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Phys. Rev. D **91**, 095017 — Published 22 May 2015

DOI: 10.1103/PhysRevD.91.095017

The Neutron Electric Dipole Moment and Probe of PeV Scale Physics

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Abstract

The experimental limit on the neutron electric dipole moment is used as a possible probe of new physics beyond the standard model. Within MSSM we use the current experimental limit on the neutron EDM and possible future improvement as a probe of high scale SUSY. Quantitative analyses show that scalar masses as large as a PeV and larger could be probed in improved experiment far above the scales accessible at future colliders. We also discuss the neutron EDM as a probe of new physics models beyond MSSM. Specifically we consider an MSSM extension with a particle content including a vectorlike multiplet. Such an extension brings in new sources of CP violation beyond those in MSSM. These CP phases contribute to the EDM of the quarks and to the neutron EDM. These contributions are analyzed in this work where we include the supersymmetric loop diagrams involving the neutralinos, charginos, the gluino, squark and mirror squark exchange diagrams at the one loop level. We also take into account the contributions from the W, Z, quark and mirror quark exchanges arising from the mixings of the vectorlike generation with the three generations. It is shown that the experimental limit on the neutron EDM can be used to probe such new physics models. In the future one expects the neutron EDM to improve an order of magnitude or more allowing one to extend the probe of high scale SUSY and of new physics models. For the MSSM the probe of high scales could go up to and beyond PeV scale masses.

Keywords: Electric Dipole Moment, Neutron, vector multiplets

PACS numbers: 13.40Em, 12.60.-i, 14.60.Fg

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1 Introduction

CP violation provides a window to new physics [For the early history of CP violation and for reviews see e.g.,[1, 2, 3, 4]]. One of the important manifestations of CP violation are that such violations generate electric dipole moment (EDM) for elementary particle, i.e., for the quarks and leptons. As is well known the EDM of elementary particles in the standard model are very small. For example, for the electron the EDM is estimated to be $|d_e| \simeq 10^{-38}$ $e$cm. The electroweak sector of the Standard Model gives an EDM for the neutron of size $|d_n| \sim 10^{-32} - 10^{-31}$ $e$cm. These sizes are too small to be observed in any foreseeable experiment. The QCD sector of the standard model also produces a non-vanishing EDM for the neutron which is of size $d_n \sim \mathcal{O}(10^{-16\theta})$ $e$cm and satisfaction of Eq. (1) requires θ to be of size 10^{-10} or smaller where θ is QCD phase which enters the QCD Lagrangian as $(\theta g_s^2/32\pi^2)G_{\mu\nu}\tilde{G}^{\mu\nu}$. We assume the absence of such a term by a symmetry such as the Peccei-Quinn symmetry. In supersymmetric models there are a variety of new sources of CP violation and typically these new sources of CP violation lead to EDM of the elementary particles in excess of the observed limits. This phenomenon is often referred to as the SUSY EDM problem. Several solutions to this problem have been suggested in the past such as small CP phases [5], mass suppression [6] and the cancellation mechanism [7, 8] where various diagrams contributing to the EDMs cancel to bring the predicted EDM below the experimental value (for an alternate possibility see [9]). The recent data from the LHC indicates the Higgs mass to be ~ 126 GeV which requires a large loop correction to lift the tree level mass to the desired experimental value. The sizable loop correction points to a high SUSY scale and specifically large scalar masses. In view of this one could turn the indication of a large SUSY scale as a possible resolution of the EDM problem of supersymmetric models. In fact it has been suggested recently [10, 11, 12, 13, 14], that one can go further and utilize the current and future improved data on the EDM limits to probe mass scales far beyond those that may be accessible at colliders. We also note in passing that a large SUSY scale also helps suppress flavor changing neutral currents (FCNC) in supersymmetric models and helps stabilize the proton against rapid decay from baryon and lepton number violating dimension five operators in grand unified theories.

In this work we will focus on the neutron electric dipole moment of the light quarks which in turn generate an EDM of the neutron as a probe of high scale physics. The current experimental limit on the EDM of the neutron is [15]

$$|d_n| < 2.9 \times 10^{-26} e\text{cm} \quad (90\% \text{ CL}). \tag{1}$$

Higher sensitivity is expected from experiments in the future [16]. In our analysis here we consider the neutron EDM as a probe of high scalar masses within the minimal supersymmetric standard model (MSSM) as well as consider the neutron EDM as a probe of an extension of MSSM with a vectorlike generation which brings in new sources of CP violation. A vectorlike generation is anomaly free. Further, a variety of grand unified models, string and D brane models contain vectorlike generations [17]. Vectorlike generations have been considered by several authors since their discovery would constitute new physics (see, e.g., [18, 19, 20, 21, 22, 23, 24, 25, 26, 13, 27, 28, 29, 30]).

Quark dipole moment have been examined in MSSM in previous works and a complete analysis at the one loop level is given in [7]. Here we compute the EDM of the neutron within an extended MSSM where the particle content contains in addition a vectorlike multiplet. The outline of the rest of the paper is as follows: In section 2 we give the relevant formulae for the extension of MSSM with a vectorlike generation. In section 3 we give the interactions of W and Z vector bosons with the quarks and mirror quarks of the extended model. Interactions of the gluino with quarks, squarks, mirror quarks and mirror squarks are given in section 4. Interactions of the charginos and neutralinos with quarks, squarks, mirror quarks and mirror squarks are given in section 5. An analysis of the electric dipole moment operator involving loop contributions from W and Z exchange, gluino exchange, and chargino and neutralino exchanges is given in section 6. A numerical estimate of the EDM of the neutron arising from these loop contributions is given in section 7. Here we also discuss the neutron EDM as a probe of PeV scale physics. Conclusions are given in section 8. In section 9 we give details of how the scalar mass square matrices are constructed in the extended model with a vectorlike generation.

2 Extension of MSSM with a Vector Multiplet

In this section we give details of the extension of MSSM to include a vectorlike generation. A vectorlike multiplet consists of an ordinary fourth generation of leptons, quarks and their mirrors. A vectorlike generation is anomaly free and thus its inclusion respects the good properties of a gauge theory. Vectorlike multiplets arise in a variety of unified models some of which could be low-lying. They have been used recently in a variety of analyses. In the analysis below we will assume an extended MSSM with just one vector multiplet. Before proceeding further we define the notation and give a very brief description of the extended model and a more detailed description can be found in the previous works mentioned above. Thus the extended MSSM contains a vectorlike multiplet. To fix notation the three generations of quarks are denoted by

$$q_{iL} \equiv \begin{pmatrix} t_{iL} \\ b_{iL} \end{pmatrix} \sim \left(3, 2, \frac{1}{6}\right) \ ; \quad t^c_{iL} \sim \left(3^*, 1, -\frac{2}{3}\right) \ ; \quad b^c_{iL} \sim \left(3^*, 1, \frac{1}{3}\right) \ ; \quad i = 1, 2, 3 \tag{2}$$

where the properties under $SU(3)_C \times SU(2)_L \times U(1)_Y$ are also exhibited. The last entry in the braces such as $(3, 2, 1/6)$ is the value of the hypercharge Y defined so that $Q = T_3 + Y$. These leptons have $V - A$ interactions. We can now add a vectorlike multiplet where we have a fourth family of leptons with $V - A$ interactions whose transformations can be gotten from Eq. (2) by letting i run from 1 to 4. A vectorlike quark multiplet also has mirrors and so we consider these mirror quarks which have $V + A$ interactions. The quantum numbers of the mirrors are given by

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

Interesting new physics arises when we allow mixings of the vectorlike generation with the three ordinary generations. Here we focus on the mixing of the mirrors in the vectorlike generation with the three generations. Thus the superpotential of the model allowing for the mixings among the three ordinary generations and the vectorlike generation is given by

$$\begin{aligned} W = & -\mu \epsilon_{ij} \hat{H}_1^i \hat{H}_2^j + \epsilon_{ij} [y_1 \hat{H}_1^i \hat{q}_{1L}^j \hat{b}_{1L}^c + y_1' \hat{H}_2^j \hat{q}_{1L}^i \hat{t}_{1L}^c + y_2 \hat{H}_1^i \hat{Q}^{cj} \hat{T}_L + y_2' \hat{H}_2^j \hat{Q}^{ci} \hat{B}_L \\ & + y_3 \hat{H}_1^i \hat{q}_{2L}^j \hat{b}_{2L}^c + y_3' \hat{H}_2^j \hat{q}_{2L}^i \hat{t}_{2L}^c + y_4 \hat{H}_1^i \hat{q}_{3L}^j \hat{b}_{3L}^c + y_4' \hat{H}_2^j \hat{q}_{3L}^i \hat{t}_{3L}^c] \\ & + h_3 \epsilon_{ij} \hat{Q}^{ci} \hat{q}_{1L}^j + h_3' \epsilon_{ij} \hat{Q}^{ci} \hat{q}_{2L}^j + h_3'' \epsilon_{ij} \hat{Q}^{ci} \hat{q}_{3L}^j + h_4 \hat{b}_{1L}^c \hat{B}_L + h_5 \hat{t}_{1L}^c \hat{T}_L \\ & + h_4' \hat{b}_{2L}^c \hat{B}_L + h_5' \hat{t}_{2L}^c \hat{T}_L + h_4'' \hat{b}_{3L}^c \hat{B}_L + h_5'' \hat{t}_{3L}^c \hat{T}_L \;, \end{aligned} \tag{4}$$

where μ is the complex Higgs mixing parameter so that $\mu = |\mu| e^{i\theta_\mu}$. The mass terms for the ups, mirror ups, downs and mirror downs arise from the term

$$\mathcal{L} = -\frac{1}{2} \frac{\partial^2 W}{\partial A_i \partial A_j} \psi_i \psi_j + \text{h.c.}, \tag{5}$$

where ψ and A stand for generic two-component fermion and scalar fields. After spontaneous breaking of the electroweak symmetry, ($\langle H_1^1 \rangle = v_1/\sqrt{2}$ and $\langle H_2^2 \rangle = v_2/\sqrt{2}$), we have the following set of mass terms written in the four-component spinor notation so that

$$-\mathcal{L}_m = \bar{\xi}_R^T (M_u) \xi_L + \bar{\eta}_R^T (M_d) \eta_L + \text{h.c.}, \tag{6}$$

where the basis vectors in which the mass matrix is written is given by

$$\begin{aligned}
\bar{\xi}_R^T &= \begin{pmatrix} \bar{t}_R & \bar{T}_R & \bar{c}_R & \bar{u}_R \end{pmatrix}, \\
\xi_L^T &= \begin{pmatrix} t_L & T_L & c_L & u_L \end{pmatrix}, \\
\bar{\eta}_R^T &= \begin{pmatrix} \bar{b}_R & \bar{B}_R & \bar{s}_R & \bar{d}_R \end{pmatrix}, \\
\eta_L^T &= \begin{pmatrix} b_L & B_L & s_L & d_L \end{pmatrix},
\end{aligned} \tag{7}$$

and the mass matrix M_u is given by

$$M_u = \begin{pmatrix} y_1' v_2/\sqrt{2} & h_5 & 0 & 0 \\ -h_3 & y_2 v_1/\sqrt{2} & -h_3' & -h_3'' \\ 0 & h_5' & y_3' v_2/\sqrt{2} & 0 \\ 0 & h_5'' & 0 & y_4' v_2/\sqrt{2} \end{pmatrix} . \tag{8}$$

