On the Possible Observation of Mirror Matter

Tarek Ibrahim \(^a\) and Pran Nath \(^b\)

\(^a\)Department of Physics, University of Alexandria, Egypt
\(^b\)Department of Physics, Northeastern University, Boston, MA 02115, USA

The possibility that mirror matter with masses in the several hundred GeV–TeV range exists is explored. Mirror matter appears quite naturally in many unified models of particle interactions both in GUTs and in strings often in vector-like combinations. Some of these vector-like multiplets could escape acquiring super heavy masses and remain light down to the low energies where they acquire vector-like masses of electroweak size. It is found that a very small mixing of the vector-like multiplets with MSSM matter (specifically with the third generation matter) can produce very large contributions to the magnetic moment of the \(\tau\) neutrino by as much as several orders of magnitude putting this moment in the range of accessibility of improved experiment. Further, it is shown that if mirror matter exists it would lead to distinctive signatures at colliders and thus such matter can be explored at the LHC energies with available luminosities.

1. Introduction

Recently it was proposed that mirror matter with masses in the several hundred GeV–TeV range could exist and can be explored at the LHC energies \(^1\). Indeed many unified models do contain mirrors \(^2,3,4,5,6\) and some work on model building using mirrors can be found in \(^7,8,9\). Also implications of mirrors are explored in several works \(^10,11,12,13,14,15\). Specifically we discuss here the implications of mirror particles arising in vector-like combinations, e.g., in \(5 + \overline{5}\) and \(10 + \overline{10}\) multiplets in \(SU(5)\) and in \(16 + \overline{16}\) multiplets in \(SO(10)\). We assume that such vector-like multiplets escape gaining super-heavy masses but acquire vector-like masses of electroweak size (assumed to be much larger than the chiral masses they may acquire via Yukawa couplings to the MSSM Higgs doublets) which could lie in the several hundred GeV to TeV range or above. (The phenomenology of vector-like multiplets has been discussed in several works \(^21,22,23\).) Such vector-like multiplets are consistent with the precision electroweak data specifically on the so called S, T, U electroweak parameters and can be made consistent with the gauge coupling unification. Thus these models escape the constraints of sequential generations \(^24,25,26,27,28,29,30,31,32,33,34,35\). We allow a small mixing between the three sequential generations and the vector-like multiplets. We assume these mixings to be rather tiny so the effect of mixings with the normal matter in the vector multiplets will have negligible effects on the analysis below and thus we focus on the mixings of the mirrors with the ordinary three generations. Here again we assume that the mixings are with the third generation. The reason for the suppression of mixings between the mirrors and the first two generations is because the mixings generate a \(V + A\) interactions for the ordinary generations. Now for the first two generations the \(V - A\) structure of the interactions is established to a great accuracy. However, this is less so for the case of the third generation.

Thus a small amount of mixing of the mirror generation and of the third generation could be allowed but such mixings would be highly suppressed for the case of the first two generations. Specifically analysis of experimental data to fix the \(\tau\) interactions allow for the possibility of a small \(V + A\) type interaction \(^36,37\). A similar situation holds for the case of the third generation quarks \(^38,39,40\). This is also what
one expects from an examination of the CKM matrix elements. For example, the mixings between the first and the second generations in the CKM matrix element can be estimated by

\[ V_{us} = \sqrt{m_d/m_s} \]

which numerically is about 0.2. On the other hand, the mixing between the first generation and the third generation is given by

\[ V_{ub} = \sqrt{m_d/m_b} \]

which numerically is 0.03 and thus much smaller. If we extrapolate these relations to include mixings with the vector-like multiplets either mirror or non-mirror, then we can expect the mixing to be roughly given by

\[ V_{uB} = \sqrt{m_d/m_V} \]

where \( m_V \) is 500 GeV. The one has

\[ V_{uB} \approx 0.003 \]

which is rather tiny. In the leptonic sector such mixings will be even smaller. Thus in the leptonic sector the mixings between the first generation and the vector multiplets may be characterized by

\[ \sqrt{m_e/m_V} \]

which is 0.0009 for \( m_e \approx 0.5 \) MeV and \( m_V \approx 500 \) GeV. In the following as a simple approximation we will assume only mixings between the mirrors and the third generation and ignore mixings of the mirrors with the first two generations. We mention here that the terminology mirror has also appeared in the literature in the context of mirror worlds \[ ^{31,42} \]

which is entirely different from the analysis here since in these models one has mirror matter with their own mirror gauge group. There is no relationship of the analysis here with those theories.

