frac{4G_F}{\sqrt{2}}} \bar{\xi}_{N,ij}^D$. In eq. (8) we take into account only internal τ -lepton contribution since, in our assumption, the Yukawa couplings $\bar{\xi}_{N,ij}^D$, $i, j = e, \mu$, are small compared to $\bar{\xi}_{N,\tau i}^D$, $i = e, \mu, \tau$ due to the possible proportionality of the Yukawa couplings to the masses of leptons under consideration in the vertices. In eq. (9) we take also the internal μ -lepton contribution besides internal τ -lepton one and ignore the one coming from the internal e -lepton respecting our assumption (see Discussion part). Note that, we make our calculations in arbitrary q^2 and take $q^2 = 0$ at the end.

Using the parametrization

$$\bar{\xi}_{N,\tau l}^D = |\bar{\xi}_{N,\tau l}^D| e^{i\theta_l} , \quad (11)$$

the Yukawa factors in eqs. (8) and (9) can be written as

$$((\bar{\xi}_{N,l\tau}^{D*})^2 - (\bar{\xi}_{N,\tau l}^D)^2) = -2 \text{isin } 2\theta_l |\bar{\xi}_{N,\tau l}^D|^2 \quad (12)$$

where $l = e, \mu, \tau$. Here θ_l are CP violating parameters which are the sources of the lepton EDM.

Now, let us consider the lepton number violating process $\mu \rightarrow e\gamma$ which is a good candidate in the determination of the Yukawa couplings and new physics beyond the SM. Since we take into account only the neutral Higgs contributions in the lepton sector of the model III, the contribution comes from neutral Higgs bosons h_0 and A_0 (see Fig. 1). In the on-shell renormalization scheme the self energy diagrams are cancelled and the vertex diagram (Fig. 1-c) contributes. Taking only τ lepton for the internal line, the decay width Γ reads as

$$\Gamma(\mu \rightarrow e\gamma) = c_1(|A_1|^2 + |A_2|^2) , \quad (13)$$

where

$$\begin{aligned} A_1 &= Q_\tau \frac{1}{8 m_\mu m_\tau} \bar{\xi}_{N,\tau e}^D \bar{\xi}_{N,\tau\mu}^D (F_1(y_{h_0}) - F_1(y_{A_0})) , \\ A_2 &= Q_\tau \frac{1}{8 m_\mu m_\tau} \bar{\xi}_{N,e\tau}^{D*} \bar{\xi}_{N,\mu\tau}^{D*} (F_1(y_{h_0}) - F_1(y_{A_0})) , \end{aligned} \quad (14)$$

$c_1 = \frac{G_F^2 \alpha_{em} m_\mu^5}{32\pi^4}$ and the function $F_1(w)$ is given in eq. (10). Here the amplitudes A_1 and A_2 have right and left chirality respectively. In eq. (13) we ignore the contributions coming from internal μ and e leptons respecting our assumption on the Yukawa couplings (see Discussion).

Another LFV process is $\tau \rightarrow \mu\gamma$ and it is rich from the theoretical point of view. The decay width of this process can be calculated using the same procedure and reads as

$$\Gamma(\tau \rightarrow \mu\gamma) = c_2(|B_1|^2 + |B_2|^2) , \quad (15)$$

where

$$\begin{aligned}
B_1 &= Q_\tau \frac{1}{48 m_\mu m_\tau} \bar{\xi}_{N,\tau\mu}^D \left\{ \bar{\xi}_{N,\tau\tau}^{D*} (G_1(y_{h_0}) + G_1(y_{A_0})) + 6 \bar{\xi}_{N,\tau\tau}^D (F_1(y_{h_0}) - F_1(y_{A_0})) \right\}, \\
B_2 &= Q_\tau \frac{1}{48 m_\mu m_\tau} \bar{\xi}_{N,\mu\tau}^{D*} \left\{ \bar{\xi}_{N,\tau\tau}^D (G_1(y_{h_0}) + G_1(y_{A_0})) + 6 \bar{\xi}_{N,\tau\tau}^{D*} (F_1(y_{h_0}) - F_1(y_{A_0})) \right\}, \quad (16)
\end{aligned}$$