We define the matrix element (22) of the mass matrix as m_T so that,

$$m_T = y_2 v_1/\sqrt{2}. \tag{9}$$

The mass matrix is not hermitian and thus one needs bi-unitary transformations to diagonalize it. We define the bi-unitary transformation so that

$$D_R^{u\dagger}(M_u)D_L^u = \mathrm{diag}(m_{u_1}, m_{u_2}, m_{u_3}, m_{u_4}). \tag{10}$$

Under the bi-unitary transformations the basis vectors transform so that

$$\begin{pmatrix} t_R \\ T_R \\ c_R \\ u_R \end{pmatrix} = D_R^u \begin{pmatrix} u_{1_R} \\ u_{2_R} \\ u_{3_R} \\ u_{4_R} \end{pmatrix}, \quad \begin{pmatrix} t_L \\ T_L \\ c_L \\ u_L \end{pmatrix} = D_L^u \begin{pmatrix} u_{1_L} \\ u_{2_L} \\ u_{3_L} \\ u_{4_L} \end{pmatrix} . \tag{11}$$

A similar analysis goes to the down mass matrix M_d where

$$M_d = \begin{pmatrix} y_1 v_1/\sqrt{2} & h_4 & 0 & 0 \\ h_3 & y_2' v_2/\sqrt{2} & h_3' & h_3'' \\ 0 & h_4' & y_3 v_1/\sqrt{2} & 0 \\ 0 & h_4'' & 0 & y_4 v_1/\sqrt{2} \end{pmatrix} . \tag{12}$$

In general $h_3, h_4, h_5, h_3', h_4', h_5', h_3'', h_4'', h_5''$ can be complex and we define their phases so that

$$h_k = |h_k| e^{i\chi_k}, \quad h_k' = |h_k'| e^{i\chi_k'}, \quad h_k'' = |h_k''| e^{i\chi_k''} \; ; k = 3, 4, 5 \; . \tag{13}$$

We introduce now the mass parameter m_B defined by the (22) element of the mass matrix above so that

$$m_B = y_2' v_2/\sqrt{2}. \tag{14}$$

Next we consider the mixing of the down squarks and the charged mirror sdowns. The mass squared matrix of the sdown - mirror sdown comes from three sources: the F term, the D term of the potential and the soft SUSY breaking terms. Using the superpotential of the mass terms arising from it after the breaking of the electroweak symmetry are given by the Lagrangian

$$\mathcal{L} = \mathcal{L}_F + \mathcal{L}_D + \mathcal{L}_{\text{soft}} \ , \tag{15}$$

where $\mathcal{L}_F$ is deduced from $F_i = \partial W/\partial A_i$, and $-\mathcal{L}_F = V_F = F_i F_i^*$ while the $\mathcal{L}_D$ is given by

$$\begin{aligned}
-\mathcal{L}_D = {} & \frac{1}{2} m_Z^2 \cos^2\theta_W \cos 2\beta \{\tilde{t}_L \tilde{t}^*_L - \tilde{b}_L \tilde{b}^*_L + \tilde{c}_L \tilde{c}^*_L - \tilde{s}_L \tilde{s}^*_L + \tilde{u}_L \tilde{u}^*_L - \tilde{d}_L \tilde{d}^*_L \\
& + \tilde{B}_R \tilde{B}^*_R - \tilde{T}_R \tilde{T}^*_R\} + \frac{1}{2} m_Z^2 \sin^2\theta_W \cos 2\beta \{-\frac{1}{3} \tilde{t}_L \tilde{t}^*_L + \frac{4}{3} \tilde{t}_R \tilde{t}^*_R - \frac{1}{3} \tilde{c}_L \tilde{c}^*_L + \frac{4}{3} \tilde{c}_R \tilde{c}^*_R \\
& - \frac{1}{3} \tilde{u}_L \tilde{u}^*_L + \frac{4}{3} \tilde{u}_R \tilde{u}^*_R + \frac{1}{3} \tilde{T}_R \tilde{T}^*_R - \frac{4}{3} \tilde{T}_L \tilde{T}^*_L - \frac{1}{3} \tilde{b}_L \tilde{b}^*_L - \frac{2}{3} \tilde{b}_R \tilde{b}^*_R \\
& - \frac{1}{3} \tilde{s}_L \tilde{s}^*_L - \frac{2}{3} \tilde{s}_R \tilde{s}^*_R - \frac{1}{3} \tilde{d}_L \tilde{d}^*_L - \frac{2}{3} \tilde{d}_R \tilde{d}^*_R + \frac{1}{3} \tilde{B}_R \tilde{B}^*_R + \frac{2}{3} \tilde{B}_L \tilde{B}^*_L\}.
\end{aligned} \tag{16}$$

For $\mathcal{L}_{\text{soft}}$ we assume the following form

$$\begin{aligned}
-\mathcal{L}_{\text{soft}} = {} & M^2_{\tilde{1}L} \tilde{q}^{k*}_{1L} \tilde{q}^k_{1L} + M^2_{\tilde{2}L} \tilde{q}^{k*}_{2L} \tilde{q}^k_{2L} + M^2_{\tilde{3}L} \tilde{q}^{k*}_{3L} \tilde{q}^k_{3L} + M^2_{\tilde{Q}} \tilde{Q}^{ck*} \tilde{Q}^{ck} + M^2_{\tilde{t}_1} \tilde{t}^{c*}_{1L} \tilde{t}^c_{1L} \\
& + M^2_{\tilde{b}_1} \tilde{b}^{c*}_{1L} \tilde{b}^c_{1L} + M^2_{\tilde{t}_2} \tilde{t}^{c*}_{2L} \tilde{t}^c_{2L} + M^2_{\tilde{t}_3} \tilde{t}^{c*}_{3L} \tilde{t}^c_{3L} + M^2_{\tilde{b}_2} \tilde{b}^{c*}_{2L} \tilde{b}^c_{2L} + M^2_{\tilde{b}_3} \tilde{b}^{c*}_{3L} \tilde{b}^c_{3L} + M^2_{\tilde{B}} \tilde{B}^*_L \tilde{B}_L + M^2_{\tilde{T}} \tilde{T}^*_L \tilde{T}_L \\
& + \epsilon_{ij} \{y_1 A_b H^i_1 \tilde{q}^j_{1L} \tilde{b}^c_{1L} - y'_1 A_t H^i_2 \tilde{q}^j_{1L} \tilde{t}^c_{1L} + y_3 A_s H^i_1 \tilde{q}^j_{2L} \tilde{b}^c_{2L} - y'_3 A_c H^i_2 \tilde{q}^j_{2L} \tilde{t}^c_{2L} \\
& + y_4 A_d H^i_1 \tilde{q}^j_{3L} \tilde{b}^c_{3L} - y'_4 A_u H^i_2 \tilde{q}^j_{3L} \tilde{t}^c_{3L} + y_2 A_T H^i_1 \tilde{Q}^{cj} \tilde{T}_L - y'_2 A_B H^i_2 \tilde{Q}^{cj} \tilde{B}_L + \text{h.c.}\} \ .
\end{aligned} \tag{17}$$

Here $M_{\tilde{1}L}, M_{\tilde{T}}$, etc are the soft masses and A_t, A_b, etc are the trilinear couplings. The trilinear couplings are complex and we define their phases so that

$$A_b = |A_b| e^{i\alpha_{A_b}} \ , \quad A_t = |A_t| e^{i\alpha_{A_t}} \ , \cdots \ . \tag{18}$$

From these terms we construct the scalar mass squared matrices.

3 Interaction with W and Z vector bosons

$$-\mathcal{L}_{dWu} = W^\dagger_\rho \sum_{i=1}^{4} \sum_{j=1}^{4} \bar{u}_j \gamma^\rho [G^W_{L_{ji}} P_L + G^W_{R_{ji}} P_R] d_i + \text{h.c.}, \tag{19}$$

where

$$G^W_{L_{ji}} = \frac{g}{\sqrt{2}} [D^{u*}_{L4j} D^d_{L4i} + D^{u*}_{L3j} D^d_{L3i} + D^{u*}_{L1j} D^d_{L1i}], \tag{20}$$

$$G^W_{R_{ji}} = \frac{g}{\sqrt{2}} [D^{u*}_{R2j} D^d_{R2i}]. \tag{21}$$

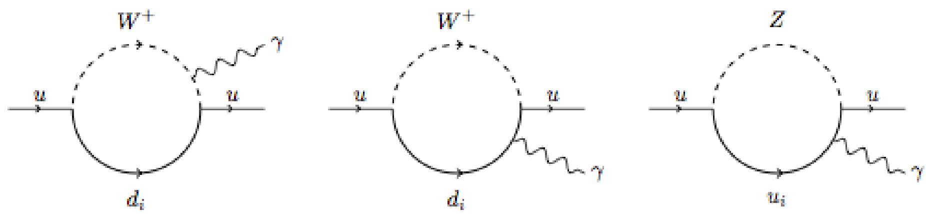

Figure 1: W and Z exchange contributions to the EDM of the up quark. Similar exchange contributions exist for the EDM of the down quark where u and d are interchanged and W^+ is replaced by W^- in the diagrams above.