2. Mirror mixings with MSSM particles

The superpotential of the model for the lepton part, describing the mixings of the mirrors with the third generation leptons may be written in the form

\[
W = \epsilon_{ij}[f_1 \tilde{H}_1 \tilde{\psi}_L^i \tilde{\tau}_L^j + f_2 \tilde{H}_2 \tilde{\psi}_L^i \tilde{\nu}_L^j + f_3 \tilde{H}_3 \tilde{\psi}_L^i \tilde{\tau}_L^j + f_4 \tilde{\psi}_L^i \tilde{\tau}_L^j \tilde{\nu}_L^j + f_5 \tilde{\psi}_L^i \tilde{\nu}_L^j \tilde{\tau}_L^j + f_6 \tilde{\psi}_L^i \tilde{\tau}_L^j \tilde{\nu}_L^j + f_7 \tilde{\psi}_L^i \tilde{\tau}_L^j \tilde{\nu}_L^j + f_8 \tilde{\psi}_L^i \tilde{\tau}_L^j \tilde{\nu}_L^j + f_9 \tilde{\psi}_L^i \tilde{\tau}_L^j \tilde{\nu}_L^j + f_{10} \tilde{\psi}_L^i \tilde{\tau}_L^j \tilde{\nu}_L^j]
\]

After spontaneous breaking of the electroweak symmetry, \((< \tilde{H}_1^1 >= v_1/\sqrt{2} \text{ and } < \tilde{H}_2^2 >= v_2/\sqrt{2})\), we have the following set of mass terms written in 4-spinors for the fermionic sector

\[
-\mathcal{L}_m = \left( \begin{array}{c}
\tilde{\tau}_R \\
\tilde{\nu}_R
\end{array} \right) \left( \begin{array}{cc}
f_1 v_1/\sqrt{2} & f_4 \\
f_3 & f_2 v_2/\sqrt{2}
\end{array} \right) \left( \begin{array}{c}
\tilde{\tau}_L \\
\nu_L
\end{array} \right) + H.c.
\]

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

\[
\left( \begin{array}{c}
\tau_R \\
\nu_R
\end{array} \right) = D_R^\tau \left( \begin{array}{c}
\tau_1 \\
\nu_2
\end{array} \right),
\]

\[
\left( \begin{array}{c}
\tau_L \\
\nu_L
\end{array} \right) = D_L^\tau \left( \begin{array}{c}
\tau_2 \\
\nu_2
\end{array} \right),
\]

such that

\[
D_R^\tau \left( \begin{array}{c}
f_1 v_1/\sqrt{2} & f_4 \\
f_3 & f_2 v_2/\sqrt{2}
\end{array} \right) D_L^\tau = diag(m_{\tau_1}, m_{\tau_2}).
\]

The same holds for the neutrino mass matrix

\[
D_R^{\nu} \left( \begin{array}{c}
f_1 v_1/\sqrt{2} & f_4 \\
f_3 & f_2 v_2/\sqrt{2}
\end{array} \right) D_L^{\nu} = diag(m_{\nu_1}, m_{\nu_2}).
\]

Here \( \tau_1, \tau_2 \) are the mass eigenstates and we identify the tau lepton with the eigenstate 1, i.e., \( \tau = \tau_1 \), and identify \( \tau_2 \) with a heavy mirror eigenstate with a mass in the hundreds of GeV. Similarly \( \nu_1, \nu_2 \) are the mass eigenstates for the neutrinos, where we identify \( \nu_1 \) with the light neutrino state and \( \nu_2 \) with the heavier mass eigenstate. By multiplying Eq.(3) by \( D_L^{\tau} \) from the right and by \( D_R^{\tau} \) from the left and by multiplying Eq.(4) by \( D_R^{\nu} \) from the right and by \( D_R^{\nu} \) from the left, one can equate the values of the parameter \( f_3 \) in both equations and we can get the following relation between the diagonalizing matrices \( D^\tau \) and \( D^{\nu} \)

\[
m_{\tau_1} D_{R_{21}}^{\tau} D_{L_{11}}^{\tau} + m_{\tau_2} D_{R_{22}}^{\tau} D_{L_{12}}^{\tau} = -[m_{\nu_1} D_{R_{21}}^{\nu} D_{L_{11}}^{\nu} + m_{\nu_2} D_{R_{22}}^{\nu} D_{L_{12}}^{\nu}].
\]

