# Top quark electric dipole moment in a minimal supersymmetric standard model extension with vectorlike multiplets

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The electric dipole moment (EDM) of the top quark is calculated in a model with a vector like multiplet which mixes with the third generation in an extension of the minimal supersymmetric standard model. Such mixings allow for new *CP* violating phases. Including these new *CP* phases, the EDM of the top in this class of models is computed. The top EDM arises from loops involving the exchange of the W, the Z as well as from the exchange involving the charginos, the neutralinos, the gluino, and the vector like multiplet and their superpartners. The analysis of the EDM of the top is more complicated than for the light quarks because the mass of the external fermion, in this case the top quark mass cannot be ignored relative to the masses inside the loops. A numerical analysis is presented and it is shown that the top EDM could be close to $10^{-19}$ ecm consistent with the current limits on the EDM of the electron, the neutron and on atomic EDMs. A top EDM of size $10^{-19}$ ecm could be accessible in collider experiments such as the International Linear Collider.

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## I. INTRODUCTION

In the standard model the electric dipole moment (EDM) of the top quark is rather small typically less than $10^{-30}$ ecm [1,2][1] In this work we carry out an analysis similar to that of [3] (see also [4]) for the EDM of the top quark arising from the mixing of the third generation with a vector like generation. (For a recent review on *CP* violation and on EDMs see [5]). Thus, vector like combinations are predicted in many unified models of particle interactions [6,7] and their implications have been explored in many works [8–17]. Such vector like combinations could lie in the TeV region and be consistent with the current precision electroweak data. In this work we allow for the possibility that there could be a small mixing of these vector like combinations with the sequential generations. The implications of such mixings for the neutrino magnetic moment and for the anomalous magnetic moment of the $\tau$ were investigated in [4] and for the EDM of the $\tau$ and $\nu_\tau$ in [3]. In this analysis we focus on the quark sector of the vector like multiplets. To simplify the analysis, we will assume that the mixings of the vector like multiplets occurs only with the third generation since such mixings are consistent with the current experimental constraints [18]. The masses of the vector multiplets could lie in a large mass range, i.e., from the current lower limits given by the LEP experiment and by the Tevatron up to a masses lying in the several TeV mass range. Mixings with the vector like generations bring in new phases which are not constrained by the current experimental limits on the EDM of the electron, of the neutron and of atomic EDMs. Further details of the vector like models can be found in [4] and in the other references mentioned therein and above.

If vector like multiplets exist and mix with the third generation, they can affect the *CP* phenomena in the third generation because of the new sources of *CP* violation arising from mixing with the new sector. The top physics is of course a well known laboratory for the study of *CP* violating phenomenona ** [19–24].** Specifically the sensitivity of these phenomena to the top EDM has been investigated in a variety of theoretical models [2,25–29]. Further, a number of analyses show that in $e^+e^- \to t\bar{t}$ and in $\gamma\gamma \to t\bar{t}$ processes the EDM of the top can be measured with great sensitivity [22,30–32], i.e., with sensitivity up to $10^{-19}$ ecm or even better. With this in mind we investigate here the top EDM in an extension of the minimal supersymmetric standard model (MSSM) with vector like multiplets. A mixing of the vector like multiplet with the sequential generations and specifically the third generation bring in new sources of *CP* violation which contribute to the top EDM and can generate a top EDM as large as $10^{-19}$ ecm well within reach of the sensitivity of the collider experiments.

The outline of the rest of the paper is as follows: In Sec. II we give an analysis of the EDM of the top allowing for mixing between the vector like combination and the third generation quarks. The EDM of the top arises from loops involving the exchange of the W, of the Z as well as from exchanges involving the charginos, the neutralinos, the gluino as well as exchanges involving the vector like multiplets and their superpartners. We note that the analysis of the top EDM is more complicated relative to EDM of the light quarks and of the light leptons (see e.g., [33]) because we cannot ignore the mass of the external fermion (i.e., of the top quark in this case) compared to the masses that run

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[1]The analysis of [1] gives the EDM of the electron while the EDM of the top is obtained by scaling the electron EDM as pointed out by Soni and Xu in [2].

 

inside the loops. So the form factors that enter the analysis of the top EDM are more complicated relative to the form factors that enter the EDM of the light quarks, since for the case of the top the loop integrals are functions of more than just one mass ratio. A numerical analysis of the size of the EDM of the top is given in Sec. III. In this section we also display the dependence of the top EDM on the phases and mixings. Conclusions are given in Sec. IV. Deductions of the mass matrices used in Sec. IIare given in the Appendix.

## II. ELECTRIC DIPOLE MOMENT OF THE TOP QUARK

The first and second loops of Fig. 1produce EDM of the top quark through the interaction of the W boson with the top and bottom quarks and the vector multiplet quarks. The relevant part of Lagrangian that generates this contribution is given by

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W^{+}_{\mu} \sum_{i} \sum_{j} \bar{t}_j \gamma^{\mu} [D^{t*}_{L1j} D^{b}_{L1i} P_L + D^{t*}_{R2j} D^{b}_{R2i} P_R] b_i + \text{H.c.} \quad (1)$$

where $i$, $j$ run over the set of quarks and mirror quarks including those from the third generation and from the vector multiplet, $t_1$ is the physical top quark, and $D^{t,b}_{L,R}$ are the diagonalizing matrices defined in the Appendix. These matrices contain phases, and these phases generate the EDM of the top quark. Using the above interaction, we get from first and second loops of Fig. 1, the contribution

$$d_t^{1(\text{first})}(W) = -\frac{1}{48\pi^2 M_W^2} \sum_i m_{b_i} \operatorname{Im}(\Gamma_i^{tb}) I_1\left(\frac{m^2_{b_i}}{M_W^2}, \frac{m^2_{t_1}}{M_W^2}\right),$$
$$d_t^{1(\text{second})}(W) = -\frac{1}{16\pi^2 M_W^2} \sum_i m_{b_i} \operatorname{Im}(\Gamma_i^{tb}) I_2\left(\frac{m^2_{b_i}}{M_W^2}, \frac{m^2_{t_1}}{M_W^2}\right). \quad (2)$$

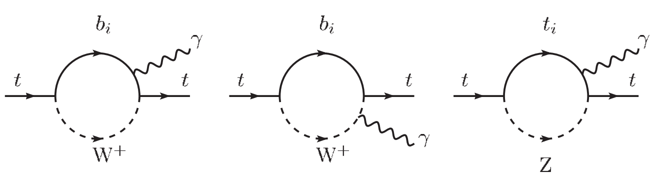


FIG. 1. One loop contribution to the top electric dipole moment from the exchange of the W boson, the Z boson and from the exchange of the top and from the exchange of the bottom quarks and their mirrors.

Here $\Gamma_i^{tb}$ is given

$$\Gamma_i^{tb} = \frac{g^2}{2} D^{t*}_{L11} D^{b}_{L1i} D^{t}_{R21} D^{b*}_{R2i}, \quad (3)$$

and $I_{1,2}(r_1, r_2)$ are given by

$$I_1(r_1, r_2) = \int_0^1 dx \frac{(4 + r_1 - r_2)x - 4x^2}{1 + (r_1 - r_2 - 1)x + r_2 x^2},$$
$$I_2(r_1, r_2) = \int_0^1 dx \frac{3 - 5x + (2 + r_1 - 2r_2)x^2 + (3 + r_2)x^3}{1 + (r_1 - r_2 - 1)x + r_2 x^2}. \quad (4)$$

While our analysis is quite general we will limit ourselves for simplicity to the case where there is mixing between the third generation and the mirror part of the vector multiplet. The inclusion of the nonmirror part is essentially trivial as it corresponds to an extension of the Cabibbo-Kobayashi-Maskawa matrix from a $3 \times 3$ to a $4 \times 4$ matrix in the standard model sector and similar straightforward extensions in the supersymmetric (susy) sector. In the rest of the analysis we will focus just on the mixings with the mirrors which is rather nontrivial. In fact, we work out, we believe, for the first time the interactions of the quarks-mirrors with the charginos, neutralinos and gluinos which are then utilized in the analysis of Figs. 2.