For the Z boson exchange the interactions that enter with the up type quarks are given by

$$-\mathcal{L}_{uuZ} \quad = Z_\rho \sum_{j=1}^4 \sum_{i=1}^4 \bar{u}_j \gamma^\rho [C^{uZ}_{L_{ji}} P_L + C^{uZ}_{R_{ji}} P_R] u_i, \tag{22}$$

where

$$C^{uZ}_{L_{ji}} = \frac{g}{\cos\theta_W}[x_1(D^{u*}_{L4j} D^u_{L4i} + D^{u*}_{L1j} D^u_{L1i} + D^{u*}_{L3j} D^u_{L3i}) + y_1 D^{u*}_{L2j} D^u_{L2i}], \tag{23}$$

and

$$C^{uZ}_{R_{ji}} = \frac{g}{\cos\theta_W}[y_1(D^{u*}_{R4j} D^u_{R4i} + D^{u*}_{R1j} D^u_{R1i} + D^{u*}_{R3j} D^u_{R3i}) + x_1 D^{u*}_{R2j} D^u_{R2i}], \tag{24}$$

where

$$x_1 = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W, \tag{25}$$

$$y_1 = -\frac{2}{3}\sin^2\theta_W. \tag{26}$$

For the Z boson exchange the interactions that enter with the down type quarks are given by

$$-\mathcal{L}_{ddZ} \quad = Z_\rho \sum_{j=1}^4 \sum_{i=1}^4 \bar{d}_j \gamma^\rho [C^{dZ}_{L_{ji}} P_L + C^{dZ}_{R_{ji}} P_R] d_i, \tag{27}$$

where

$$C^{dZ}_{L_{ji}} = \frac{g}{\cos\theta_W}[x_2(D^{d*}_{L4j} D^d_{L4i} + D^{d*}_{L1j} D^d_{L1i} + D^{d*}_{L3j} D^d_{L3i}) + y_2 D^{d*}_{L2j} D^d_{L2i}], \tag{28}$$

and

$$C^{dZ}_{R_{ji}} = \frac{g}{\cos\theta_W}[y_2(D^{d*}_{R4j} D^d_{R4i} + D^{d*}_{R1j} D^d_{R1i} + D^{d*}_{R3j} D^d_{R3i}) + x_2 D^{d*}_{R2j} D^d_{R2i}], \tag{29}$$

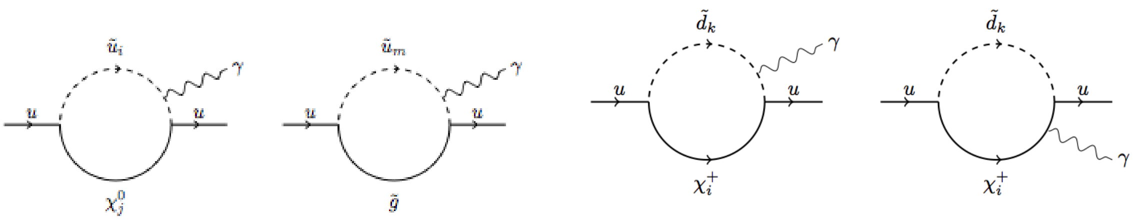

Figure 2: Supersymmetric loop contributions to the EDM of the up-quark. Left panel: Loop diagram involving the neutralinos and up-squarks. Middle left panel: Gluino and up-squark loop contribution. Middle right panel: Loop contribution with chargino and d-squark exchange with the photon emission from the d-squark line. Right panel: Loop contribution with chargino and d-squark exchange with the photon emission from the chargino line. Similar loop contributions exist for the EDM of the down quark, where u and d are interchanged, $\tilde{u}$ and $\tilde{d}$ are interchanged and χ^+ is replaced by χ^- in the diagrams above.

where

$$x_2 = -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W, \tag{30}$$

$$y_2 = \frac{1}{3}\sin^2\theta_W. \tag{31}$$

4 Interaction with gluinos

$$-\mathcal{L}_{qq\tilde{g}} = \sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{a=1}^{8}\sum_{l=1}^{4}\sum_{m=1}^{8} \bar{q}_j[C^a_{L_{jklm}}P_L + C^a_{R_{jklm}}P_R]\tilde{g}_a\tilde{q}^k_m + \text{h.c.}, \tag{32}$$

where

$$C^a_{L_{jklm}} = \sqrt{2}g_s T^a_{jk}(D^{q*}_{R2l}\tilde{D}^q_{4m} - D^{q*}_{R4l}\tilde{D}^q_{8m} - D^{q*}_{R3l}\tilde{D}^q_{6m} - D^{q*}_{R1l}\tilde{D}^q_{3m})e^{-i\xi_3/2}, \tag{33}$$

and

$$C^a_{R_{jklm}} = \sqrt{2}g_s T^a_{jk}(D^{q*}_{L4l}\tilde{D}^q_{7m} + D^{q*}_{L3l}\tilde{D}^q_{5m} + D^{q*}_{L1l}\tilde{D}^q_{1m} - D^{q*}_{L2l}\tilde{D}^q_{2m})e^{i\xi_3/2}, \tag{34}$$

where ξ_3 is the phase of the gluino mass.

5 Interactions with charginos and neutralinos

In this section we discuss the interactions in the mass diagonal basis involving squarks, charginos and quarks. Thus we have

$$-\mathcal{L}_{d-\tilde{u}-\chi^-} = \sum_{j=1}^{4}\sum_{i=1}^{2}\sum_{k=1}^{8}\bar{d}_j(C^{Ld}_{jik}P_L + C^{Rd}_{jik}P_R)\tilde{\chi}^{ci}\tilde{u}_k + \text{h.c.}, \tag{35}$$

such that,

$$
\begin{aligned}
C^{Ld}_{jik} =& g(-\kappa_d U^*_{i2} D^{d*}_{R4j} \tilde{D}^u_{7k} - \kappa_s U^*_{i2} D^{d*}_{R3j} \tilde{D}^u_{5k} - \kappa_b U^*_{i2} D^{d*}_{R1j} \tilde{D}^u_{1k} - \kappa_T U^*_{i2} D^{d*}_{R2j} \tilde{D}^u_{2k} + U^*_{i1} D^{d*}_{R2j} \tilde{D}^u_{4k}), \qquad (36)\\
C^{Rd}_{jik} =& g(-\kappa_u V_{i2} D^{d*}_{L4j} \tilde{D}^u_{8k} - \kappa_c V_{i2} D^{d*}_{L3j} \tilde{D}^u_{6k} - \kappa_t V_{i2} D^{d*}_{L1j} \tilde{D}^u_{3k} - \kappa_B V_{i2} D^{d*}_{L2j} \tilde{D}^u_{4k}\\
&+ V_{i1} D^{d*}_{L4j} \tilde{D}^u_{7k} + V_{i1} D^{d*}_{L3j} \tilde{D}^u_{5k} + V_{i1} D^{d*}_{L1j} \tilde{D}^u_{1k}), \qquad (37)
\end{aligned}
$$

and

$$
-\mathcal{L}_{u-\tilde{d}-\chi^-} = \sum_{j=1}^{4} \sum_{i=1}^{2} \sum_{k=1}^{8} \bar{u}_j (C^{Lu}_{jik} P_L + C^{Ru}_{jik} P_R) \tilde{\chi}^{ci} \tilde{d}_k + \text{h.c.}, \qquad (38)
$$

such that,

$$
\begin{aligned}
C^{Lu}_{jik} =& g(-\kappa_u V^*_{i2} D^{u*}_{R4j} \tilde{D}^d_{7k} - \kappa_c V^*_{i2} D^{u*}_{R3j} \tilde{D}^d_{5k} - \kappa_t V^*_{i2} D^{u*}_{R1j} \tilde{D}^d_{1k} - \kappa_B V^*_{i2} D^{u*}_{R2j} \tilde{D}^d_{2k} + V^*_{i1} D^{u*}_{R2j} \tilde{D}^d_{4k}), \qquad (39)\\
C^{Ru}_{jik} =& g(-\kappa_d U_{i2} D^{u*}_{L4j} \tilde{D}^d_{8k} - \kappa_s U_{i2} D^{u*}_{L3j} \tilde{D}^d_{6k} - \kappa_b U_{i2} D^{u*}_{L1j} \tilde{D}^d_{3k} - \kappa_T U_{i2} D^{u*}_{L2j} \tilde{D}^d_{4k}\\
&+ U_{i1} D^{u*}_{L4j} \tilde{D}^d_{7k} + U_{i1} D^{u*}_{L3j} \tilde{D}^d_{5k} + U_{i1} D^{u*}_{L1j} \tilde{D}^d_{1k}), \qquad (40)
\end{aligned}
$$

with

$$
(\kappa_T, \kappa_b, \kappa_s, \kappa_d) = \frac{(m_T, m_b, m_s, m_d)}{\sqrt{2} m_W \cos\beta}, \qquad (41)
$$

$$
(\kappa_B, \kappa_t, \kappa_c, \kappa_u) = \frac{(m_B, m_t, m_c, m_u)}{\sqrt{2} m_W \sin\beta}. \qquad (42)
$$

and

$$
U^* M_C V = \text{diag}(m_{\tilde{\chi}_1^-}, m_{\tilde{\chi}_2^-}). \qquad (43)
$$

We now discuss the interactions in the mass diagonal basis involving up quarks, up squarks and neutralinos. Thus we have,

$$
-\mathcal{L}_{u-\tilde{u}-\chi^0} = \sum_{i=1}^{4} \sum_{j=1}^{4} \sum_{k=1}^{8} \bar{u}_i (C'^L_{uijk} P_L + C'^R_{uijk} P_R) \tilde{\chi}^0_j \tilde{u}_k + \text{h.c.}, \qquad (44)
$$

such that

$$
\begin{aligned}
C'^L_{uijk} =& \sqrt{2}(\alpha_{uj} D^{u*}_{R4i} \tilde{D}^u_{7k} - \gamma_{uj} D^{u*}_{R4i} \tilde{D}^u_{8k} + \alpha_{cj} D^{u*}_{R3i} \tilde{D}^u_{5k} - \gamma_{cj} D^{u*}_{R3i} \tilde{D}^u_{6k} + \alpha_{tj} D^{u*}_{R1i} \tilde{D}^u_{1k}\\
&- \gamma_{tj} D^{u*}_{R1i} \tilde{D}^u_{3k} + \beta_{Tj} D^{u*}_{R2i} \tilde{D}^u_{4k} - \delta_{Tj} D^{u*}_{R2i} \tilde{D}^u_{2k}), \qquad (45)
\end{aligned}
$$

$$
\begin{aligned}
C'^R_{uijk} =& \sqrt{2}(\beta_{uj} D^{u*}_{L4i} \tilde{D}^u_{7k} - \delta_{uj} D^{u*}_{L4i} \tilde{D}^u_{8k} + \beta_{cj} D^{u*}_{L3i} \tilde{D}^u_{5k} - \delta_{cj} D^{u*}_{L3i} \tilde{D}^u_{6k} + \beta_{tj} D^{u*}_{L1i} \tilde{D}^u_{1k}\\
&- \delta_{tj} D^{u*}_{L1i} \tilde{D}^u_{3k} + \alpha_{Tj} D^{u*}_{L2i} \tilde{D}^u_{4k} - \gamma_{Tj} D^{u*}_{L2i} \tilde{D}^u_{2k}), \qquad (46)
\end{aligned}
$$

where

$$\alpha_{Tj} = \frac{g m_T X^*_{3j}}{2 m_W \cos\beta}\ ; \qquad \beta_{Tj} = -\frac{2}{3} e X'_{1j} + \frac{g}{\cos\theta_W} X'_{2j} \left(-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W\right) \tag{47}$$

$$\gamma_{Tj} = -\frac{2}{3} e X'^*_{1j} + \frac{2}{3} \frac{g \sin^2\theta_W}{\cos\theta_W} X'^*_{2j}\ ; \qquad \delta_{Tj} = -\frac{g m_T X_{3j}}{2 m_W \cos\beta} \tag{48}$$

and

$$\alpha_{tj} = \frac{g m_t X_{4j}}{2 m_W \sin\beta}\ ; \qquad \alpha_{cj} = \frac{g m_c X_{4j}}{2 m_W \sin\beta}\ ; \qquad \alpha_{uj} = \frac{g m_u X_{4j}}{2 m_W \sin\beta} \tag{49}$$

$$\delta_{tj} = -\frac{g m_t X^*_{4j}}{2 m_W \sin\beta}\ ; \qquad \delta_{cj} = -\frac{g m_c X^*_{4j}}{2 m_W \sin\beta}\ ; \qquad \delta_{uj} = -\frac{g m_u X^*_{4j}}{2 m_W \sin\beta} \tag{50}$$

and where

$$\beta_{tj} = \beta_{cj} = \beta_{uj} = \frac{2}{3} e X'^*_{1j} + \frac{g}{\cos\theta_W} X'^*_{2j} \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right) \tag{51}$$

$$\gamma_{tj} = \gamma_{cj} = \gamma_{uj} = \frac{2}{3} e X'_{1j} - \frac{2}{3} \frac{g \sin^2\theta_W}{\cos\theta_W} X'_{2j} \tag{52}$$