Eq.(5) is an important relation as it constraints the symmetry breaking parameters and this constraint must be taken into account in numerical analyses.
Let us now write the charged current interaction in the leptonic sector for the 3rd generation
and for the mirror sector with the W boson.
\[
\mathcal{L}_{CC} = -\frac{g_2}{2\sqrt{2}} W^\mu \phi_\mu \gamma^\mu (1 - \gamma_5) \tau + \bar{N} \gamma^\mu (1 + \gamma_5) E_\tau + H.c. \tag{6}
\]
In the mass diagonal basis the charged current interactions are given by
\[
\mathcal{L}_{CC} = -\frac{g_2}{2\sqrt{2}} W^\mu \phi_\mu \sum_{\alpha,\beta,\gamma,\delta} \bar{\nu}_\alpha \gamma^\mu [D^\nu_{\alpha\beta} g_{\gamma\delta} D^\nu_{\delta\beta} (1 - \gamma_5) + D^\nu_{\alpha\beta} g_{\gamma\delta} D^\nu_{\delta\beta} (1 + \gamma_5)]_{\tau} + H.c. \tag{7}
\]
where \(g_{\alpha\beta}^{LR}\) are defined so that
\[
g_{11}^L = 1, g_{12}^L = 0 = g_{21}^L = g_{L2}^L, g_{R}^L = 0 = g_{R}^R = g_{21}^R = g_{R2}^R = 1. \tag{8}
\]
Assuming \(D^\nu_{\tau} = D^\nu_{\tau} \equiv D^\nu\) we may parametrize \(D^\tau\) as follows
\[
D^\tau = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}. \tag{9}
\]
Similarly assuming \(D^\nu_{\tau} = D^\nu_{\tau} \equiv D^\nu\) we may parametrize the mixing between \(\nu\) and \(N\) by the angle \(\phi\) where
\[
D^\nu = \begin{pmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{pmatrix}. \tag{10}
\]
With the above simplifications the charged current interaction including mirrors is given by
\[
\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} W^\mu \phi_\mu \gamma^\mu + H.c. \tag{11}
\]
where
\[
J^\mu_{\nu1} = \{\bar{\nu}_1 \gamma^\mu \tau_1 \cos(\theta - \phi) + \bar{\nu}_1 \gamma^\mu \tau_2 \sin(\theta - \phi) - \bar{\nu}_1 \gamma^\mu \gamma_5 \tau_1 \cos(\theta + \phi) - \bar{\nu}_1 \gamma^\mu \gamma_5 \tau_2 \sin(\theta - \phi) - \bar{\nu}_2 \gamma^\mu \gamma_5 \tau_1 \sin(\theta + \phi) + \bar{\nu}_2 \gamma^\mu \gamma_5 \tau_2 \cos(\theta + \phi)\}. \tag{12}
\]
Here \(\tau_1, \tau_2\) are the mass eigenstates for the charged leptons, with \(\tau_1\) identified as the physical tau state, and \(\nu_1, \nu_2\) are the mass eigenstates
for the neutrino with \(\nu_1\) identified as the observed neutrino. [The result of Ref. 11 regarding Eq. (11) and Eq. (12) agrees with Eq. (1) of 11 after correction of a typo in 11]. The result of Eq. (11) and Eq. (12) correctly reduces to the result of Eq. (6) in the limit when \(\theta = 0 = \phi\).