Next we consider the third loop of Fig. 1 which produces the EDM of the top quark through the interaction with the Z boson. The relevant part of Lagrangian that generates this contribution is given by

$$\mathcal{L}_{\text{NC}} = -Z_{\mu} \sum_{i=1}^{2} \sum_{j=1}^{2} \bar{t}_j \gamma^{\mu} [S_{Lji} P_L + S_{Rji} P_R] t_i, \quad (5)$$

where

$$S_{Lji} = -\frac{g}{6\cos\theta_W} [-3 D^{t*}_{L1j} D^{t}_{L1i} + 4\sin^2\theta_W (D^{t*}_{L1j} D^{t}_{L1i} + D^{t*}_{L2j} D^{t}_{L2i})],$$
$$S_{Rji} = -\frac{g}{6\cos\theta_W} [-3 D^{t*}_{R2j} D^{t}_{R2i} + 4\sin^2\theta_W (D^{t*}_{R1j} D^{t}_{R1i} + D^{t*}_{R2j} D^{t}_{R2i})]. \quad (6)$$

Using the above interaction, we get from third loop of Fig. 1, the contribution

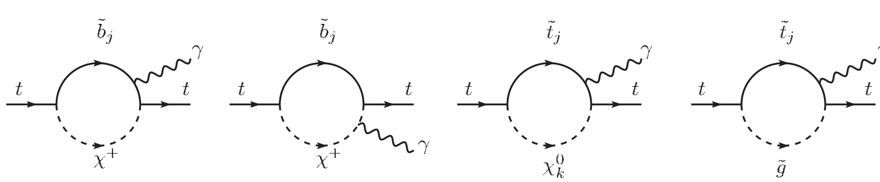


FIG. 2. One loop contribution to the top electric dipole moment from the exchange of the charginos, the neutralinos, the gluino and from the exchange of the stops and from the exchange of the sbottoms and their mirrors.

$$d_t^{1(\text{third})}(Z) = \frac{1}{24\pi^2 M_Z^2} \sum_{i=1}^{2} m_{t_i} \operatorname{Im}(S_{L1i}S_{R1i}^*) I_1\left(\frac{m_{t_i}^2}{M_Z^2}, \frac{m_{t_1}^2}{M_Z^2}\right). \tag{7}$$

The first and the second loops of Fig. 2, produce EDM of the top through the interaction with the charginos. The relevant part of Lagrangian that generates this contribution is given by

$$-\mathcal{L}_{t-\tilde{b}-\chi^+} = \sum_{k=1}^{2}\sum_{i=1}^{2}\sum_{j=1}^{4} \bar{t}_k[\Gamma_{Lkji}P_L + \Gamma_{Rkji}P_R] \times \tilde{\chi}^+{}_i \tilde{b}_j + \text{H.c.} \tag{8}$$

where

$$\begin{aligned}\Gamma_{Lkji} &= -g[V_{i2}^*\kappa_t D_{R1k}^{t*}\tilde{D}_{1j}^b - D_{R2k}^{t*}V_{i1}^*\tilde{D}_{4j}^b \\ &\quad + D_{R2k}^{t*}\kappa_B V_{i2}^*\tilde{D}_{2j}^b],\\ \Gamma_{Rkji} &= g[U_{i1}D_{L1k}^{t*}\tilde{D}_{1j}^b - D_{L1k}^{t*}\kappa_b U_{i2}\tilde{D}_{3j}^b \\ &\quad - D_{L2k}^{t*}\kappa_T U_{i2}\tilde{D}_{4j}^b],\end{aligned} \tag{9}$$

where $\tilde{D}^b$ is the diagonalizing matrix of the scalar $4\times 4$ mass matrices for the scalar quarks as defined in the Appendix. These elements contain $CP$ violating phases too and can contribute to the EDM of the top. The couplings $\kappa_f$ are defined as

$$(\kappa_T, \kappa_b) = \frac{(m_T, m_b)}{\sqrt{2}M_W\cos\beta}, \qquad (\kappa_B, \kappa_t) = \frac{(m_B, m_t)}{\sqrt{2}M_W\sin\beta}. \tag{10}$$

Here $U$ and $V$ are the matrices that diagonalize the chargino mass matrix $M_C$ so that

$$U^* M_C V^{-1} = \text{diag}(m_{\tilde{\chi}_1}^+, m_{\tilde{\chi}_2}^+). \tag{11}$$

Using the above interaction, we get from the first and the second loops of Fig. 2 the contributions

$$\begin{aligned} d_t^{2(\text{first})}(\chi^+) &= -\frac{1}{48\pi^2}\sum_{i=1}^{2}\sum_{j=1}^{4}\frac{m_{\chi_i^+}}{m_{\tilde{b}_j}^2}\operatorname{Im}(\Gamma_{L1ji}\Gamma_{R1ji}^*) \\ &\quad\times I_3\left(\frac{m_{\chi_i^+}^2}{m_{\tilde{b}_j}^2}, \frac{m_{t_1}^2}{m_{\tilde{b}_j}^2}\right),\\ d_t^{2(\text{second})}(\chi^+) &= -\frac{1}{16\pi^2}\sum_{i=1}^{2}\sum_{j=1}^{4}\frac{m_{\chi_i^+}}{m_{\tilde{b}_j}^2}\operatorname{Im}(\Gamma_{L1ji}\Gamma_{R1ji}^*) \\ &\quad\times I_4\left(\frac{m_{\chi_i^+}^2}{m_{\tilde{b}_j}^2}, \frac{m_{t_1}^2}{m_{\tilde{b}_j}^2}\right),\end{aligned} \tag{12}$$

where $I_{3,4}(r_1, r_2)$ are given by

$$\begin{aligned} I_3(r_1, r_2) &= \int_0^1 dx \frac{x - x^2}{1 + (r_1 - r_2 - 1)x + r_2 x^2},\\ I_4(r_1, r_2) &= \int_0^1 dx \frac{x^2}{1 + (r_1 - r_2 - 1)x + r_2 x^2}.\end{aligned} \tag{13}$$

We note that the limits of $I_3(r_1, r_2)$ and $I_4(r_1, r_2)$ for $r_2 \sim 0$ are the well known form factors $B(r_1)$ and $-A(r_1)$ in the case of light leptons and quarks [33].