The interaction of the down quarks, down squarks and neutralinos is given by

$$-\mathcal{L}_{d-\tilde{d}-\chi^0} = \sum_{i=1}^{4} \sum_{j=1}^{4} \sum_{k=1}^{8} \bar{d}_i (C'^{L}_{dijk} P_L + C'^{R}_{dijk} P_R) \tilde{\chi}^0_j \tilde{d}_k + \text{h.c.}, \tag{53}$$

such that

$$\begin{aligned} C'^{L}_{dijk} =& \sqrt{2} (\alpha_{dj} D^{d*}_{R4i} \tilde{D}^d_{7k} - \gamma_{dj} D^{d*}_{R4i} \tilde{D}^d_{8k} + \alpha_{sj} D^{d*}_{R3i} \tilde{D}^d_{5k} - \gamma_{sj} D^{d*}_{R3i} \tilde{D}^d_{6k} + \alpha_{bj} D^{d*}_{R1i} \tilde{D}^d_{1k} - \gamma_{bj} D^{d*}_{R1i} \tilde{D}^d_{3k} \\ & + \beta_{Bj} D^{d*}_{R2i} \tilde{D}^d_{4k} - \delta_{Bj} D^{d*}_{R2i} \tilde{D}^d_{2k}), \end{aligned} \tag{54}$$

$$\begin{aligned} C'^{R}_{dijk} =& \sqrt{2} (\beta_{dj} D^{d*}_{L4i} \tilde{D}^d_{7k} - \delta_{dj} D^{d*}_{L4i} \tilde{D}^d_{8k} + \beta_{sj} D^{d*}_{L3i} \tilde{D}^d_{5k} - \delta_{sj} D^{d*}_{L3i} \tilde{D}^d_{6k} + \beta_{bj} D^{d*}_{L1i} \tilde{D}^d_{1k} - \delta_{bj} D^{d*}_{L1i} \tilde{D}^d_{3k} \\ & + \alpha_{Bj} D^{d*}_{L2i} \tilde{D}^d_{4k} - \gamma_{Bj} D^{d*}_{L2i} \tilde{D}^d_{2k}), \end{aligned} \tag{55}$$

where

$$\alpha_{Bj} = \frac{g m_B X^*_{4j}}{2 m_W \sin\beta}\ ; \qquad \beta_{Bj} = \frac{1}{3} e X'_{1j} + \frac{g}{\cos\theta_W} X'_{2j} \left(\frac{1}{2} - \frac{1}{3}\sin^2\theta_W\right) \tag{56}$$

$$\gamma_{Bj} = \frac{1}{3} e X'^*_{1j} - \frac{1}{3} \frac{g \sin^2\theta_W}{\cos\theta_W} X'^*_{2j}\ ; \qquad \delta_{Bj} = -\frac{g m_B X_{4j}}{2 m_W \sin\beta} \tag{57}$$

and

$$\alpha_{bj} = \frac{gm_b X_{3j}}{2m_W \cos\beta}\ ; \qquad \alpha_{sj} = \frac{gm_s X_{3j}}{2m_W \cos\beta}\ ; \qquad \alpha_{dj} = \frac{gm_d X_{3j}}{2m_W \cos\beta} \tag{58}$$

$$\delta_{bj} = -\frac{gm_b X^*_{3j}}{2m_W \cos\beta}\ ; \qquad \delta_{sj} = -\frac{gm_s X^*_{3j}}{2m_W \cos\beta}\ ; \qquad \delta_{dj} = -\frac{gm_d X^*_{3j}}{2m_W \cos\beta} \tag{59}$$

and where

$$\beta_{bj} = \beta_{sj} = \beta_{dj} = -\frac{1}{3} e X'^*_{1j} + \frac{g}{\cos\theta_W} X'^*_{2j} \left(-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W\right) \tag{60}$$

$$\gamma_{bj} = \gamma_{sj} = \gamma_{dj} = -\frac{1}{3} e X'_{1j} + \frac{1}{3}\frac{g\sin^2\theta_W}{\cos\theta_W} X'_{2j} \tag{61}$$

Here X' are defined by

$$X'_{1i} = X_{1i}\cos\theta_W + X_{2i}\sin\theta_W \tag{62}$$

$$X'_{2i} = -X_{1i}\sin\theta_W + X_{2i}\cos\theta_W, \tag{63}$$

where X diagonalizes the neutralino mass matrix and is defined by

$$X^T M_{\chi^0} X = \text{diag}\left(m_{\tilde{\chi}^0_1}, m_{\tilde{\chi}^0_2}, m_{\tilde{\chi}^0_3}, m_{\tilde{\chi}^0_4}\right). \tag{64}$$

6 The analysis of Electric Dipole Moment Operator

The up quark will have five different operators arising from the W, Z, gluino, chargino and neutralino contributions. The same thing holds for the down quark. We denote the EDM contributions from these loops by d^W_u, d^Z_u, $d^{\tilde{g}}_u$, $d^{\chi^+}_u$ and $d^{\chi^0}_u$, respectively. The same thing holds for the down quarks.

$$d^W_u = -\frac{1}{16\pi^2}\sum_{i=1}^{4}\frac{m_{d_i}}{m^2_W}\text{Im}(G^W_{L4i}G^{W*}_{R4i})\left[I_1\left(\frac{m^2_{d_i}}{m^2_W}\right) + \frac{1}{3}I_2\left(\frac{m^2_{d_i}}{m^2_W}\right)\right], \tag{65}$$

where the functions C^W_L and C^W_R are given in Appendix B and the form factor I_1 is given by

$$I_1(x) = \frac{2}{(1-x)^2}\left[1 - \frac{11}{4}x + \frac{1}{4}x^2 - \frac{3x^2\ln x}{2(1-x)}\right]. \tag{66}$$

and where the form factor I_2 is given by

$$I_2(x) = \frac{2}{(1-x)^2}\left[1 + \frac{1}{4}x + \frac{1}{4}x^2 + \frac{3x\ln x}{2(1-x)}\right]. \tag{67}$$

The W contribution to the down quark EDM is given by

$$d_d^W = \frac{1}{16\pi^2}\sum_{i=1}^{4}\frac{m_{u_i}}{m_W^2}\mathrm{Im}(G_{Li4}^{W*}G_{Ri4}^{W})\left[I_1\left(\frac{m_{u_i}^2}{m_W^2}\right) + \frac{2}{3}I_2\left(\frac{m_{u_i}^2}{m_W^2}\right)\right]. \tag{68}$$

The Z exchange contributions to the up and down quarks are given by

$$d_u^Z = \frac{1}{24\pi^2}\sum_{i=1}^{4}\frac{m_{u_i}}{m_Z^2}\mathrm{Im}(C_{L_{4i}}^{uZ}C_{R_{4i}}^{uZ*})I_2\left(\frac{m_{u_i}^2}{m_Z^2}\right) \tag{69}$$

$$d_d^Z = -\frac{1}{48\pi^2}\sum_{i=1}^{4}\frac{m_{d_i}}{m_Z^2}\mathrm{Im}(C_{L_{4i}}^{dZ}C_{R_{4i}}^{dZ*})I_2\left(\frac{m_{d_i}^2}{m_Z^2}\right) \tag{70}$$

The gluino contributions to the up and down quarks EDMs are given by

$$d_u^{\tilde{g}} = \frac{g_s^2}{9\pi^2}\sum_{m=1}^{8}\frac{m_{\tilde{g}}}{M_{\tilde{u}_m}^2}\mathrm{Im}(K_{L_{um}}K_{R_{um}}^*)B\left(\frac{m_{\tilde{g}}^2}{M_{\tilde{u}_m}^2}\right) \tag{71}$$

$$d_d^{\tilde{g}} = -\frac{g_s^2}{18\pi^2}\sum_{m=1}^{8}\frac{m_{\tilde{g}}}{M_{\tilde{d}_m}^2}\mathrm{Im}(K_{L_{dm}}K_{R_{dm}}^*)B\left(\frac{m_{\tilde{g}}^2}{M_{\tilde{d}_m}^2}\right), \tag{72}$$

where $K_{L_{qm}}$ and $K_{R_{qm}}$ are given by

$$K_{L_{qm}}^a = (D_{R24}^{q*}\tilde{D}_{4m}^q - D_{R44}^{q*}\tilde{D}_{8m}^q - D_{R34}^{q*}\tilde{D}_{6m}^q - D_{R14}^{q*}\tilde{D}_{3m}^q)e^{-i\xi_3/2} \tag{73}$$

and

$$K_{R_{qm}}^a = (D_{L44}^{q*}\tilde{D}_{7m}^q + D_{L34}^{q*}\tilde{D}_{5m}^q + D_{L14}^{q*}\tilde{D}_{1m}^q - D_{L24}^{q*}\tilde{D}_{2m}^q)e^{i\xi_3/2} \tag{74}$$

and

$$B(x) = \frac{1}{2(1-x)^2}\left(1 + x + \frac{2x\ln x}{1-x}\right). \tag{75}$$

The chargino contribution to the up and down quarks EDMs are given by

$$d_u^{\chi^+} = \frac{1}{16\pi^2}\sum_{i=1}^{2}\sum_{k=1}^{8}\frac{m_{\chi_i^+}}{M_{\tilde{d}_k}^2}\mathrm{Im}(C_{4ik}^{Lu}C_{4ik}^{Ru*})\left[A\left(\frac{m_{\chi_i^+}^2}{M_{\tilde{d}_k}^2}\right) - \frac{1}{3}B\left(\frac{m_{\chi_i^+}^2}{M_{\tilde{d}_k}^2}\right)\right] \tag{76}$$

$$d_d^{\chi^+} = \frac{1}{16\pi^2}\sum_{i=1}^{2}\sum_{k=1}^{8}\frac{m_{\chi_i^+}}{M^2_{\tilde{u}_k}}\text{Im}(C^{Ld}_{4ik}C^{Rd*}_{4ik})\left[-A\left(\frac{m^2_{\chi_i^+}}{M^2_{\tilde{u}_k}}\right)+\frac{2}{3}B\left(\frac{m^2_{\chi_i^+}}{M^2_{\tilde{u}_k}}\right)\right], \tag{77}$$

where $A(x)$ is given by

$$A(x) = \frac{1}{2(1-x)^2}\left(3 - x + \frac{2\ln x}{1-x}\right). \tag{78}$$

Finally the neutralino contributions are given by

$$d_u^{\chi^0} = \frac{1}{24\pi^2}\sum_{i=1}^{4}\sum_{k=1}^{8}\frac{m_{\chi_i^0}}{M^2_{\tilde{u}_k}}\text{Im}(C'^{L}_{u4ik}C'^{R*}_{u4ik})B\left(\frac{m^2_{\chi_i^0}}{M^2_{\tilde{u}_k}}\right) \tag{79}$$

and

$$d_d^{\chi^0} = -\frac{1}{48\pi^2}\sum_{i=1}^{4}\sum_{k=1}^{8}\frac{m_{\chi_i^0}}{M^2_{\tilde{d}_k}}\text{Im}(C'^{L}_{d4ik}C'^{R*}_{d4ik})B\left(\frac{m^2_{\chi_i^0}}{M^2_{\tilde{d}_k}}\right). \tag{80}$$