Next we consider the mixings of the charged sleptons and the charged mirror sleptons. These mixings will in general contain new sources of CP phases beyond those in the MSSM (for a review see 15). However, for the analysis here we set these phases to zero. The mass matrix in the basis \((\bar{\tau}_L, \bar{E}_L, \bar{\tau}_R, \bar{E}_R)\) will be a hermitian \(4 \times 4\) mass matrix. We diagonalize this hermitian mass\(^2\) matrix by the following unitary transformation
\[
\bar{D}^\dagger M^2_\nu \bar{D}^{\nu} = \text{diag}(M^2_{\nu1}, M^2_{\nu2}, M^2_{\nu3}, M^2_{\nu4}). \tag{13}
\]
The mixing between \(\bar{\tau}_L\) and \(\bar{E}_R\) vanishes as well as the mixing between \(\bar{\tau}_R\) and \(\bar{E}_L\). The mixing of \(\bar{\tau}_L\) and \(\bar{E}_R\) is given by \(m_\nu (A_\nu - \mu \tan \beta)\) and of \(\bar{E}_L\) and \(\bar{E}_R\) is given by \(m_E (A_E - \mu \cot \beta)\). We could choose the parameters of the superpotential and the soft breaking parameters such that the latter two mixings vanish as well. Thus we make the assumption that the mixings between the mirror charged sleptons and the staus arising principally from the mixing between \(\bar{\tau}_L\) and \(\bar{E}_L\) and between \(\bar{\tau}_R\) and \(\bar{E}_R\). Under this assumption one has
\[
\bar{D}^\dagger M^2_\nu \bar{D}^{\nu} = \begin{pmatrix} \cos \tilde{\theta}_1 & \sin \tilde{\theta}_1 & 0 & 0 \\ -\sin \tilde{\theta}_1 & \cos \tilde{\theta}_1 & 0 & 0 \\ 0 & 0 & \cos \tilde{\theta}_2 & \sin \tilde{\theta}_2 \\ 0 & 0 & -\sin \tilde{\theta}_2 & \cos \tilde{\theta}_2 \end{pmatrix}. \tag{14}
\]
A similar mass\(^2\) matrix exists in the sneutrino sector. In the basis \((\tilde{\nu}_L, \bar{N}_L, \bar{\nu}_R, \bar{N}_R)\) we again get a hermitian \(4 \times 4\) matrix which can be diagonalized by the following unitary transformation
\[
\bar{D}^{\nu}_\nu M^2_\nu \bar{D}^{\nu}_\nu = \text{diag}(M^2_{\nu1}, M^2_{\nu2}, M^2_{\nu3}, M^2_{\nu4}). \tag{14}
\]
The physical tau and neutrino states are \(\tau \equiv \tau_1, \nu \equiv \nu_1\), and the states \(\tau_2, \nu_2\) are heavy states with mostly mirror particle content. The states \(\tilde{\nu}_i, i = 1 - 4\) are the slepton and sneutrino states. As in the case of the mixings of the staus and of the charged mirror sleptons we assume that the mixings of sneutrinos and of the sneutrinos
arises principally due to mixings between $\tilde{\nu}_L$ and $\tilde{N}_L$ and between $\tilde{\nu}_R$ and $\tilde{N}_R$. Under these simplifying assumptions one has

$$
\bar{D}_\nu = \begin{pmatrix}
\cos \tilde{\phi}_1 & \sin \tilde{\phi}_1 & 0 & 0 \\
-\sin \tilde{\phi}_1 & \cos \tilde{\phi}_1 & 0 & 0 \\
0 & 0 & \cos \tilde{\phi}_2 & \sin \tilde{\phi}_2 \\
0 & 0 & -\sin \tilde{\phi}_2 & \cos \tilde{\phi}_2
\end{pmatrix}.
$$

Under further simplifying assumptions one can get $\tilde{\theta}_1 = \tilde{\theta}_2 = \tilde{\theta}$, $\tilde{\phi}_1 = \tilde{\phi}_2 = \tilde{\phi}$. For the case of no mixing these limit as follows

$$
\tilde{\tau}_1 \rightarrow \tilde{\tau}_L, \quad \tilde{\tau}_2 \rightarrow \tilde{\tau}_L, \quad \tilde{\tilde{\tau}}_3 \rightarrow \tilde{\tau}_R, \quad \tilde{\tilde{\tau}}_4 \rightarrow \tilde{\tilde{E}}_R,
$$
$$
\tilde{\nu}_1 \rightarrow \tilde{\nu}_L, \quad \tilde{\nu}_2 \rightarrow \tilde{N}_L, \quad \tilde{\nu}_3 \rightarrow \tilde{\nu}_R, \quad \tilde{\nu}_4 \rightarrow \tilde{N}_R.
$$

Next we look at the neutral current interactions and focus on the charged leptons. Here the Z boson interactions are given by

$$
\mathcal{L}_{NC} = -\frac{g}{4\cos\theta_W} Z_\mu [\bar{\tau}_1 \gamma^\mu (4x - 1 + \gamma_5) \tau_1 \\
+ \bar{\nu}_1 \gamma^\mu (4x - 1 - \gamma_5) \nu_1] E^\tau, (16)
$$

where $x = \sin^2 \theta_W$. We can also write these results in the mass diagonal basis.