The third loop of Fig. 2 produces EDM of the top through the interaction of the neutralinos. The relevant part of Lagrangian that generates this contribution is given by

$$-\mathcal{L}_{t-\tilde{t}-\chi^0} = \sum_{k=1}^{4}\sum_{i=1}^{4}\sum_{j=1}^{2} \bar{t}_j[C_{Ljki}P_L + C_{Rjki}P_R] \times \tilde{\chi}^0{}_i \tilde{t}_k + \text{H.c.}, \tag{14}$$

where

$$\begin{aligned} C_{Ljki} &= \sqrt{2}[\alpha_{ti}D_{R1j}^{t*}\tilde{D}_{1k}^t - \gamma_{ti}D_{R1j}^{t*}\tilde{D}_{3k}^t \\ &\quad + \beta_{Ti}D_{R2j}^{t*}\tilde{D}_{4k}^t - \delta_{Ti}D_{R2j}^{t*}\tilde{D}_{2k}^t],\\ C_{Rjki} &= \sqrt{2}[\beta_{ti}D_{L1j}^{t*}\tilde{D}_{1k}^t - \delta_{ti}D_{L1j}^{t*}\tilde{D}_{3k}^t \\ &\quad + \alpha_{Ti}D_{L2j}^{t*}\tilde{D}_{4k}^t - \gamma_{Ti}D_{L2j}^{t*}\tilde{D}_{2k}^t].\end{aligned} \tag{15}$$

The matrix $\tilde{D}^t$ is the diagonalizing matrix of the $4\times 4$ stop mixed with scalar mirrors mass$^2$ matrix as shown in the Appendix. The couplings that enter the above equations are given by

$$\begin{aligned} \alpha_{tj} &= \frac{g m_t X_{4j}}{2m_W\sin\beta},\\ \beta_{tj} &= \frac{2}{3}eX_{1j}'^* + \frac{g}{\cos\theta_W}X_{2j}'^*\left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right),\\ \gamma_{tj} &= \frac{2}{3}eX_{1j}' - \frac{2}{3}\frac{g\sin^2\theta_W}{\cos\theta_W}X_{2j}', \qquad \delta_{tj} = -\frac{g m_t X_{4j}^*}{2m_W\sin\beta}.\end{aligned} \tag{16}$$

Here

$$\begin{aligned} \alpha_{Tj} &= \frac{g m_T X_{3j}^*}{2m_W\cos\beta},\\ \beta_{Tj} &= -\frac{2}{3}eX_{1j}' + \frac{g}{\cos\theta_W}X_{2j}'\left(-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W\right),\\ \gamma_{Tj} &= -\frac{2}{3}eX_{1j}'^* + \frac{2}{3}\frac{g\sin^2\theta_W}{\cos\theta_W}X_{2j}'^*,\\ \delta_{Tj} &= -\frac{g m_T X_{3j}}{2m_W\cos\beta},\end{aligned} \tag{17}$$

where

$$\begin{aligned} X_{1j}' &= (X_{1j}\cos\theta_W + X_{2j}\sin\theta_W),\\ X_{2j}' &= (-X_{1j}\sin\theta_W + X_{2j}\cos\theta_W),\end{aligned} \tag{18}$$

and where the matrix $X$ diagonlizes the neutralino mass matrix so that

$$X^T M_{\tilde{\chi}^0} X = \mathrm{diag}(m_{\chi^0{}_1}, m_{\chi^0{}_2}, m_{\chi^0{}_3}, m_{\chi^0{}_4}). \tag{19}$$

Using the above interaction, we get from the third loop of Fig. 2 the neutralino contributions to the top EDM to be

$$d_t^{2(\mathrm{third})}(\chi^0) = \frac{1}{24\pi^2} \sum_{i=1}^{4} \sum_{k=1}^{4} \frac{m_{\chi_i^0}}{m^2_{\tilde{t}_k}} \mathrm{Im}(C_{L1ki} C^*_{R1ki}) \times I_3\left(\frac{m^2_{\chi_i^0}}{m^2_{\tilde{t}_k}}, \frac{m^2_{t_1}}{m^2_{\tilde{t}_k}}\right). \tag{20}$$

Finally the gluino contribution to the electric dipole moment of the top comes from the fourth loop of Fig. 2. The relevant part of Lagrangian that generates this contribution is given by

$$-\mathcal{L}_{t\tilde{t}\tilde{g}} = \sqrt{2} g_s \sum_{a=1}^{8} \sum_{j,k=1}^{3} \sum_{n=1}^{2} \sum_{m=1}^{4} T^a_{jk} \bar{t}^j_n [K_{L_{nm}} P_L + K_{R_{nm}} P_R] \tilde{g}_a \tilde{t}^k_m + \mathrm{H.c.}, \tag{21}$$

where

$$K_{L_{nm}} = e^{-i\xi_3/2}[D^{t*}_{R_{2n}} \tilde{D}^t_{4m} - D^{t*}_{R_{1n}} \tilde{D}^t_{3m}],$$
$$K_{R_{nm}} = e^{i\xi_3/2}[D^{t*}_{L_{1n}} \tilde{D}^t_{1m} - D^{t*}_{L_{2n}} \tilde{D}^t_{2m}], \tag{22}$$

where $\xi_3$ is the phase of the gluino mass. The above Lagrangian gives a contribution

$$d_t^{2(\mathrm{fourth})}(\tilde{g}) = \frac{g_s^2}{9\pi^2} \sum_{j=1}^{4} \frac{m_{\tilde{g}}}{m^2_{\tilde{t}_j}} \mathrm{Im}(K_{L_{1j}} K^*_{R_{1j}}) I_3\left(\frac{m^2_{\tilde{g}}}{m^2_{\tilde{t}_j}}, \frac{m^2_{t_1}}{m^2_{\tilde{t}_j}}\right). \tag{23}$$

## III. NUMERICAL ANALYSIS

The mixing matrices between the quarks and the mirrors are diagonalized using bi-unitary matrices (see the Appendix). So we parametrize the mixing between $t$ and $T$ by the angles $\theta_L$, $\theta_R$, $\chi_L$ and $\chi_R$, and the mixing between $b$ and $B$ by the angle $\phi_L$, $\phi_R$, $\xi_L$ and $\xi_R$, where

$$D^t_L = \begin{pmatrix} \cos\theta_L & -\sin\theta_L e^{-i\chi_L} \\ \sin\theta_L e^{i\chi_L} & \cos\theta_L \end{pmatrix},$$
$$D^b_L = \begin{pmatrix} \cos\phi_L & -\sin\phi_L e^{-i\xi_L} \\ \sin\phi_L e^{i\xi_L} & \cos\phi_L \end{pmatrix}, \tag{24}$$

and $D^t_R$ and $D^b_R$ can be gotten from $D^t_L$ and $D^b_L$ by the following substitution: $D^t_L \to D^t_R$, $\theta_L \to \theta_R$, $\chi_L \to \chi_R$, and $D^b_L \to D^b_R$, $\phi_L \to \phi_R$, $\xi_L \to \xi_R$. We note that the phases $\chi_{L,R}$ arise from the couplings $h_3$ and $h_5$ while the phases $\xi_{L,R}$ arise from the couplings $h_4$ and $h_3$ through the relations

$$\chi_R = \arg(-m_t h_3 + m_T h_5^*),$$
$$\chi_L = \arg(m_t h_5^* - m_T h_3),$$
$$\xi_R = \arg(m_b h_3 + m_B h_4^*),$$
$$\xi_L = \arg(m_b h_4^* + m_B h_3). \tag{25}$$

For the case of top and bottom masses arising from Hermitian matrices, i.e., when $h_5 = -h_3^*$ and $h_4 = h_3^*$ we