and $c_2 = \frac{G_F^2 \alpha_{em} m_\tau^5}{32\pi^4}$. Here the amplitudes B_1 and B_2 have right and left chirality respectively. The function $G_1(w)$ is given by

$$G_1(w) = \frac{w(2 + 3w - 6w^2 + w^3 + 6w \ln w)}{(-1 + w)^4}.$$

Note that, in the case of the possible loop induced mixing of the neutral Higgs bosons h_0 and the SM one H_0 , the functions $F_1(y_{h_0})$, $F_2(r_{h_0})$, $\ln(z_{h_0})$ and $G_1(y_{h_0})$ in eqs. (8, 9, 14, 16) should be multiplied by $\cos^2 \alpha$ where α is the small mixing angle.

3 Discussion

The Yukawa couplings $\bar{\xi}_{N,ij}^D$, $i, j = e, \mu, \tau$ play the main role in the determination of the lepton EDM and the physical quantities for LFV interactions, in the model III. These couplings are complex in general and they are free parameters which can be fixed by present and forthcoming experiments. The experimental results on the EDM of leptons e, μ, τ and LFV process $\mu \rightarrow e\gamma$ are our starting point of the predictions on Yukawa couplings related with leptons. Note that, in our predictions, we assume that the Yukawa couplings $\bar{\xi}_{N,ij}^D$, $i, j = e, \mu$, are small compared to $\bar{\xi}_{N,\tau i}^D$, $i = e, \mu, \tau$ since the strength of these couplings are related with the masses of leptons denoted by the indices of them, similar to the Cheng-Sher scenerio [21]. Further, we assume that $\bar{\xi}_{N,ij}^D$ is symmetric with respect to the indices i and j .

Since non-zero EDM can be obtained in case of complex couplings, there exist a CP violating parameter θ_l coming from the parametrization eq. (11). At this stage, we find a restriction for $\bar{\xi}_{N,\tau\mu}^D$ using eq. (8) and the experimental result of μ EDM [22],

$$0.3 \times 10^{-19} e - cm < d_\mu < 7.1 \times 10^{-19} e - cm. \quad (17)$$

Fig. 2 shows m_{A_0} dependence of $\bar{\xi}_{N,\tau\mu}^D$ for $\sin\theta_\mu = 0.5$ and $m_{h_0} = 70 \text{ GeV}$. Here the coupling is restricted in the region between solid lines. As shown in the figure, $\bar{\xi}_{N,\tau\mu}^D$ is at the order of the magnitude 10^2 and take smaller values if m_{A_0} takes larger values compared to m_{h_0} in the theory. If neutral Higgs masses are almost degenerate, namely $m_{A_0} = m_{h_0}$, $\bar{\xi}_{N,\tau\mu}^D$ should be very large since the contributions of h_0 and A_0 have opposite signs and the same functional

dependences. Therefore to be able control the numerical value of the coupling $\bar{\xi}_{N,\tau\mu}^D$, the masses should not be degenerate.

Now, we use the upper limit of the BR of the process $\mu \rightarrow e\gamma$ to restrict the Yukawa combination $\bar{\xi}_{N,\tau\mu}^D \bar{\xi}_{N,\tau e}^D$ (see eq. (14)). Here we take into account only the internal τ -lepton contribution. Using the restrictions for $\bar{\xi}_{N,\tau\mu}^D$ and $\bar{\xi}_{N,\tau\mu}^D \bar{\xi}_{N,\tau e}^D$ we find a constraint region for $\bar{\xi}_{N,\tau e}^D$. In Fig. 3 we plot $\bar{\xi}_{N,\tau e}^D$ as a function of m_{A_0} for $\sin\theta_\mu = 0.5$ and $m_{h_0} = 70 \text{ GeV}$. Here the coupling is restricted in the region between solid lines. As shown in the figure $\bar{\xi}_{N,\tau e}^D$ is at the order of the magnitude 10^{-4} and becomes smaller if the mass of the particle A_0 is larger compared to m_{h_0} in the theory, similar to the coupling $\bar{\xi}_{N,\mu\tau}^D$. Fig. 4 represents the effect of possible mixing between CP even neutral Higgs bosons h_0 and H_0 on the coupling $\bar{\xi}_{N,\tau e}^D$. When the mixing parameter $\sin\alpha$ changes in the range $0 - 0.1$, the upper limit of $\bar{\xi}_{N,\tau e}^D$ is affected at the order of the magnitude 3% for the fixed values of $\sin\theta_\mu = 0.5$, $m_{h_0} = 70 \text{ GeV}$ and $m_{A_0} = 80 \text{ GeV}$. The lower limit of the coupling is almost non-sensitive to the mixing as shown in the figure.