7 The neutron EDM and probe of PeV scale physics

To obtain the neutron EDM from the quark EDM, we use the non-relativistic $SU(6)$ quark model which gives

$$d_n = \frac{1}{3}[4d_d - d_u]\,. \tag{81}$$

The above value of d_n holds at the electroweak scale and we need to bring it down to the hadronic scale where it can be compared with experiment. This can be done by evolving d_n from the electroweak scale down to the hadronic scale by using renormalization group evolution which gives

$$d_n^E = \eta_E d_n\,, \tag{82}$$

where η_E is a renomalization group evolution factor. Numerically it is estimated to be ~ 1.5. We, now, present a numerical analysis of the neutron EDM first for the case of MSSM and next for the MSSM extension. The first analysis involves no mixing with the vectorlike generation and the only CP phases that appear are those from the MSSM sector. Thus in this case all the mixing parameters, given in Eq. (13), are set to zero. The second analysis is for the MSSM extension where the mixings of the vectorlike generation with the three generations are switched on. In the analysis, in the squark sector we assume $m_0^{u^2} = M^2_{\tilde{T}} = M^2_{\tilde{t}_1} = M^2_{\tilde{t}_2} = M^2_{\tilde{t}_3}$ and $m_0^{d^2} = M^2_{\tilde{1}L} = M^2_{\tilde{B}} = M^2_{\tilde{b}_1} = M^2_{\tilde{Q}} = M^2_{\tilde{2}L} = M^2_{\tilde{b}_2} = M^2_{\tilde{3}L} = M^2_{\tilde{b}_3}$. To simplify the numerical analysis further we assume $m_0^u = m_0^d = m_0$. Additionally the trilinear couplings are chosen as such: $A_0^u = A_t = A_T = A_c = A_u$ and $A_0^d = A_b = A_B = A_s = A_d$.

As mentioned above first we explore the possibility of probing high SUSY scales using the neutron EDM and specifically to see if such scales can lie beyond those that are accessible at colliders. For this analysis we consider the case when there is no mixing with the vectorlike generation and the neutron EDM arises from the exchange of the MSSM particles alone which are the charginos, the neutralinos, the gluino and the squarks. An analysis of this case is presented in fig. 3- fig. 5. In fig. 3 we display the neutron EDM as a function of the universal scalar mass m_0 where the various curves are for values of $\tan\beta$ ranging from $5-60$. The analysis shows that increase in future sensitivities of the neutron EDM will allow us to probe m_0 in the domain of hundreds of TeV and up to a PeV and even beyond. This is in contrast to the RUN-II of the LHC which will allow one to explore the squark masses only in the few TeV region. Since there are no mixings with the vectorlike generation in this case, the only CP violating phases are from the MSSM sector. We discuss the dependence of the neutron EDM on two of these. In the left panel of fig. 4 we show the dependence of the neutron EDM on the phase ξ_3 of the gluino mass. We note the very sharp variation of the neutron EDM with ξ_3 which shows that the gluino exchange diagram makes a very significant contribution to the neutron EDM. The very strong dependence of the neutron EDM on the gluino exchange diagram is further emphasized in the right panel of fig. 4 where a variation of the neutron EDM with the gluino mass is exhibited. The electroweak sector of the theory also makes a substantial contribution to the neutron EDM via the chargino, neutralino and the squark exchange diagrams which involve the phases $\theta_\mu, \alpha_A, \xi_1, \xi_2$ and the electroweak gaugino mass parameters m_1, m_2 and μ. The dependence of the neutron EDM on θ_μ is exhibited in the left panel of fig. 5. Similar to the left panel of fig. 4, this figure too shows a strong dependence of the neutron EDM on the CP phase. In the right panel of fig. 5 we exhibit the dependence of $|d_n^E|$ on $\tilde{m}$ where we have assumed the supergravity boundary condition of the gaugino masses at the electroweak scale, i.e., $m_1 = \tilde{m}, m_2 = 2\tilde{m}, m_g = 6\tilde{m}$. Similar to the right panel of fig. 4 one finds a sharp dependence of $|d_n^E|$ on $\tilde{m}$.

In table 1 we exhibit the individual contributions of the chargino, neutralino and gluino exchange diagrams for two benchmark points. The exchange contributions from W and Z vanish because of no mixing with the vectorlike generation in this case and are not exhibited. The analysis shows that typically the chargino and the gluino contributions are the larger ones and the neutralino contribution is suppressed. Further, one finds that typically there is a cancellation among the three pieces which reduces the overall size of the quark EDMs. Other choices of the phases would lead to other patterns of interference among the terms which explains the rapid phase dependence seen, for example, in fig. 4 and fig. 5.

Contribution	(i) Up	(i) Down	(ii) Up	(ii) Down
Chargino, $d_q^{\chi^{\pm}}$	1.45×10^{-29}	-7.44×10^{-28}	1.67×10^{-28}	-9.48×10^{-27}
Neutralino, $d_q^{\chi^0}$	-2.76×10^{-34}	1.88×10^{-31}	-5.36×10^{-32}	4.66×10^{-29}
Gluino, d_q^{g}	5.14×10^{-30}	9.17×10^{-29}	7.81×10^{-30}	1.39×10^{-28}
Total, d_q	1.96×10^{-29}	-6.53×10^{-28}	1.75×10^{-28}	-9.30×10^{-27}
Total EDM, $\|d_n^E\|$	1.34×10^{-27}		1.91×10^{-26}	

Table 1: An exhibition of the chargino, neutralino, gluino exchange contributions and their sum for two benchmark points (i) and (ii). Benchmark (i): $m_g = 2$ TeV, $\xi_3 = 3.3$ and $m_0 = m_0^u = m_0^d = 10$ TeV. Benchmark (ii): $m_g = 30$ TeV, $\xi_3 = 3.3$ and $m_0 = 2$ TeV. The parameter space common between the two are: $\tan\beta = 25$, $|m_1| = 70$, $|m_2| = 200$, $|A_0^u| = 680$, $|A_0^d| = 600$, $|\mu| = 350$, $m_T = 300$, $m_B = 260$, $|h_3| = |h_3'| = |h_3''| = |h_4| = |h_4'| = |h_4''| = |h_5| = |h_5'| = |h_5''| = 0$, $\xi_1 = 2\times10^{-2}$, $\xi_2 = 2\times10^{-3}$, $\alpha_{A_0^u} = 2\times10^{-2}$, $\alpha_{A_0^d} = 3.0$, $\theta_\mu = 1\times10^{-3}$. All masses, other than m_0 and m_g, are in GeV, phases in rad and the electric dipole moment in $e$cm.

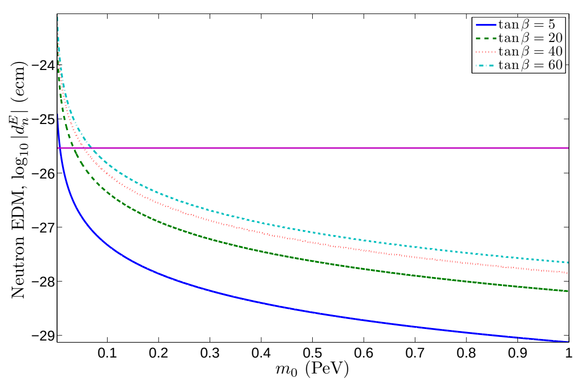

Figure 3: Variation of the neutron EDM $|d_n^E|$ (log scale) versus m_0 ($m_0 = m_0^u = m_0^d$) for four values of $\tan\beta$ which are (from bottom to top) $\tan\beta = 5, 20, 40, 60$. The common parameters are: $|m_1| = 70$, $|m_2| = 200$, $|A_0^u| = 680$, $|A_0^d| = 600$, $|\mu| = 400$, $m_g = 1000$, $m_T = 300$, $m_B = 260$, $|h_3| = |h_3'| = |h_3''| = |h_4| = |h_4'| = |h_4''| = |h_5| = |h_5'| = |h_5''| = 0$, $\xi_3 = 1\times10^{-3}$, $\xi_1 = 2\times10^{-2}$, $\xi_2 = 2\times10^{-3}$, $\alpha_{A_0^u} = 2\times10^{-2}$, $\alpha_{A_0^d} = 3.0$, $\theta_\mu = 2.0$. All masses unless otherwise stated are in GeV and phases in rad.

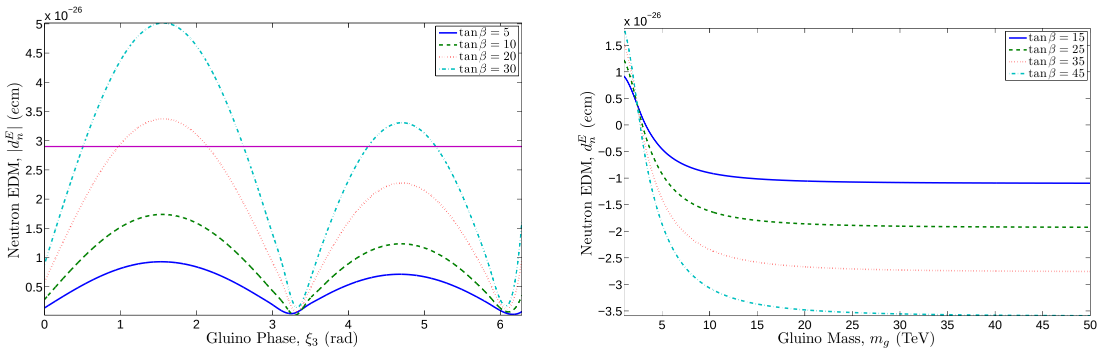

Figure 4: Left panel: Variation of the neutron EDM $|d_n^E|$ versus the gluino phase ξ_3 for four values of $\tan\beta$. From bottom to top at $\xi_3 = 0$ they are: $\tan\beta = 5$, 10, 20, 30. The common parameters are: $|m_1| = 70$, $|m_2| = 200$, $m_0^u = m_0^d = 3500$, $|A_0^u| = 680$, $|A_0^d| = 600$, $|\mu| = 400$, $m_g = 1000$, $m_T = 300$, $m_B = 260$, $|h_3| = |h_3'| = |h_3''| = |h_4| = |h_4'| = |h_4''| = |h_5| = |h_5'| = |h_5''| = 0$, $\xi_1 = 2\times 10^{-2}$, $\xi_2 = 2\times 10^{-3}$, $\alpha_{A_0^u} = 2\times 10^{-2}$, $\alpha_{A_0^d} = 3.0$, $\theta_\mu = 1\times 10^{-3}$. All masses are in GeV and phases in rad. Right panel: Variation of the neutron EDM d_n^E versus the gluino mass m_g for four values of $\tan\beta$. From bottom to top at $m_g = 50$ TeV they are: $\tan\beta = 45$, 35, 25, 15. The common parameters are: $|m_1| = 70$, $|m_2| = 200$, $m_0^u = m_0^d = 2000$, $|A_0^u| = 680$, $|A_0^d| = 600$, $|\mu| = 350$, $m_T = 300$, $m_B = 260$, $|h_3| = |h_3'| = |h_3''| = |h_4| = |h_4'| = |h_4''| = |h_5| = |h_5'| = |h_5''| = 0$, $\xi_1 = 2\times 10^{-2}$, $\xi_2 = 2\times 10^{-3}$, $\alpha_{A_0^u} = 2\times 10^{-2}$, $\alpha_{A_0^d} = 3.0$, $\theta_\mu = 1\times 10^{-3}$, $\xi_3 = 3.3$. All masses, other than m_g, are in GeV and phases in rad.