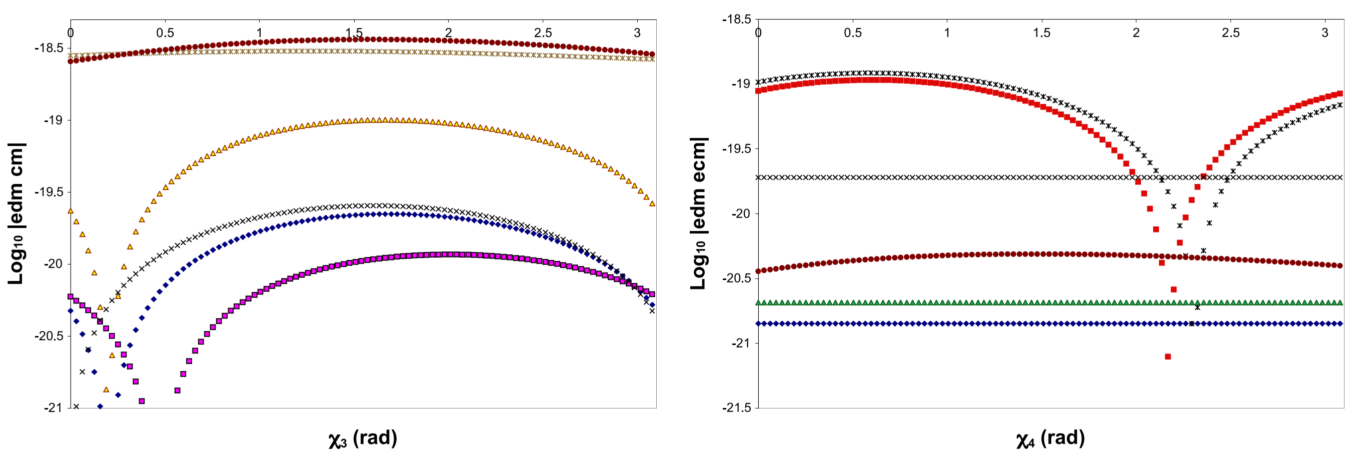


FIG. 3 (color online). Left: An exhibition of the dependence of $d_t$ on $\chi_3$ when $\tan\beta = 10$, $m_T = 300$, $|h_3| = 80$, $|h_4| = 70$, $m_B = 150$, $|h_5| = 90$, $m_0 = 100$, $|A_0| = 150$, $\tilde{m}_1 = 50$, $\tilde{m}_2 = 100$, $\mu = 150$, $\tilde{m}_g = 400$, $\chi_4 = 0.7$, $\chi_5 = -0.6$, $\alpha_T = 0.7$, and $\alpha_B = 0.1$. (The six curves correspond to the contributions from the neutralino, W, Z, chargino, total EDM, and gluino. They are shown in ascending order at $\chi_3 = 0$). Here and in subsequent figures all masses are in GeV and all angles are in rad. Right: An exhibition of the dependence of $d_t$ on $\chi_4$ when $\tan\beta = 20$, $m_T = 400$, $|h_4| = 60$, $m_B = 100$, $|h_3| = 70$, $|h_5| = 60$, $m_0 = 150$, $|A_0| = 100$, $\tilde{m}_1 = 50$, $\tilde{m}_2 = 100$, $\mu = 150$, $\tilde{m}_g = 400$, $\chi_3 = 0.5$, $\chi_5 = 0.3$, $\alpha_T = 0.1$and $\alpha_B = 0.7$ (The six curves correspond to the contributions from the Z, neutralino, W, gluino, chargino, and total EDM. They are shown in ascending order at $\chi_4 = 0$).

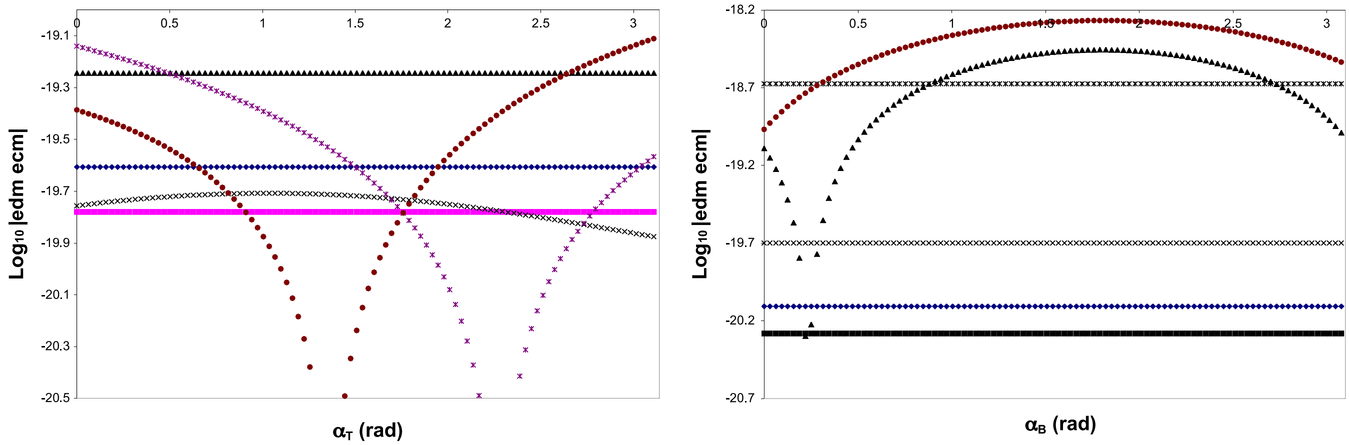


FIG. 4 (color online). Left: An exhibition of the dependence of $d_t$ on $\alpha_T$ when $\tan\beta = 15$, $m_T = 350$, $|h_3| = 85$, $m_B = 150$, $|h_4| = 75$, $|h_5| = 65$, $m_0 = 200$, $|A_0| = 200$, $\tilde{m}_1 = 50$, $\tilde{m}_2 = 100$, $\mu = 150$, $\tilde{m}_g = 400$, $\chi_3 = 0.5$, $\chi_4 = 0.5$, $\chi_5 = -0.6$, and $\alpha_B = -0.4$ (The six curves correspond to the Z, neutralino, W, total EDM, chargino, and gluino contributions. They are shown in ascending order at $\alpha_T = 0$). Right: An exhibition of the dependence of $d_t$ on $\alpha_B$ when $\tan\beta = 5$, $m_T = 280$, $|h_3| = 90$, $m_B = 200$, $|h_4| = 80$, $|h_5| = 70$, $m_0 = 220$, $|A_0| = 250$, $\tilde{m}_1 = 50$, $\tilde{m}_2 = 100$, $\mu = 150$, $\tilde{m}_g = 400$, $\chi_3 = 0.5$, $\chi_4 = 0.4$, $\chi_5 = -0.5$, and $\alpha_T = 1.2$ (The six curves correspond to the Z, W, neutralino, chargino, total EDM, and gluino contributions. They are shown in ascending order at $\alpha_B = 0$).

have $\theta_L = \theta_R$, $\phi_L = \phi_R$, $\chi_L = \chi_R = \chi$ and $\xi_L = \xi_R = \xi$. Further, here we have the relation $\xi = \chi + \pi$ and thus the W-exchange and Z-exchange terms in the EDM for the top vanish. However, more generally the top and the bottom mass matrices are not Hermitian and they generate nonvanishing contributions to the EDMs. Thus the input parameters for this sector of the parameter space are $m_{t1}$, $m_T$, $h_3$, $h_5$, $m_{b1}$, $m_B$, $h_4$ with $h_3$, $h_4$ and $h_5$ being complex masses with the corresponding $CP$ violating phases $\chi_3$, $\chi_4$ and $\chi_5$. For the sbottom and stop mass$^2$ matrices we need the extra input parameters of the susy breaking sector, $\tilde{M}_q$, $\tilde{M}_B$, $\tilde{M}_b$, $\tilde{M}_Q$, $\tilde{M}_t$, $\tilde{M}_T$, $A_b$, $A_T$, $A_t$, $A_B$, $\mu$, $\tan\beta$. The chargino, neutralino and gluino sectors need the extra parameters $\tilde{m}_1$, $\tilde{m}_2$ and $m_{\tilde{g}}$. We will assume that the only parameters that have phases in the above set are $A_T$, $A_B$, $A_t$ and $A_b$ with the corresponding phases given by $\alpha_T$, $\alpha_B$, $\alpha_t$ and $\alpha_b$.