At this stage we are ready to predict the electron EDM, d_e . Using eq. (8) and the restriction for $\bar{\xi}_{N,\tau e}^D$, d_e is plotted with respect to $\sin\theta_e$ in Fig. 5 for fixed values of $\sin\theta_\mu = 0.5$, $m_{h_0} = 70 \text{ GeV}$ and $m_{A_0} = 80 \text{ GeV}$. For the intermediate values of $\sin\theta_e$, d_e is at the order of the magnitude 10^{-32} which lies in the experimental restriction region [14]

$$d_e = 1.8 \pm 1.2 \pm 1.0 \times 10^{-27} e - cm \quad (18)$$

We also present m_{h_0} dependence of d_e for fixed values of $\sin\theta_e = 0.5$ and $m_{A_0} = 80 \text{ GeV}$ in Fig. 6. This figure shows that d_e is bounded by the solid lines and decreases with increasing values of m_{h_0} . For completeness, we study h_0 - H_0 mixing effect on d_e . Fig. 7 shows that d_e is not sensitive to mixing of two CP-even bosons in the given range of $\sin\alpha$.

Finally, we would like to predict the behaviour of d_τ with respect to $BR(\tau \rightarrow \mu\gamma)$. Since we take into account internal τ and μ leptons in the calculation of d_τ , it has a functional dependence (see eq. (9))

$$d_\tau = f_1 + f_2 |\bar{\xi}_{N,\tau\tau}^D|^2, \quad (19)$$

where f_1 contains the coupling $\bar{\xi}_{N,\tau\mu}^D$ and its complex conjugate, which can be fixed by the constraint plotted in Fig. 2. On the other hand $BR(\tau \rightarrow \mu\gamma)$ has in the form

$$BR(\tau \rightarrow \mu\gamma) = g_1 |\bar{\xi}_{N,\tau\mu}^D|^2 |\bar{\xi}_{N,\tau\tau}^D|^2, \quad (20)$$

where $|\bar{\xi}_{N,\tau\mu}^D|^2$ is again fixed by the constraint we have. As a result, we connect d_τ and $BR(\tau \rightarrow \mu\gamma)$ by an expression in the form

$$d_\tau = f_1 + g_2 BR(\tau \rightarrow \mu\gamma) . \quad (21)$$

Here the lower limit of f_1 is at the order of the magnitude of 10^{-15} for the fixed values of $m_{h_0} = 70 \text{ GeV}$, $m_{A_0} = 80 \text{ GeV}$ and $\sin\theta_\mu = 0.5$. Therefore, even internal μ -lepton causes to exceed the upper limit of experimental value of d_τ [16]

$$d_\tau = 3.1 \times 10^{-16} e - cm , \quad (22)$$

In eq. (21), the part $g_2 BR(\tau \rightarrow \mu\gamma)$ is due to the internal τ -lepton contribution. Here g_2 is at the order of the magnitude of 10^{-14} . Therefore it is not possible to get a strict bound for $BR(\tau \rightarrow \mu\gamma)$ using the eqs. (21) and the experimental result eq. (22).