$$
\mathcal{L}_{NC} = -\frac{g}{4\cos\theta_W} Z_\mu J^\mu_N, (17)
$$

$$
J^\mu_N = \{\bar{\tau}_1 \gamma^\mu (4 \cos^2 \theta_W - 1 + \cos 2 \theta_5) \tau_1 \\
+ \bar{\nu}_1 \gamma^\mu (4 \cos^2 \theta_W - 1 - \cos 2 \theta_5) \nu_1 \\
+ \bar{\tilde{\tau}}_2 \gamma^\mu (4 \cos^2 \theta_W - 1 - \cos 2 \theta_5) \tilde{\tau}_2 \\
+ \bar{\tilde{\nu}}_2 \gamma^\mu (4 \cos^2 \theta_W - 1 + \cos 2 \theta_5) \tilde{\nu}_2 \\
+ \bar{\tilde{\tau}}_3 \gamma^\mu \gamma_5 \sin 2 \theta \tau_3 + \bar{\tilde{\nu}}_3 \gamma^\mu \gamma_5 \sin 2 \theta \nu_3 \\
+ \bar{\tilde{\tau}}_4 \gamma^\mu \gamma_5 \sin 2 \theta \tilde{\tau}_4 + \bar{\tilde{\nu}}_4 \gamma^\mu \gamma_5 \sin 2 \theta \tilde{\nu}_4 \},
$$

We discuss next the implications of the above interactions for the anomalous magnetic moment of the tau lepton and for the magnetic moment of the tau neutrino.

### 3. Tau neutrino magnetic moment

The existence of neutrino masses is now well established with the current experimental limits on their mass arising from WMAP obeying the constraint [46]

$$
\sum_i |m_{\nu_i}| \leq (.7 - 1)eV. (18)
$$

The nature of the neutrino masses is not yet determined. They could be either Majorana or Dirac. The smallness of the neutrino masses is easy to understand if the masses of the neutrinos are Majorana as they could arise from a see saw mechanism. On other hand it is not so easy to understand their smallness if the masses are Dirac and this topic continues to be subject of much current activity. If the neutrino masses are Dirac, they can have both a magnetic moment and an electric dipole moment. We will focus here on the magnetic moment. In the standard model enhanced by a right handed neutrino, a tau neutrino has a magnetic moment arising from the exchange of a W boson which gives a magnetic moment of $1.148$

$$
\mu_\nu = O(10^{-19})(m_\nu/eV)\mu_B. (19)
$$

where $\mu_B = (e/2m_e)$ is the Bohr magneton. One may compare this result with the current limits on the tau neutrino magnetic moment from experiment which gives [19]

$$
|\mu(\nu_\tau)| \leq 1.3 \times 10^{-7}\mu_B. (20)
$$

One may note that the SM prediction is twelve orders of magnitude smaller than the experimental limit, and thus beyond the reach of experimental test in any near future experiment. One can extend the above analysis to MSSM and include the supersymmetric exchange, i.e., the chargino exchange. However, inclusion of the supersymmetric exchanges does not change the order of the contribution which is still of the size given by Eq. (19). However, there is very drastic change when one includes the mirror particles and their supersymmetric partners. Specifically, an extension to include mirrors brings in the following additional contributions: (1) Mirror lepton and W exchange, and (2) Mirror slepton and chargino exchange. In this case neutrino magnetic moments which are larger by as much as ten orders of magnitude than the SM contribution can be obtained. Thus the magnetic moments in these models come within the realms of observability if improvement in experiment by one to two orders of magnitude can occur.

In addition to the above one must also take into account the constraints arising from the limits on
the \( \tau \) magnetic moment. The current experimental limit on the \( \tau \) magnetic moment is

\[
a_\tau(SM) = 117721(50 \times 10^{-8}),
\]

(21)

where \( a_\tau = (g_\tau - 2)/2 \) while the current experimental limit on the parameter is

\[-0.052 < a_\tau(\text{exp}) < 0.013. \quad (22)\]

A comparison of Eq. (21) and Eq. (22) shows that the current experimental sensitivity is just below an order of magnitude of what the SM predicts. Because of these constraints it is important to examine what the correction of the mirror states is to the SM correction. In Ref. [1] an analysis of the \( \tau \) anomalous magnetic moment at one loop is given taking into account several contributions. Thus the analysis gives in Ref. [1] includes the Standard Model contribution involving the W and Z exchange as well as the supersymmetric contribution involving the exchange of the chargino and the neutralinos. Additionally exchanges of mirror leptons and mirror sleptons are included. The analysis shows that the contributions from the mirror sector this time are of the same order as the contribution from the SM sector. This in sharp contrast to the contribution to the \( \tau \) neutrino case where the contributions from the mirror sector are orders of magnitude larger than the SM contribution. In Table (1) we give an analysis of the neutrino magnetic moment and of the \( \tau \) anomalous magnetic moment within the framework of the supergravity grand unified model [50].