To simplify the analysis further we set some of the phases to zero, i.e., specifically we set $\alpha_t = \alpha_b = 0$. With this in mind the only contributions to the EDM of the top quark arises from mixing terms between the scalars and the mirror scalars, between the fermions—and the mirror fermions and finally among the mirror scalars themselves. Thus in the absence of the mirror part of the Lagrangian, the top EDM vanishes and so we can isolate the role of the $CP$ violating phases in this sector and see the size of its contribution. The $4 \times 4$ mass$^2$ matrices of stops and sbottoms are diagonalized numerically. Thus the $CP$ violating phases that would play a role in this analysis are

$$\chi_3, \chi_4, \chi_5, \alpha_T, \alpha_B. \tag{26}$$

To reduce the number of input parameters we assume $\tilde{M}_a = m_0$, $a = q, B, b, Q, T, t$ and $|A_i| = |A_0|$, $i = T, B, t, b$. In the left panel of Fig. 3, we give a numerical analysis of the top EDM and discuss its variation with the phase $\chi_3$. We note that $\chi_3$ enters $D^t$, $D^b$, $\tilde{D}^t$ and $\tilde{D}^b$ and as a consequences all diagrams in Fig. 1 and in Fig. 2 that contribute to the top EDM have a $\chi_3$ dependence.

Further, the various diagrams that contribute to the top EDM may add constructively or destructively as shown in the Z, W, neutralino and chargino contributions. In the case of destructive interference, we have large cancellations reminiscent of the cancellation mechanism for the EDM of the electron and for the neutron [34,35]. Of course the desirable larger contributions for the top EDM occur away from the cancellation regions. In the right panel of Fig. 3,

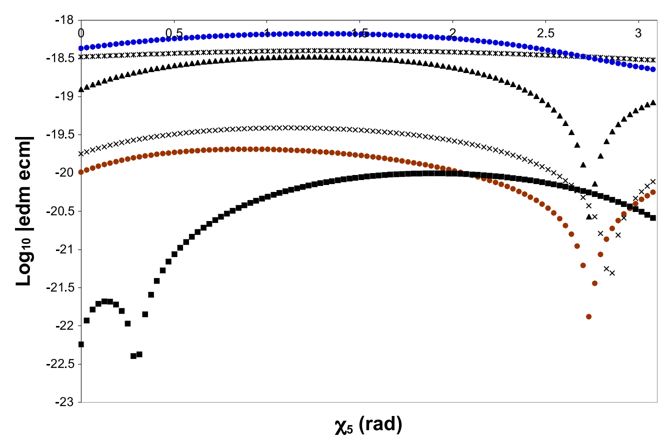


FIG. 5 (color online). An exhibition of the dependence of $d_t$ on $\chi_5$ when $\tan\beta = 7$, $m_T = 500$, $|h_3| = 60$, $m_B = 120$, $|h_4| = 70$, $|h_5| = 80$, $m_0 = 100$, $|A_0| = 200$, $\tilde{m}_1 = 50$, $\tilde{m}_2 = 100$, $\mu = 150$, $\tilde{m}_g = 400$, $\chi_3 = 0.3$, $\chi_4 = 0.5$, $\alpha_B = .2$ and $\alpha_T = .7$ (The six curves correspond to the Z, W, neutralino, chargino, gluino, and total EDM. They are shown in ascending order at $\chi_5 = 0$).

TABLE I. A sample illustration of the various contributions to the electric dipole moment of the top quark. The inputs are $\tan\beta = 10$, $m_T = 300$, $|h_3| = 80$, $|h_4| = 70$, $m_B = 150$, $|h_5| = 90$, $m_0 = 100$, $|A_0| = 150$, $\tilde{m}_1 = 50$, $\tilde{m}_2 = 100$, $\mu = 150$, $\tilde{m}_g = 400$, $\chi_4 = 0.7$, $\chi_5 = -0.6$, $\alpha_T = 0.7$, and $\alpha_B = 0.1$. All masses are in units of GeV and all angles are in radian.

| $\chi_3$ (rad) | $d_t(W)$ ecm | $d_t(Z)$ ecm | $d_t(\chi^+)$ ecm | $d_t(\chi^0)$ ecm | $d_t(\tilde{g})$ ecm |
|---|---|---|---|---|---|
| 0.0 | $4.73 \times 10^{-21}$ | $-5.94 \times 10^{-21}$ | $-7.04 \times 10^{-20}$ | $-2.85 \times 10^{-22}$ | $2.98 \times 10^{-19}$ |
| 0.5 | $-7.11 \times 10^{-21}$ | $4.84 \times 10^{-22}$ | $1.02 \times 10^{-19}$ | $-1.21 \times 10^{-20}$ | $3.08 \times 10^{-19}$ |
| 1.0 | $-1.69 \times 10^{-20}$ | $6.38 \times 10^{-21}$ | $2.36 \times 10^{-19}$ | $-2.12 \times 10^{-20}$ | $3.11 \times 10^{-19}$ |
| 1.5 | $-2.19 \times 10^{-20}$ | $1.03 \times 10^{-20}$ | $2.98 \times 10^{-19}$ | $-2.53 \times 10^{-20}$ | $3.07 \times 10^{-19}$ |
| 2.0 | $-2.13 \times 10^{-20}$ | $1.16 \times 10^{-20}$ | $2.87 \times 10^{-19}$ | $-2.37 \times 10^{-20}$ | $2.96 \times 10^{-19}$ |

we study the variation of the different components of $d_t$ as the magnitude of the phase $\chi_4$ varies. The sparticle masses and couplings in the bottom sector and thus the top EDM arising from the exchange of the W and the charginos are sensitive to $\chi_4$ and thus only these two contributions to the top EDM have dependence on this parameter.

The left panel of Fig. 4 exhibits the variation of the different components of $d_t$ on the phase $\alpha_T$. We observe that the components that vary with this phase are the neutralino and the gluino contributions while the W, Z, and chargino contributions have no dependence on this phase. The reason for the above is that $\alpha_T$ enters the scalar top mass$^2$ matrix and the EDM arising from W, Z, and chargino exchanges are independent of $\tilde{D}^t$. However, the neutralino and the gluino contributions are affected by it. It is clear that we see here too the cancellation mechanism working since the components are close to each other with different signs, so we have the possibility of a destructive cancellation. In the right panel of Fig. 4, we study the variation of the different components of $d_t$ as the phase $\alpha_B$ changes. We note that the only component that varies with this phase is the chargino component. This is expected since $\alpha_B$ enters the scalar bottom mass$^2$ matrix and the chargino contribution to the EDM is controlled by $\tilde{D}^b$ which depends on $\alpha_B$ while the other contributions are independent of this phase. In Fig. 5 we study the variation of the different components of $d_t$ as the phase $\chi_5$ changes. This phase enters the top quark mass matrix and the scalar top mass$^2$ matrix and consequently the matrices $D^t_{L,R}$ and $\tilde{D}^t$. Thus, the contributions to the EDM of the top arising from the W, Z, neutralino, chargino and gluino exchanges all have a dependence on $\chi_5$ as exhibited in Fig. 5.