In our work we choose the 2HDM type III and assume that only FCNC interactions exist at tree level. First we obtain constraints for the couplings $\bar{\xi}_{N,\tau e}^D$ and $\bar{\xi}_{N,\tau\mu}^D$. The previous one is at the order of the magnitude of 10^{-4} and the last one is 10^2 . Numerical values of these couplings decrease when the mass difference of neutral Higgs bosons h_0 and A_0 increases. Further, we predict the d_e as $10^{-32} e - cm$ using the experimental result of d_μ and the upper limit of $BR(\mu \rightarrow e\gamma)$. This lies in the experimental restriction region of d_e , however it is far from the present limits. Finally, we calculated the $BR(\tau \rightarrow \mu\gamma)$ and d_τ and connect these physical quantities in the form of a linear expression (eq. (21)). This expression does not provide a strict bound for $BR(\tau \rightarrow \mu\gamma)$ and the constraint region for the coupling $\bar{\xi}_{N,\tau\tau}^D$.

In future, with the reliable experimental result of $BR(\tau \rightarrow \mu\gamma)$ and obtaining more strict bounds for $BR(\mu \rightarrow e\gamma)$, d_e , d_μ and d_τ it would be possible to test models and free parameters underconsideration more accurately.

4 Acknowledgement

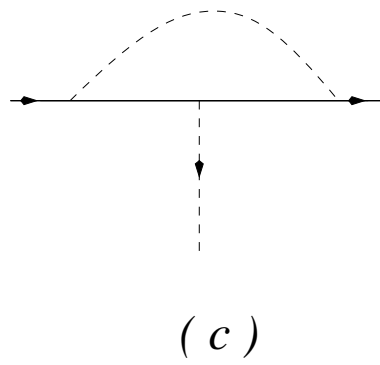
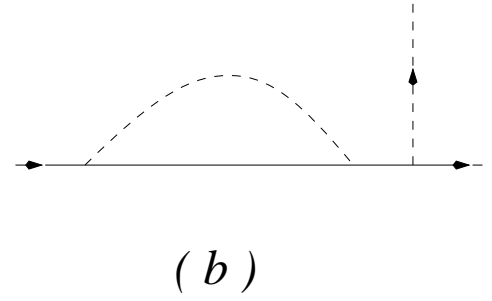
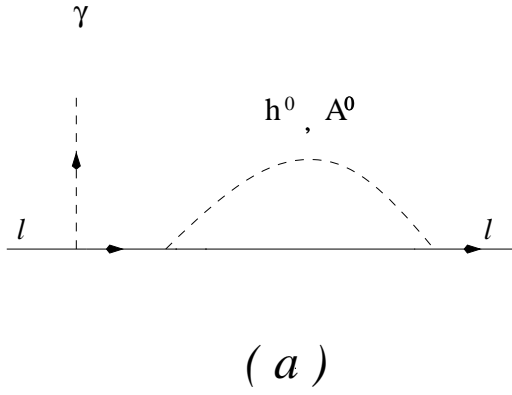
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Figure 1: One loop diagrams contribute to EDM of l -lepton and LFV interactions (if external leptons l have different flavors) due to the neutral Higgs bosons h_0 and A_0 in the 2HDM. Dashed lines represent the electromagnetic field, h_0 and A_0 fields.