| \( \theta \) | \( \tilde{\theta} \) | \( \phi \) | \( \Delta a_\tau \times 10^6 \) | \( \mu_\nu/\mu_B \times 10^{10} \) |
|---|---|---|---|---|
| 0.2 | 0.4 | 0.3 | 6.95 | -9 |
| 0.15 | 0.45 | 0.35 | 3.46 | -5.3 |
| 0.10 | 0.3 | 0.2 | 1.64 | -2.4 |

Table caption: A sample illustration of the contributions to the magnetic moments of \( \nu_\tau \) and of \( \tau \) including corrections from exchange of the third generation leptons and their superpartners and from exchange of the mirror particles and mirror super partners. The analysis is for the parameter set \( m_0 = 400, m_{1/2} = 150, \tan \beta = 20, A_0 = 400 \), \( \mu > 0, m_E = 200, m_N = 220, M_{\tilde{\tau}} = 400, M_{\tilde{\tau}_2} = 500, m_\tilde{\psi}_1 = 420 \) and \( m_\tilde{\psi}_2 = 520 \). The mixing angles \( \theta \), \( \tilde{\theta} \) and \( \phi \) are as exhibited. All masses are in units of GeV and all angles are in radian.

4. Signatures for mirrors at the LHC

A variety of signatures can arise for the mirror fermions and mirror sfermions if they exist at the LHC. We discuss these below.

4.1. Lepton and jet signatures of mirrors at the LHC

In the extension of MSSM with a mirror generation, one has new fermions, i.e., the mirror fermions \( B, T, E, N \) (see the Appendix for notation) all Dirac, as well as mirror sfermions. For the mirror sleptons we have the new states

\[
\tilde{E}_1, \tilde{E}_2, \tilde{N}_1, \tilde{N}_2, \tilde{N}_3, \quad (23)
\]

where \( \tilde{E}_1, \tilde{E}_2 \) are the charged mirror sleptons and \( \tilde{N}_1, \tilde{N}_2, \tilde{N}_3 \) are the three new sneutrino states. The reason of these extra three sneutrino is that we started out with two extra chiral singlets, one
in the MSSM sector and another in the mirror sector. Along with the two chiral neutrino states that arise from the doublet they produce four sneutrino states, one of which is in the MSSM sector and the other three are new and listed in the equation above. For the mirror squarks we have

\[ \tilde{B}_1, \tilde{B}_2, \tilde{T}_1, \tilde{T}_2. \]  

(24)

The decay modes of the mirrors will produce interesting signatures. Thus, for example, the decay of the mirror lepton \( E^- \) gives

\[ E^- \rightarrow \tau^- Z \rightarrow \tau^- l^+ l^-, \tau^- \text{jets}, \]  

(25)

and decay of the Dirac \( N \) gives

\[ N \rightarrow E^- W^+, N \rightarrow \nu_\tau \gamma. \]  

(26)

where the decay \( N \rightarrow \nu_\tau \gamma \) occurs via transition magnetic moment. Similarly there will be the mirror slepton with the decay

\[ \tilde{E}^- \rightarrow \tilde{\tau}^- Z, \tau^- \tilde{\chi}_i^0 \rightarrow \tau^- l^+ l^- + E_T^{\text{miss}}, \]  

(27)

where \( E_T^{\text{miss}} \) is typically the lightest neutralino (the LSP). Similarly the mirror sneutrinos will have the decay

\[ \tilde{\nu}_i \rightarrow \tilde{\tau}^- W^+, \tilde{E}^- \tilde{\chi}^+ \rightarrow \tau^- l^+ + E_T^{\text{miss}}. \]  

(28)

The above will give rise to the following processes at the LHC.

\[ pp \rightarrow W^* \rightarrow \tilde{E} N \rightarrow [\tau l_i l_i, 3\tau, \tau + 2 \text{jets}] E_T^{\text{miss}} \]

\[ pp \rightarrow Z^* \rightarrow E^+ E^- \rightarrow 2\tau 4l, 4\tau 2l, 6\tau, 2\tau 2l 2\text{jets}, 2\tau 4\text{jets}. \]  

(29)

where \( l_1, l_2 = e, \mu \). Similar signatures but with much more missing energy arise via the production and decay of mirror sfermions. We note that the trileptonic signature of Eq. (29) is distinctly different from the trileptonic signature arising from the off shell decay of a \( W \) in supersymmetry (25). Similarly the 4 lepton decay in Eq. (29) is also distinctly different from the 4 lepton decay in supersymmetry (25). This is because in Eq. (29) there is always a tau in the final final state.