As mentioned in the introduction the top EDM can be explored in the $e^+e^- \to t\bar{t}$ and $\gamma\gamma \to t\bar{t}$ processes [22,30–32]. Specifically, it is demonstrated that at a linear $e^+e^-$ collider (such as the ILC), one can explore the top EDM at the level of $10^{-19}$–$10^{-20}$ ecm.[2] Thus the top EDM predicted in the model with extra vector multiplets falls within the realm of exploration in future collider experiments. In Table I we give a sample exhibition of the size and the sign of every component to the top quark EDM. The analysis of Table I and of Fig. 3–5) show that a top EDM as large $10^{-19}$ ecm can be gotten which falls within reach of the experiments at the ILC. It would be interesting to explore also the sensitivity of the LHC experiments to the top EDM. Finally we note that models of the type discussed here can produce interesting signatures at the LHC some of which are discussed in [4,36].

## IV. CONCLUSION

As is well known EDMs are probes of new physics beyond the Standard Model. In this paper we have given an analysis of the EDM of the top quark in an extended MSSM model which includes an extra vector like multiplet containing quarks and mirror quarks and their superpartners which can mix with the third generation. A small mixings of this type is not excluded by experiment for the third generation. Such mixings bring in new sources of $CP$ violation which do not enter in the analysis of the EDMs of the first two generations. Thus these phases are typically unconstrained and can be large. The relevant parts of the MSSM Lagrangian interactions involving mirror quarks, charginos, neutralinos and gluinos have been worked out, we believe, for the first time in this analysis. The EDM of the top in computed using these interactions. The analysis has many one loop diagrams involving the exchange of the W, the Z as shown in Fig. 1, and also from loops involving the exchange of the charginos, the neutralinos, the gluino as shown in Fig. 2, each involving also the exchange of vector multiplets in the loops. It is found that the analysis of the top EDM is more involved in this case as compared to the analysis for the light quarks or for the leptons. This is so because the mass of the external fermion cannot be ignored relative to the mass of the exchanged particles in this case, as their masses are comparable. Because of this, the loop integrals in this case are functions of more than just one mass ratio. Finally, we have carried out a numerical analysis of the top EDM in this model. The analysis shows that with large $CP$ phases arising from the new sector the top EDM can be as large as $10^{-19}$ ecm which can be probed in processes such as $e^+e^- \to t\bar{t}$ and $\gamma\gamma \to t\bar{t}$ in collider experiments. It should be interesting to also analyze the sensitivity that the LHC can achieve for

[2]The analysis of [22] indicates that an $e^+e^-$ collider at $\sqrt{s} = 500$ GeV with 10 fb$^{-1}$ of integrated luminosity will be sensitive to the $t - Z$ electric dipole moment up to $8 \times 10^{-20}$ ecm.

the top EDM. Finally, we note that the contributions of the chromoelectric dipole moment and of the purely gluonic dimension six operator were not considered in the current work. These contributions entail computations of a new set of diagrams involving external gluon vertices and require a separate analysis. However, we expect these contributions to be of similar size as the one computed here.

## ACKNOWLEDGMENTS

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## APPENDIX: MASS MATRICES FOR QUARKS AND SQUARKS AND FOR THEIR MIRRORS

In this Appendix we exhibit the mass matrices for the top quarks, the bottom quarks, the scalar quarks and their mirrors that enter in the computations of the EDM of the top. In the deduction of the mass matrices we need the transformation properties of the quarks and their mirrors. Thus under $SU(3)_C \times SU(2)_L \times U(1)_Y$ the quarks transform as follows:

$$q \equiv \begin{pmatrix} t_L \\ b_L \end{pmatrix} \sim \left(3, 2, \frac{1}{6}\right), \qquad t_L^c \sim \left(3^*, 1, -\frac{2}{3}\right), \qquad b_L^c \sim \left(3^*, 1, \frac{1}{3}\right), \tag{A1}$$

while the mirror quarks transform as

$$Q^c \equiv \begin{pmatrix} B_L^c \\ T_L^c \end{pmatrix} \sim \left(3^*, 2, -\frac{1}{6}\right), \qquad T_L \sim \left(3, 1, \frac{2}{3}\right), \qquad B_L \sim \left(3^*, 1, -\frac{1}{3}\right). \tag{A2}$$

For the Higgs multiplets we have the MSSM Higgs doublets with the $SU(3)_C \times SU(2)_L \times U(1)_Y$ transformation properties as follows:

$$H_1 \equiv \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} \sim \left(1, 2, -\frac{1}{2}\right), \qquad H_2 \equiv \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} \sim \left(1, 2, \frac{1}{2}\right). \tag{A3}$$

We assume that the mirrors of the vector like generation escape acquiring mass at the grand unified theory scale and remain light down to the electroweak scale where the superpotential of the model for the quark part may be written in the form

$$W = \epsilon_{ij}[h_1 \hat{H}_1^i \hat{q}_L^j \hat{b}_L^c + h_1' \hat{H}_2^j \hat{q}_L^i \hat{t}_L^c + h_2 \hat{H}_1^i \hat{Q}^{cj} \hat{T}_L + h_2' \hat{H}_2^j \hat{Q}^{ci} \hat{B}_L] + h_3 \epsilon_{ij} \hat{Q}^{ci} \hat{q}_L^j + h_4 \hat{b}_L^c \hat{B}_L + h_5 \hat{t}_L^c \hat{T}_L. \tag{A4}$$

Mixings of the above type can arise via nonrenormalizable interactions [7]. To get the mass matrices of the quarks and of the mirror quarks we replace the superfields in the superpotential by their component scalar fields. The relevant parts in the superpotential that produce the quark and mirror quark mass matrices are

$$W = h_1 H_1^1 \tilde{b}_L \tilde{b}_R^* + h_1' H_2^2 \tilde{t}_L \tilde{t}_R^* + h_2 H_1^1 \tilde{T}_R^* \tilde{T}_L + h_2' H_2^2 \tilde{B}_R^* \tilde{B}_L + h_3 \tilde{B}_R^* \tilde{b}_L - h_3 \tilde{T}_R^* \tilde{t}_L + h_4 \tilde{b}_R^* \tilde{B}_L + h_5 \tilde{t}_R^* \tilde{T}_L. \tag{A5}$$

The mass terms for the quarks and their mirrors arise from the part of the Lagrangian

$$\mathcal{L} = -\frac{1}{2} \frac{\partial^2 W}{\partial A_i \partial A_j} \psi_i \psi_j + \text{H.c.}, \tag{A6}$$

where $\psi$ and $A$ stand for generic two-component fermion and scalar fields. After spontaneous breaking of the electroweak symmetry, ($\langle H_1^1 \rangle = v_1$ and $\langle H_2^2 \rangle = v_2$), we have the following set of mass terms written in the 4-spinor notation for the fermionic sector

$$-\mathcal{L}_m = (\bar{b}_R \quad \bar{B}_R) \begin{pmatrix} h_1 v_1 & h_4 \\ h_3 & h_2' v_2 \end{pmatrix} \begin{pmatrix} b_L \\ B_L \end{pmatrix} + (\bar{t}_R \quad \bar{T}_R) \times \begin{pmatrix} h_1' v_2 & h_5 \\ -h_3 & h_2 v_1 \end{pmatrix} \begin{pmatrix} t_L \\ T_L \end{pmatrix} + \text{H.c.}$$