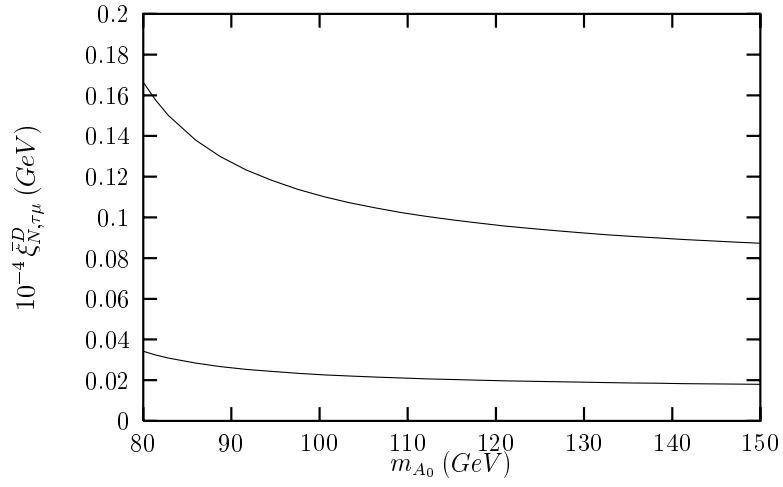


Figure 2: $\bar{\xi}_{N,\tau\mu}^D$ as a function of m_{A_0} for $m_{h_0} = 70 \text{ GeV}$ and $\sin \theta_\mu = 0.5$. Here the coupling is restricted in the region between solid lines.

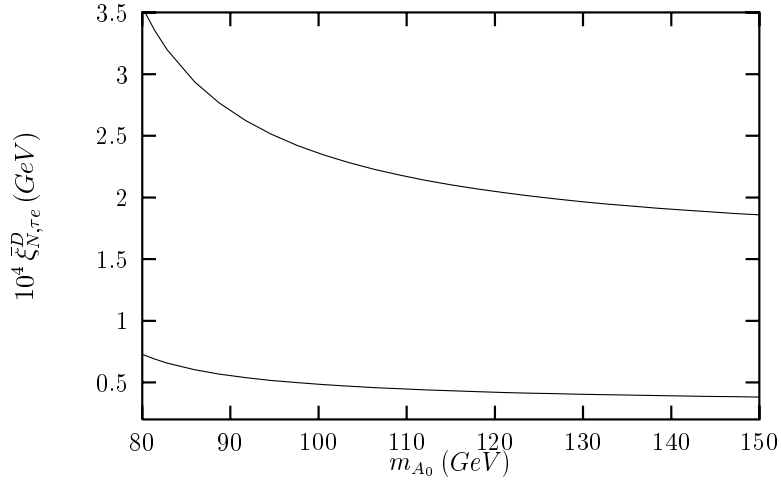


Figure 3: The same as Fig. 2 but for $\bar{\xi}_{N,\tau e}^D$.

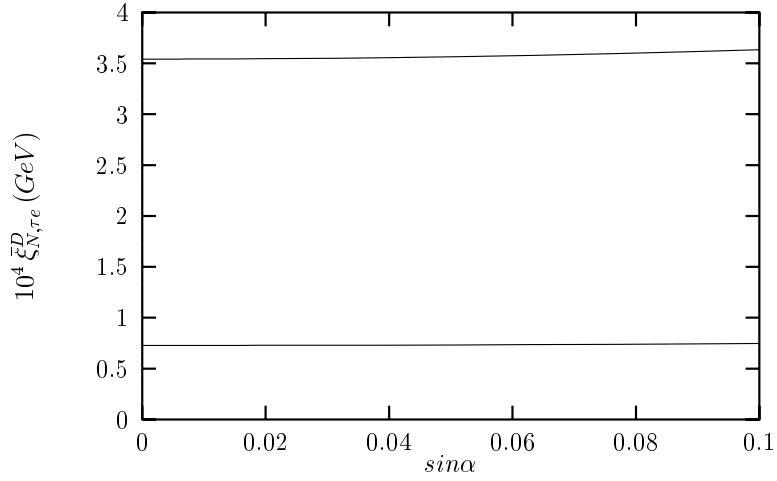


Figure 4: $\bar{\xi}_{N,\tau e}^D$ as a function of $\sin \alpha$ for $m_{h_0} = 70 \text{ GeV}$, $m_{A_0} = 80 \text{ GeV}$ and $\sin \theta_\mu = 0.5$. Here the coupling is restricted in the region between solid lines.