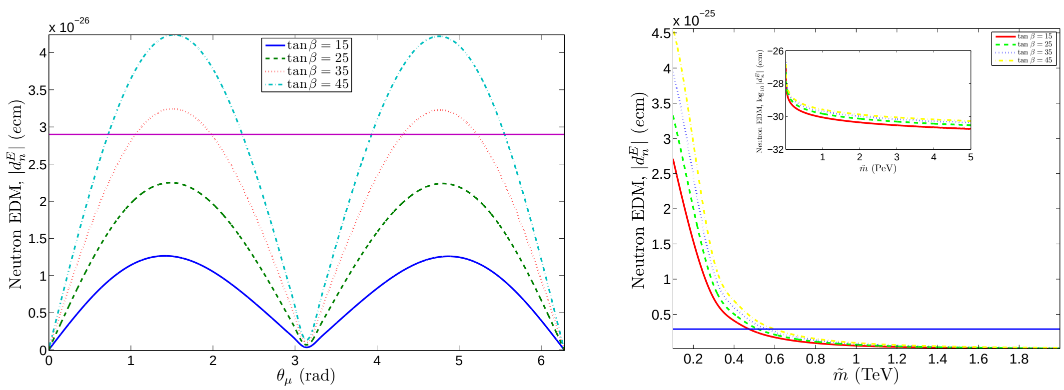

Figure 5: Left panel: Variation of the neutron EDM $|d_n^E|$ versus θ_μ for four values of $\tan\beta$. From bottom to top they are: $\tan\beta = 15$, 25, 35, 45. The common parameters are: $|m_1| = 70$, $|m_2| = 200$, $m_0^u = m_0^d = 50000$, $|A_0^u| = 680$, $|A_0^d| = 600$, $|\mu| = 400$, $m_T = 300$, $m_B = 260$, $m_g = 2000$, $|h_3| = |h_3'| = |h_3''| = |h_4| = |h_4'| = |h_4''| = |h_5| = |h_5'| = |h_5''| = 0$, $\xi_1 = 2\times 10^{-2}$, $\xi_2 = 2\times 10^{-3}$, $\alpha_{A_0^u} = 2\times 10^{-2}$, $\alpha_{A_0^d} = 2.8$, $\xi_3 = 3.3$. All masses are in GeV and all phases in rad. Right panel: Variation of the neutron EDM $|d_n^E|$ versus $\tilde{m}$ for four values of $\tan\beta$. From bottom to top at $\tilde{m} = 100$ they are: $\tan\beta = 15$, 25, 35, 45. The common parameters are: $|m_1| = \tilde{m}$, $|m_2| = 2\tilde{m}$, $m_g = 6\tilde{m}$, $m_0^u = m_0^d = 500$, $|A_0^u| = 880$, $|A_0^d| = 600$, $|\mu| = 300$, $m_T = 300$, $m_B = 260$, $|h_3| = |h_3'| = |h_3''| = |h_4| = |h_4'| = |h_4''| = |h_5| = |h_5'| = |h_5''| = 0$, $\xi_1 = 2\times 10^{-2}$, $\xi_2 = 2\times 10^{-3}$, $\theta_\mu = 1\times 10^{-3}$, $\alpha_{A_0^u} = 2\times 10^{-3}$, $\alpha_{A_0^d} = 2.8$, $\xi_3 = 1\times 10^{-3}$.

Next we discuss the case when there is mixing between the vector generation and the three generations of quarks. Here one finds that along with the chargino, neutralino and gluino exchange diagrams, one has contributions also from the W and Z exchange diagrams of Fig. (3). Indeed the contributions from the W and Z exchange diagrams can be comparable and even larger than the exchange contributions from the chargino, neutralino and the gluino. The relative contributions from the chargino, the neutralino, the gluino, and from the W and Z bosons are shown in table 2 for two benchmark points. In this case we note that even for the case when m_0 becomes very large so that the supersymmetric loops give a negligible contribution there will be a non-SUSY contribution from the exchange of W and Z and of quarks and mirror quarks which will give a non-vanishing contribution. This is exhibited in fig. 6. Here we note that the EDM does not fall with increasing m_0 when m_0 gets large but rather levels off. The asymptotic value of the EDM for very large m_0, is precisely the contribution from the vectorlike generation. Obviously the EDM here depends also on the new sources of CP violation such as the phases χ_3, χ_4, χ_5'' in addition to the MSSM phases such as θ_μ. The dependence of $|d_n^E|$ on χ_3 is exhibited in the left panel of fig. 7, on χ_4 in the right panel of fig. 7, on χ_5'' in the left panel of fig. 8 and on θ_μ in the right panel of fig. 8.

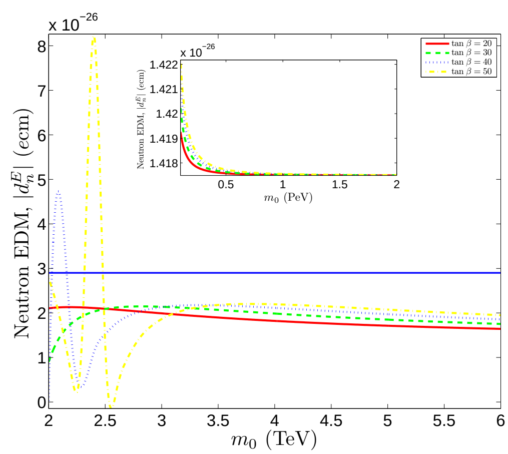

Figure 6: Variation of the neutron EDM $|d_n^E|$ versus m_0 ($m_0 = m_0^u = m_0^d$) for three values of $\tan\beta$. From bottom to top at $m_0 = 6$ TeV, they are: $\tan\beta = 20,\ 30,\ 40,\ 50$. The common parameters are: $|m_1| = 70$, $|m_2| = 200$, $|A_0^u| = 680$, $|A_0^d| = 600$, $|\mu| = 400$, $m_g = 1000$, $m_T = 300$, $m_B = 260$, $|h_3| = 1.58$, $|h_3'| = 6.34 \times 10^{-2}$, $|h_3''| = 1.97 \times 10^{-2}$, $|h_4| = 4.42$, $|h_4'| = 5.07$, $|h_4''| = 2.87$, $|h_5| = 6.6$, $|h_5'| = 2.67$, $|h_5''| = 1.86 \times 10^{-1}$, $\xi_3 = 1 \times 10^{-3}$, $\theta_\mu = 1 \times 10^{-3}$, $\xi_1 = 2 \times 10^{-2}$, $\xi_2 = 2 \times 10^{-3}$, $\alpha_{A_0^u} = 2 \times 10^{-2}$, $\alpha_{A_0^d} = 3.0$, $\chi_3 = 2 \times 10^{-2}$, $\chi_3' = 1 \times 10^{-3}$, $\chi_3'' = 4 \times 10^{-3}$, $\chi_4 = 7 \times 10^{-3}$, $\chi_4' = \chi_4'' = 1 \times 10^{-3}$, $\chi_5 = 9 \times 10^{-3}$, $\chi_5' = 5 \times 10^{-3}$, $\chi_5'' = 2 \times 10^{-3}$.

Contribution	$m_0 = 3$ TeV		$m_0 = 15$ TeV	
	Up	Down	Up	Down
Chargino, $d_q^{\chi^\pm}$	1.63×10^{-28}	-3.15×10^{-27}	5.09×10^{-30}	-5.15×10^{-28}
Neutralino, $d_q^{\chi^0}$	1.64×10^{-31}	2.15×10^{-29}	7.24×10^{-33}	1.37×10^{-31}
Gluino, d_q^g	3.50×10^{-29}	-3.22×10^{-28}	9.27×10^{-32}	-8.58×10^{-31}
W Boson, d_q^W	-3.30×10^{-28}	-6.49×10^{-27}	-3.30×10^{-28}	-6.49×10^{-27}
Z Boson, d_q^Z	-6.07×10^{-29}	-5.58×10^{-28}	-6.07×10^{-29}	-5.58×10^{-28}
Total, d_q	1.05×10^{-28}	2.28×10^{-26}	-3.85×10^{-28}	-7.56×10^{-27}
Total EDM, $\lvert d_n^E \rvert$	2.13×10^{-26}		1.52×10^{-26}	

Table 2: An exhibition of the chargino, neutralino, gluino, W and Z exchange contributions to the quark and the neutron EDM and their sum for the case when there is mixing of the vectorlike generation with the three generations. The analysis is for two benchmark points with $m_0 = 3$ TeV and $m_0 = 15$ TeV. The common parameter are: $\tan\beta = 40$, $|m_1| = 70$, $|m_2| = 200$, $|A_0^u| = 680$, $|A_0^d| = 600$, $|\mu| = 400$, $m_g = 1000$, $m_T = 300$, $m_B = 260$, $|h_3| = 1.58$, $|h_3'| = 6.34\times10^{-2}$, $|h_3''| = 1.97\times10^{-2}$, $|h_4| = 4.42$, $|h_4'| = 5.07$, $|h_4''| = 2.87$, $|h_5| = 6.6$, $|h_5'| = 2.67$, $|h_5''| = 1.86\times10^{-1}$, $\xi_3 = 1\times10^{-3}$, $\theta_\mu = 1\times10^{-3}$, $\xi_1 = 2\times10^{-2}$, $\xi_2 = 2\times10^{-3}$, $\alpha_{A_0^u} = 2\times10^{-2}$, $\alpha_{A_0^d} = 3.0$, $\chi_3 = 2\times10^{-2}$, $\chi_3' = 1\times10^{-3}$, $\chi_3'' = 4\times10^{-3}$, $\chi_4 = 7\times10^{-3}$, $\chi_4' = \chi_4'' = 1\times10^{-3}$, $\chi_5 = 9\times10^{-3}$, $\chi_5' = 5\times10^{-3}$, $\chi_5'' = 2\times10^{-3}$. All masses are in GeV, all phases in rad and the electric dipole moment in $e$cm.