Here the mass matrices are not Hermitian and one needs to use bi-unitary transformations to diagonalize them. Thus, we write the linear transformations

$$\begin{pmatrix} b_R \\ B_R \end{pmatrix} = D_R^b \begin{pmatrix} b_{1_R} \\ b_{2_R} \end{pmatrix}, \qquad \begin{pmatrix} b_L \\ B_L \end{pmatrix} = D_L^b \begin{pmatrix} b_{1_L} \\ b_{2_L} \end{pmatrix}, \tag{A7}$$

such that

$$D_R^{b\dagger} \begin{pmatrix} h_1 v_1 & h_4 \\ h_3 & h_2' v_2 \end{pmatrix} D_L^b = \text{diag}(m_{b_1}, m_{b_2}), \tag{A8}$$

and the same holds for the top mass matrix so that

$$D_R^{t\dagger} \begin{pmatrix} h_1' v_2 & h_5 \\ -h_3 & h_2 v_1 \end{pmatrix} D_L^t = \text{diag}(m_{t_1}, m_{t_2}). \tag{A9}$$

Here $b_1, b_2$ are the mass eigenstates and we identify the bottom quark with the eigenstate 1, i.e., $b = b_1$, and identify $b_2$ with a heavy mirror eigenstate with a mass in the hundreds of GeV. Similarly $t_1, t_2$ are the mass eigenstates for the top quarks, where we identify $t_1$ with the physical top quark with the lighter mass, and $t_2$ with the heavier mass eigenstate. By multiplying Eq. (A8) by $D_L^{b\dagger}$ from the right and by $D_R^b$ from the left and by multiplying Eq. (A9) by $D_L^{t\dagger}$ from the right and by $D_R^t$ from the left, one can equate the values of the parameter $h_3$ in both equations and we can get the following relation between the diagonalizing matrices $D^b$ and $D^t$

$$m_{b1} D_{R21}^b D_{L11}^{b*} + m_{b2} D_{R22}^b D_{L12}^{b*} = -[m_{t1} D_{R21}^t D_{L11}^{t*} + m_{t2} D_{R22}^t D_{L12}^{t*}]. \tag{A10}$$

Equation (A10) is an important constraint relating $D^b$ and $D^t$ which is used as a check on the numerical analysis.

Next we consider the mixings of the squarks and the mirror squarks. We write the superpotential in terms of the scalar fields of interest as follows

$$W = -\mu\epsilon_{ij}H_1^iH_2^j + \epsilon_{ij}[h_1H_1^i\tilde{q}_L^j\tilde{b}_L^c + h_1'H_2^j\tilde{q}_L^i\tilde{t}_L^c + h_2H_1^i\tilde{Q}^{cj}\tilde{T}_L + h_2'H_2^j\tilde{Q}^{ci}\tilde{B}_L] + h_3\epsilon_{ij}\tilde{Q}^{ci}\tilde{q}_L^j + h_4\tilde{b}_L^c\tilde{B}_L + h_5\tilde{t}_L^c\tilde{T}_L. \quad (A11)$$

The mass$^2$ matrix of the squark—mirror squark comes from three sources, i.e., the $F$ term, the $D$ term, and the soft susy breaking terms. Using the above superpotential and after the breaking of the electroweak symmetry we get for the mass part of the Lagrangian $\mathcal{L}_F$ and $\mathcal{L}_D$ the following set of terms:

$$\begin{aligned}-\mathcal{L}_F = {}&(m_B^2+|h_3|^2)\tilde{B}_R\tilde{B}_R^* + (m_T^2+|h_3|^2)\tilde{T}_R\tilde{T}_R^* + (m_B^2+|h_4|^2)\tilde{B}_L\tilde{B}_L^* + (m_T^2+|h_5|^2)\tilde{T}_L\tilde{T}_L^* + (m_b^2+|h_4|^2)\tilde{b}_R\tilde{b}_R^*\\ &+(m_t^2+|h_5|^2)\tilde{t}_R\tilde{t}_R^* + (m_b^2+|h_3|^2)\tilde{b}_L\tilde{b}_L^* + (m_t^2+|h_3|^2)\tilde{t}_L\tilde{t}_L^* + \{-m_b\mu^*\tan\beta\tilde{b}_L\tilde{b}_R^* - m_T\mu^*\tan\beta\tilde{T}_L\tilde{T}_R^*\\ &-m_t\mu^*\cot\beta\tilde{t}_L\tilde{t}_R^* - m_B\mu^*\cot\beta\tilde{B}_L\tilde{B}_R^* + (m_Bh_3^*+m_bh_4)\tilde{B}_L\tilde{b}_L^* + (m_Bh_4+m_bh_3^*)\tilde{B}_R\tilde{b}_R^*\\ &+(m_th_5-m_Th_3^*)\tilde{T}_L\tilde{t}_L^* + (m_Th_5-m_th_3^*)\tilde{T}_R\tilde{t}_R^* + \text{H.c.}\},\end{aligned} \quad (A12)$$

and

$$\begin{aligned}-\mathcal{L}_D = {}&\tfrac{1}{2}m_Z^2\cos^2\theta_W\cos2\beta\{\tilde{t}_L\tilde{t}_L^* - \tilde{b}_L\tilde{b}_L^* + \tilde{B}_R\tilde{B}_R^* - \tilde{T}_R\tilde{T}_R^*\} + \tfrac{1}{2}m_Z^2\sin^2\theta_W\cos2\beta\{-\tfrac{1}{3}\tilde{t}_L\tilde{t}_L^* + \tfrac{4}{3}\tilde{t}_R\tilde{t}_R^*\\ &-\tfrac{1}{3}\tilde{b}_L\tilde{b}_L^* - \tfrac{4}{3}\tilde{T}_L\tilde{T}_L^* + \tfrac{1}{3}\tilde{B}_R\tilde{B}_R^* + \tfrac{1}{3}\tilde{T}_R\tilde{T}_R^* + \tfrac{2}{3}\tilde{B}_L\tilde{B}_L^* - \tfrac{2}{3}\tilde{b}_R\tilde{b}_R^*\}.\end{aligned} \quad (A13)$$

Next we add the general set of soft supersymmetry breaking terms to the scalar potential so that

$$\begin{aligned}V_{\text{soft}} = {}&\tilde{M}_q^2\tilde{q}_L^{i*}\tilde{q}_L^i + \tilde{M}_Q^2\tilde{Q}^{ci*}\tilde{Q}^{ci} + \tilde{M}_t^2\tilde{t}_L^{c*}\tilde{t}_L^c + \tilde{M}_b^2\tilde{b}_L^{c*}\tilde{b}_L^c + \tilde{M}_B^2\tilde{B}_L^*\tilde{B}_L + \tilde{M}_T^2\tilde{T}_L^*\tilde{T}_L + \epsilon_{ij}\{h_1A_bH_1^i\tilde{q}_L^j\tilde{b}_L^c\\ &-h_1'A_tH_2^i\tilde{q}_L^j\tilde{t}_L^c + h_2A_TH_1^i\tilde{Q}^{cj}\tilde{T}_L - h_2'A_BH_2^i\tilde{Q}^{cj}\tilde{B}_L + \text{H.c.}\}.\end{aligned} \quad (A14)$$