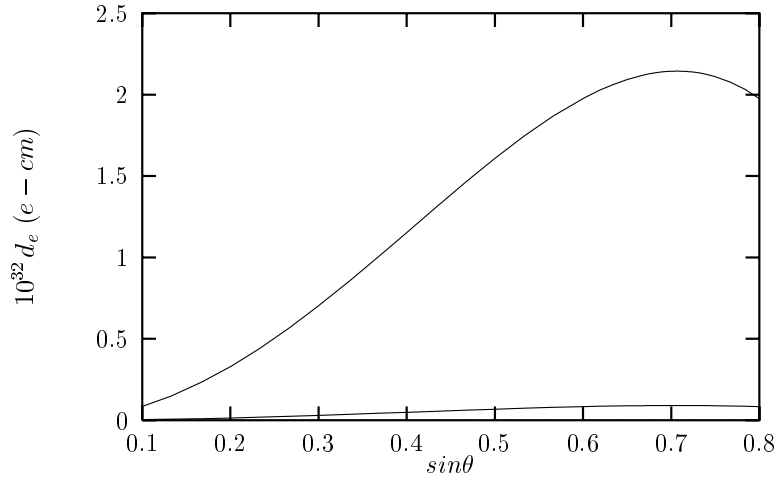


Figure 5: d_e as a function of $\sin \theta_e$ for $m_{h_0} = 70 \text{ GeV}$ and $m_{A_0} = 80 \text{ GeV}$. Here d_e is restricted in the region bounded by solid lines.

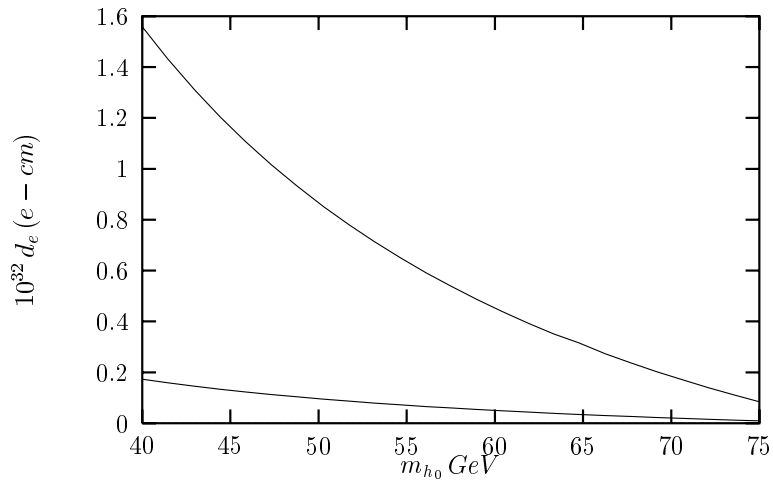


Figure 6: The same as Fig. 5 but d_e as a function of m_{h_0} for $\sin \theta_e = 0.5$.

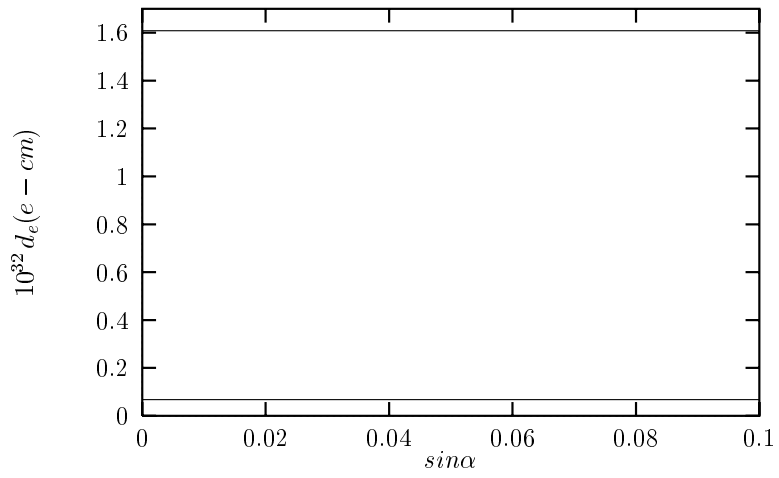


Figure 7: d_e as a function of $\sin \alpha$ for $m_{h_0} = 70 \text{ GeV}$, $m_{A_0} = 80 \text{ GeV}$ and $\sin \theta_e = 0.5$. Here d_e is restricted in the region bounded by solid lines.