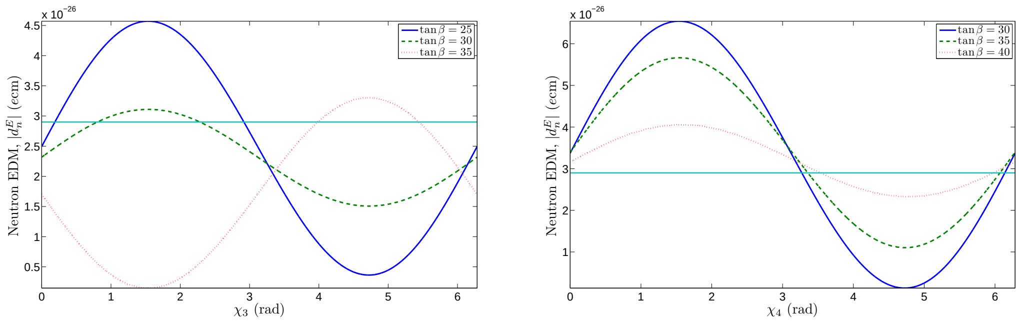

Figure 7: Left panel: Variation of the neutron EDM $|d_n^E|$ versus χ_3 for three values of $\tan\beta$. From top to bottom at $\chi_3 = 0$ they are: $\tan\beta = 25$, 30, 35. The common parameters are: $|m_1| = 70$, $|m_2| = 200$, $|\mu| = 400$, $|A_0^u| = 680$, $|A_0^d| = 600$, $m_0^u = m_0^d = 2000$, $m_g = 1000$, $m_T = 250$, $m_B = 240$, $|h_3| = 1.58$, $|h_3'| = 6.34 \times 10^{-2}$, $|h_3''| = 1.97 \times 10^{-2}$, $|h_4| = 4.42$, $|h_4'| = 5.07$, $|h_4''| = 2.87$, $|h_5| = 6.6$, $|h_5'| = 2.67$, $|h_5''| = 1.86 \times 10^{-1}$, $\xi_3 = 1 \times 10^{-3}$, $\xi_1 = 2 \times 10^{-2}$, $\xi_2 = 2 \times 10^{-3}$, $\alpha_{A_0^u} = 4 \times 10^{-3}$, $\alpha_{A_0^d} = 1 \times 10^{-2}$, $\theta_\mu = 1 \times 10^{-3}$, $\chi_3' = 1 \times 10^{-3}$, $\chi_3'' = 4 \times 10^{-3}$, $\chi_4 = 7 \times 10^{-3}$, $\chi_4' = \chi_4'' = 1 \times 10^{-3}$, $\chi_5 = 9 \times 10^{-3}$, $\chi_5' = 5 \times 10^{-3}$, $\chi_5'' = 2 \times 10^{-3}$. Right panel: Variation of the neutron EDM $|d_n^E|$ versus χ_4 for three values of $\tan\beta$. From top to bottom at $\chi_4 = 0$ they are: $\tan\beta = 30$, 35, 40. The common parameters are: $|m_1| = 70$, $|m_2| = 200$, $|\mu| = 300$, $|A_0^u| = 680$, $|A_0^d| = 600$, $m_0^u = m_0^d = 2000$, $m_g = 1000$, $m_T = m_B = 260$, $|h_3| = 1.58$, $|h_3'| = 6.34 \times 10^{-2}$, $|h_3''| = 1.97 \times 10^{-2}$, $|h_4| = 4.42$, $|h_4'| = 5.07$, $|h_4''| = 2.87$, $|h_5| = 6.6$, $|h_5'| = 2.67$, $|h_5''| = 1.86 \times 10^{-1}$, $\xi_3 = 1 \times 10^{-3}$, $\xi_1 = 2 \times 10^{-2}$, $\xi_2 = 2 \times 10^{-3}$, $\alpha_{A_0^u} = 2 \times 10^{-2}$, $\alpha_{A_0^d} = 1 \times 10^{-2}$, $\theta_\mu = 1 \times 10^{-3}$, $\chi_3 = 2 \times 10^{-2}$, $\chi_3' = 1 \times 10^{-3}$, $\chi_3'' = 4 \times 10^{-3}$, $\chi_4' = \chi_4'' = 1 \times 10^{-3}$, $\chi_5 = 9 \times 10^{-3}$, $\chi_5' = 5 \times 10^{-3}$, $\chi_5'' = 2 \times 10^{-3}$.

8 Conclusion

In this work we have investigated the neutron EDM as a possible probe of new physics. For the case of MSSM it is shown that the experimental limit on the neutron EDM can be used to probe high scale physics. Specifically scalar masses as large a PeV and even larger can be probed. We have also investigated the neutron EDM within an extended MSSM where the particle content of the model contains in addition a vectorlike multiplet. In section 6 we have given a complete analytic analysis of the neutron EDM which contains all the relevant diagrams at the one loop level including both the supersymmetric as well as the non-supersymmetric loops. Thus the analysis includes loops involving exchanges of charginos, neutralinos, gluino, squarks and mirror squarks. In addition the analysis includes W and Z exchange diagrams with exchange of quarks and mirror quarks. The vectorlike generation brings in new sources of CP violation which contribute to the quark EDMs. It is shown that in the absence of the cancellation mechanism the experimental limit on the neutron EDM acts as a probe of new physics. Specifically it is shown that assuming CP phases to be $\mathcal{O}(1)$, and with no cancellation mechanism at work, one can probe scalar masses up to the PeV scale for the MSSM case. Further, it is shown that the neutron EDM also acts as a probe of the

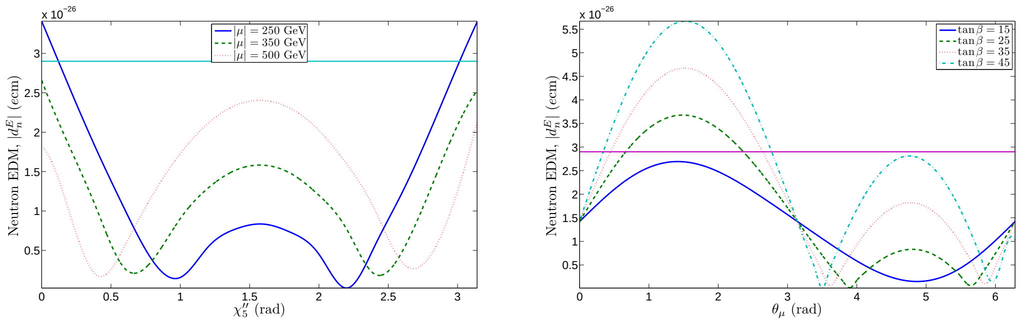

Figure 8: Left panel: Variation of the neutron EDM $|d_n^E|$ versus χ_5'' for three values of $|\mu|$. From bottom to top at $\chi_5'' = 1.5$ they are: $|\mu| = 250$, 350, 500. The common parameters are: $\tan\beta = 20$, $|m_1| = 70$, $|m_2| = 200$, $|A_0^u| = 580$, $|A_0^d| = 600$, $m_0^u = m_0^d = 2000$, $m_g = 1000$, $m_T = 250$, $m_B = 260$, $|h_3| = 1.58$, $|h_3'| = 6.34 \times 10^{-2}$, $|h_3''| = 1.97 \times 10^{-2}$, $|h_4| = 4.42$, $|h_4'| = 5.07$, $|h_4''| = 2.87$, $|h_5| = 6.6$, $|h_5'| = 2.67$, $|h_5''| = 1.86 \times 10^{-1}$, $\xi_3 = 1 \times 10^{-3}$, $\xi_1 = 2 \times 10^{-2}$, $\xi_2 = 2 \times 10^{-3}$, $\alpha_{A_0^u} = 2 \times 10^{-2}$, $\alpha_{A_0^d} = 1 \times 10^{-2}$, $\theta_\mu = 1 \times 10^{-3}$, $\chi_3 = 2 \times 10^{-2}$, $\chi_3' = 1 \times 10^{-3}$, $\chi_3'' = 4 \times 10^{-3}$, $\chi_4 = 7 \times 10^{-3}$, $\chi_4' = \chi_4'' = 1 \times 10^{-3}$, $\chi_5 = 9 \times 10^{-3}$, $\chi_5' = 5 \times 10^{-3}$. Right panel: Variation of the neutron EDM $|d_n^E|$ versus θ_μ for three values of $\tan\beta$. From bottom to top at $\theta_\mu = 0$ they are: $\tan\beta = 15$, 25, 35, 45. The common parameters are: $|m_1| = 70$, $|m_2| = 200$, $m_0 = m_0^u = m_0^d = 50000$, $|A_0^u| = 680$, $|A_0^d| = 600$, $|\mu| = 400$, $m_g = 2000$, $m_T = 300$, $m_B = 260$, $|h_3| = 1.58$, $|h_3'| = 6.34 \times 10^{-2}$, $|h_3''| = 1.97 \times 10^{-2}$, $|h_4| = 4.42$, $|h_4'| = 5.07$, $|h_4''| = 2.87$, $|h_5| = 6.6$, $|h_5'| = 2.67$, $|h_5''| = 1.86 \times 10^{-1}$, $\xi_3 = 3.3$, $\xi_1 = 2 \times 10^{-2}$, $\xi_2 = 2 \times 10^{-3}$, $\alpha_{A_0^u} = 2 \times 10^{-2}$, $\alpha_{A_0^d} = 2.8$, $\chi_3 = 2 \times 10^{-2}$, $\chi_3' = 1 \times 10^{-3}$, $\chi_3'' = 4 \times 10^{-3}$, $\chi_4 = 7 \times 10^{-3}$, $\chi_4' = \chi_4'' = 1 \times 10^{-3}$, $\chi_5 = 9 \times 10^{-3}$, $\chi_5' = 5 \times 10^{-3}$, $\chi_5'' = 2 \times 10^{-3}$.

extended MSSM model which includes a vectorlike multiplet in its particle content. One expects significant improvements in the sensitivity of the measurement of the neutron EDM in the future. Thus, for instance, the nEDM Collaboration plans to measure the neutron EDM with an accuracy of $\sim 9 \times 10^{-28}$ $e$cm which is more than an order of magnitude better than the current limit. Such an improvement will allow one to extend the probe of new physics even further [31].

Acknowledgments: PN's research is supported in part by the NSF grant PHY-1314774.