From $\mathcal{L}_{F,D}$ and by giving the neutral Higgs their vacuum expectation values in $V_{\text{soft}}$ we can produce the mass$^2$ matrix $M_{\tilde{b}}^2$ for the sbottom and the mirror sbottoms in the basis $(\tilde{b}_L, \tilde{B}_L, \tilde{b}_R, \tilde{B}_R)$. We label the matrix elements of these as $(M_{\tilde{b}}^2)_{ij} = M_{ij}^2$ where

$$\begin{aligned}&M_{11}^2 = \tilde{M}_q^2 + m_b^2 + |h_3|^2 - m_Z^2\cos2\beta(\tfrac{1}{2} - \tfrac{1}{3}\sin^2\theta_W), \qquad M_{22}^2 = \tilde{M}_B^2 + m_B^2 + |h_4|^2 + \tfrac{1}{3}m_Z^2\cos2\beta\sin^2\theta_W,\\ &M_{33}^2 = \tilde{M}_b^2 + m_b^2 + |h_4|^2 - \tfrac{1}{3}m_Z^2\cos2\beta\sin^2\theta_W, \qquad M_{44}^2 = \tilde{M}_Q^2 + m_B^2 + |h_3|^2 + m_Z^2\cos2\beta(\tfrac{1}{2} - \tfrac{1}{3}\sin^2\theta_W),\\ &M_{12}^2 = M_{21}^{2*} = m_Bh_3^* + m_bh_4, \qquad M_{13}^2 = M_{31}^{2*} = m_b(A_b^* - \mu\tan\beta), \qquad M_{14}^2 = M_{41}^{2*} = 0,\\ &M_{23}^2 = M_{32}^{2*} = 0, \qquad M_{24}^2 = M_{42}^{2*} = m_B(A_B^* - \mu\cot\beta), \qquad M_{34}^2 = M_{43}^{2*} = m_Bh_4 + m_bh_3^*.\end{aligned} \quad (A15)$$

Here the terms $M_{11}^2, M_{13}^2, M_{31}^2, M_{33}^2$ arise from soft breaking in the sector $\tilde{b}_L, \tilde{b}_R$. Similarly the terms $M_{22}^2, M_{24}^2, M_{42}^2, M_{44}^2$ arise from soft breaking in the sector $\tilde{B}_L$, $\tilde{B}_R$. The terms $M_{12}^2$, $M_{21}^2$, $M_{23}^2$, $M_{32}^2$, $M_{14}^2$, $M_{41}^2$, $M_{34}^2$, $M_{43}^2$, arise from mixing between the sbottoms and the mirrors. We assume that all the masses are of the electroweak scale so all the terms enter in the mass$^2$ matrix. We diagonalize this Hermitian mass$^2$ matrix by the unitary transformation $\tilde{D}^{b\dagger}M_{\tilde{b}}^2\tilde{D}^b = \text{diag}(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, m_{\tilde{b}_3}^2, m_{\tilde{b}_4}^2)$. There is a similar mass$^2$ matrix in the stop sector. In the basis $(\tilde{t}_L, \tilde{T}_L, \tilde{t}_R, \tilde{T}_R)$ we can write the mass$^2$ matrix for the stops and the mirror stops in the form $(M_{\tilde{t}}^2)_{ij} = m_{ij}^2$ where

$$\begin{aligned}&m_{11}^2 = \tilde{M}_q^2 + m_t^2 + |h_3|^2 + m_Z^2\cos2\beta(\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W), \qquad m_{22}^2 = \tilde{M}_T^2 + m_T^2 + |h_5|^2 - \frac{2}{3}m_Z^2\cos2\beta\sin^2\theta_W,\\ &m_{33}^2 = \tilde{M}_t^2 + m_t^2 + |h_5|^2 + \tfrac{2}{3}m_Z^2\cos2\beta\sin^2\theta_W, \qquad m_{44}^2 = \tilde{M}_Q^2 + m_T^2 + |h_3|^2 - m_Z^2\cos2\beta(\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W),\\ &m_{12}^2 = m_{21}^{2*} = -m_Th_3^* + m_th_5, \qquad m_{13}^2 = m_{31}^{2*} = m_t(A_t^* - \mu\cot\beta), \qquad m_{14}^2 = m_{41}^{2*} = 0, \qquad m_{23}^2 = m_{32}^{2*} = 0,\\ &m_{24}^2 = m_{42}^{2*} = m_T(A_T^* - \mu\tan\beta), \qquad m_{34}^2 = m_{43}^{2*} = m_Th_5 - m_th_3^*.\end{aligned} \quad (A16)$$

As in the sbottom—mirror sbottom sector here also the terms $m_{11}^2$, $m_{13}^2$, $m_{31}^2$, $m_{33}^2$ arise from soft breaking in the sector $\tilde{t}_L$, $\tilde{t}_R$. Similarly the terms $m_{22}^2$, $m_{24}^2$, $m_{42}^2$, $m_{44}^2$ arise from soft breaking in the sector $\tilde{T}_L$, $\tilde{T}_R$. The terms $m_{12}^2$, $m_{21}^2$, $m_{23}^2$, $m_{32}^2$, $m_{14}^2$, $m_{41}^2$, $m_{34}^2$, $m_{43}^2$, arise from mixing between the physical sector and the mirror sector. Again as in the sbottom- mirror sbottom sector we assume that all the masses are of the electroweak size so all the terms enter in the mass$^2$ matrix. This mass$^2$ matrix can be diagonalized by the unitary transformation $\tilde{D}^{t\dagger}M_{\tilde{t}}^2\tilde{D}^t = \text{diag}(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, m_{\tilde{t}_3}^2, m_{\tilde{t}_4}^2)$. The physical bottom and top states are $b \equiv b_1$, $t \equiv t_1$, and the states $b_2$, $t_2$ are heavy states with mostly mirror particle content. The states $\tilde{b}_i$, $\tilde{t}_i$; $i = 1$–4 are the sbottom and stop states and their mirrors. For the case of no mixing these limits are as follows:

$$\tilde{b}_1 \to \tilde{b}_L, \quad \tilde{b}_2 \to \tilde{B}_L, \quad \tilde{b}_3 \to \tilde{b}_R, \quad \tilde{b}_4 \to \tilde{B}_R,$$
$$\tilde{t}_1 \to \tilde{t}_L, \quad \tilde{t}_2 \to \tilde{T}_L, \quad \tilde{t}_3 \to \tilde{t}_R, \quad \tilde{t}_4 \to \tilde{T}_R. \tag{A17}$$

The couplings $h_3$, $h_4$ and $h_5$ can be complex and thus the matrices $D^b_{L,R}$ and $D^t_{L,R}$ will have complex elements that would produce electric dipole moments through their arguments discussed in the text of the paper. Also the trilinear couplings $A_{t,b,B,T}$ could be complex and produce electric dipole moment through the arguments of $\tilde{D}^t$ and $\tilde{D}^b$. We will assume for simplicity that this is the only part in the theory that has $CP$ violating phases. Thus the $\mu$ parameter is considered real along with the other trilinear couplings in the theory. The above allows one to automatically satisfy the constraints from the upper limits on the EDMs of the electron, the neutron and of Hg and of Thallium.


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