9 Appendix: Mass squared matrices for the scalars

We define the scalar mass squared matrix $M^2_{\tilde d}$ in the basis $(\tilde b_L, \tilde B_L, \tilde b_R, \tilde B_R, \tilde s_L, \tilde s_R, \tilde d_L, \tilde d_R)$. We label the matrix elements of these as $(M^2_{\tilde d})_{ij} = M^2_{ij}$ where the elements of the matrix are given by

$$M^2_{11} = M^2_{\tilde 1 L} + \frac{v_1^2|y_1|^2}{2} + |h_3|^2 - m_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{1}{3}\sin^2\theta_W\right),$$
$$M^2_{22} = M^2_{\tilde B} + \frac{v_2^2|y_2'|^2}{2} + |h_4|^2 + |h_4'|^2 + |h_4''|^2 + \frac{1}{3} m_Z^2 \cos 2\beta \sin^2\theta_W,$$
$$M^2_{33} = M^2_{\tilde b_1} + \frac{v_1^2|y_1|^2}{2} + |h_4|^2 - \frac{1}{3} m_Z^2 \cos 2\beta \sin^2\theta_W,$$
$$M^2_{44} = M^2_{\tilde Q} + \frac{v_2^2|y_2'|^2}{2} + |h_3|^2 + |h_3'|^2 + |h_3''|^2 + m_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{1}{3}\sin^2\theta_W\right),$$

$$M^2_{55} = M^2_{\tilde 2 L} + \frac{v_1^2|y_3|^2}{2} + |h_3'|^2 - m_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{1}{3}\sin^2\theta_W\right),$$
$$M^2_{66} = M^2_{\tilde b_2} + \frac{v_1^2|y_3|^2}{2} + |h_4'|^2 - \frac{1}{3} m_Z^2 \cos 2\beta \sin^2\theta_W,$$
$$M^2_{77} = M^2_{\tilde 3 L} + \frac{v_1^2|y_4|^2}{2} + |h_3''|^2 - m_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{1}{3}\sin^2\theta_W\right),$$
$$M^2_{88} = M^2_{\tilde b_3} + \frac{v_1^2|y_4|^2}{2} + |h_4''|^2 - \frac{1}{3} m_Z^2 \cos 2\beta \sin^2\theta_W \ .$$

$$M^2_{12} = M^{2*}_{21} = \frac{v_2 y_2' h_3^*}{\sqrt{2}} + \frac{v_1 h_4 y_1^*}{\sqrt{2}}, M^2_{13} = M^{2*}_{31} = \frac{y_1^*}{\sqrt{2}}(v_1 A_b^* - \mu v_2), M^2_{14} = M^{2*}_{41} = 0,$$
$$M^2_{15} = M^{2*}_{51} = h_3' h_3^*, M^{2*}_{16} = M^{2*}_{61} = 0, M^{2*}_{17} = M^{2*}_{71} = h_3'' h_3^*, M^{2*}_{18} = M^{2*}_{81} = 0,$$
$$M^2_{23} = M^{2*}_{32} = 0, M^2_{24} = M^{2*}_{42} = \frac{y_2'^*}{\sqrt{2}}(v_2 A_B^* - \mu v_1), M^2_{25} = M^{2*}_{52} = \frac{v_2 h_3' y_2'^*}{\sqrt{2}} + \frac{v_1 y_3 h_4^*}{\sqrt{2}},$$
$$M^2_{26} = M^{2*}_{62} = 0, M^2_{27} = M^{2*}_{72} = \frac{v_2 h_3'' y_2'^*}{\sqrt{2}} + \frac{v_1 y_4 h_4''^*}{\sqrt{2}}, M^2_{28} = M^{2*}_{82} = 0,$$
$$M^2_{34} = M^{2*}_{43} = \frac{v_2 h_4 y_2'^*}{\sqrt{2}} + \frac{v_1 y_1 h_3^*}{\sqrt{2}}, M^2_{35} = M^{2*}_{53} = 0, M^2_{36} = M^{2*}_{63} = h_4 h_4'^*,$$
$$M^2_{37} = M^{2*}_{73} = 0, M^2_{38} = M^{2*}_{83} = h_4 h_4''^*,$$
$$M^2_{45} = M^{2*}_{54} = 0, M^2_{46} = M^{2*}_{64} = \frac{v_2 y_2' h_4'^*}{\sqrt{2}} + \frac{v_1 h_3' y_3^*}{\sqrt{2}},$$
$$M^2_{47} = M^{2*}_{74} = 0, M^2_{48} = M^{2*}_{84} = \frac{v_2 y_2' h_4''^*}{\sqrt{2}} + \frac{v_1 h_3'' y_4^*}{\sqrt{2}},$$
$$M^2_{56} = M^{2*}_{65} = \frac{y_3^*}{\sqrt{2}}(v_1 A_s^* - \mu v_2), M^2_{57} = M^{2*}_{75} = h_3'' h_3'^*,$$
$$M^2_{58} = M^{2*}_{85} = 0, M^2_{67} = M^{2*}_{76} = 0,$$
$$M^2_{68} = M^{2*}_{86} = h_4' h_4''^*, M^2_{78} = M^{2*}_{87} = \frac{y_4^*}{\sqrt{2}}(v_1 A_d^* - \mu v_2) \ .$$

We can diagonalize this hermitian mass squared matrix by the unitary transformation

$$\tilde{D}^{d\dagger} M^2_{\tilde{d}} \tilde{D}^d = diag(M^2_{\tilde{d}_1}, M^2_{\tilde{d}_2}, M^2_{\tilde{d}_3}, M^2_{\tilde{d}_4}, M^2_{\tilde{d}_5}, M^2_{\tilde{d}_6}, M^2_{\tilde{d}_7}, M^2_{\tilde{d}_8}) \ . \tag{83}$$

Next we write the mass^2 matrix in the sups sector the basis $(\tilde{t}_L, \tilde{T}_L, \tilde{t}_R, \tilde{T}_R, \tilde{c}_L, \tilde{c}_R, \tilde{u}_L, \tilde{u}_R)$. Thus here we denote the sups mass^2 matrix in the form $(M^2_{\tilde{u}})_{ij} = m^2_{ij}$ where

$$\begin{aligned}
m^2_{11} &= M^2_{\tilde{1}L} + \frac{v_2^2|y_1'|^2}{2} + |h_3|^2 + m_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right), \\
m^2_{22} &= M^2_{\tilde{T}} + \frac{v_1^2|y_2|^2}{2} + |h_5|^2 + |h_5'|^2 + |h_5''|^2 - \frac{2}{3} m_Z^2 \cos 2\beta \sin^2\theta_W, \\
m^2_{33} &= M^2_{\tilde{t}_1} + \frac{v_2^2|y_1'|^2}{2} + |h_5|^2 + \frac{2}{3} m_Z^2 \cos 2\beta \sin^2\theta_W, \\
m^2_{44} &= M^2_{\tilde{Q}} + \frac{v_1^2|y_2|^2}{2} + |h_3|^2 + |h_3'|^2 + |h_3''|^2 - m_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right),
\end{aligned}$$

$$\begin{aligned}
m^2_{55} &= M^2_{\tilde{2}L} + \frac{v_2^2|y_3'|^2}{2} + |h_3'|^2 + m_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right), \\
m^2_{66} &= M^2_{\tilde{t}_2} + \frac{v_2^2|y_3'|^2}{2} + |h_5'|^2 + \frac{2}{3} m_Z^2 \cos 2\beta \sin^2\theta_W, \\
m^2_{77} &= M^2_{\tilde{3}L} + \frac{v_2^2|y_4'|^2}{2} + |h_3''|^2 + m_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right), \\
m^2_{88} &= M^2_{\tilde{t}_3} + \frac{v_2^2|y_4'|^2}{2} + |h_5''|^2 + \frac{2}{3} m_Z^2 \cos 2\beta \sin^2\theta_W \ .
\end{aligned}$$

$$
\begin{aligned}
&m^2_{12} = m^{2*}_{21} = -\frac{v_1 y_2 h_3^*}{\sqrt{2}} + \frac{v_2 h_5 y_1'^*}{\sqrt{2}}, m^2_{13} = m^{2*}_{31} = \frac{y_1'^*}{\sqrt{2}}(v_2 A_t^* - \mu v_1), m^2_{14} = m^{2*}_{41} = 0,\\
&m^2_{15} = m^{2*}_{51} = h_3' h_3^*, m^{2*}_{16} = m^{2*}_{61} = 0, m^{2*}_{17} = m^{2*}_{71} = h_3'' h_3^*, m^{2*}_{18} = m^{2*}_{81} = 0,\\
&m^2_{23} = m^{2*}_{32} = 0, m^2_{24} = m^{2*}_{42} = \frac{y_2^*}{\sqrt{2}}(v_1 A_T^* - \mu v_2), m^2_{25} = m^{2*}_{52} = -\frac{v_1 h_3' y_2^*}{\sqrt{2}} + \frac{v_2 y_3' h_5'^*}{\sqrt{2}},\\
&m^2_{26} = m^{2*}_{62} = 0, m^2_{27} = m^{2*}_{72} = -\frac{v_1 h_3'' y_2^*}{\sqrt{2}} + \frac{v_2 y_4' h_5''^*}{\sqrt{2}}, m^2_{28} = m^{2*}_{82} = 0,\\
&m^2_{34} = m^{2*}_{43} = \frac{v_1 h_5 y_2^*}{\sqrt{2}} - \frac{v_2 y_1' h_3^*}{\sqrt{2}}, m^2_{35} = m^{2*}_{53} = 0, m^2_{36} = m^{2*}_{63} = h_5 h_5'^*,\\
&m^2_{37} = m^{2*}_{73} = 0, m^2_{38} = m^{2*}_{83} = h_5 h_5''^*,\\
&m^2_{45} = m^{2*}_{54} = 0, m^2_{46} = m^{2*}_{64} = -\frac{y_3'^* v_2 h_3'}{\sqrt{2}} + \frac{v_1 y_2 h_5'^*}{\sqrt{2}},\\
&m^2_{47} = m^{2*}_{74} = 0, m^2_{48} = m^{2*}_{84} = \frac{v_1 y_2 h_5''^*}{\sqrt{2}} - \frac{v_2 y_4'^* h_3''}{\sqrt{2}},\\
&m^2_{56} = m^{2*}_{65} = \frac{y_3'^*}{\sqrt{2}}(v_2 A_c^* - \mu v_1),\\
&m^2_{57} = m^{2*}_{75} = h_3'' h_3'^*, m^2_{58} = m^{2*}_{85} = 0,\\
&m^2_{67} = m^{2*}_{76} = 0, m^2_{68} = m^{2*}_{86} = h_5' h_5''^*,\\
&m^2_{78} = m^{2*}_{87} = \frac{y_4'^*}{\sqrt{2}}(v_2 A_u^* - \mu v_1).
\end{aligned} \tag{84}
$$

We can diagonalize the sneutrino mass square matrix by the unitary transformation

$$
\tilde{D}^{u\dagger} M^2_{\tilde{u}} \tilde{D}^u = \mathrm{diag}(M^2_{\tilde{u}_1}, M^2_{\tilde{u}_2}, M^2_{\tilde{u}_3}, M^2_{\tilde{u}_4}, M^2_{\tilde{u}_5}, M^2_{\tilde{u}_6}, M^2_{\tilde{u}_7}, M^2_{\tilde{u}_8})\ . \tag{85}
$$

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