4.2. Forward-backward asymmetry

The forward backward asymmetry defined by

\[ A_{FB} = \frac{\int_0^1 (d\sigma/dz)dz - \int_{-1}^0 (d\sigma/dz)dz}{\int_{-1}^1 (d\sigma/dz)dz} \]

in the process \( f \tilde{f} \rightarrow f_4 \tilde{f}_4 \) vs the process \( f \tilde{f} \rightarrow f_m \tilde{f}_m \) where \( f_4 \) is the 4th generation fermion and \( f_m \) is the mirror fermion can allow one to discriminate between ordinary fermions and mirror fermions since \( A_{FB} \) is sensitive to the Lorentz structure of the interaction. Thus a measurement of the forward-backward asymmetry provides an important test of the presence of a \( V + A \) vs a \( V - A \) interaction and will allow one to discriminate from normal particles in collider experiments. Finally we mention that simulations of models with vector-like multiplets are needed in order to make concrete predictions of the event rates of various signatures listed in this section for LHC luminosities similar to the ones done for the supergravity models (for some recent works see [53]).

4.3. FCNC processes

The presence of mirror particles in vector-like multiplets which mix with the third generation would tend to vitiate the GIM mechanism and produce FCNC processes. This will lead to couplings of the \( Z \) boson of the type \( Z \tilde{E}, ZbB, Z\tilde{T} \). Thus in Drell-Yan processes one will be able to produce final states with \( \tilde{\tau} E, bB \) etc. Of course such processes would be suppressed by small mixing angles as well as by the largeness of the mirror fermion masses. One needs detailed simulations on the production of such events at the LHC energies and luminosities.

5. Conclusion

We have discussed here the possibility that mirror particles may exist with low masses, i.e., masses in the electroweak region. The simplest possibility is that the mirrors are part of vector-like multiplets which survive superheavy mass growth but gain masses of electroweak size. Further, mixings can arise between the vector-like multiplets and the three sequential generations. While such mixings are severely limited by experimental data for the first two generations, a small mixing between the vector-like multiplets
and the third generation is not excluded. We focus here on the mixings between the mirrors and the third generation. As a consequence of this mixing the third generation fermions develop a small \((V + A)\) interaction in addition to their normal \((V - A)\) interactions. One consequence of this new interaction is an enhancement of the \(\tau\) neutrino magnetic moment by as much as ten orders of magnitude bringing it within the realm of observation in future experiment. There are also important collider implications of mirror fermions and mirror sfermions. Is it estimated that mirror particles can be observed at the LHC with about 50 fb\(^{-1}\) of data. Further, there would be some very unique features associated with the production of the mirror particles. Specifically because of the mixing of the mirrors with the third generation, the leptonic decay modes of the mirrors will always contain a tau lepton. Other signatures involve the forward-backward asymmetry in the production of the mirror fermion -anti mirror fermion pair which is different from that of an ordinary fermion-anti fermion pair.

Acknowledgments
This research is supported in part by NSF grant PHY-0757959.

6. Appendix: Mirror fermions

The transformation properties of the mirror fermions and those of the ordinary fermions are as follows. The corresponding transformations for the mirror quarks are

\[
q^T \equiv (t_L, b_L) \sim (3, 2, \frac{1}{6}),
\]
\[
t^c_L \sim (3^*, 1, -\frac{2}{3}),
\]
\[
b^c_L \sim (3^*, 1, \frac{1}{3}).
\]

(30)
The corresponding transformations for the mirror leptons are

\[
\psi^T_L \equiv (\nu_L, \tau_L) \sim (1, 2, -\frac{1}{2}),
\]
\[
\tau^c_L \sim (1, 1, 1),
\]
\[
\nu^c_L \sim (1, 1, 0),
\]

while those of the mirror leptons are

\[
\chi^c \equiv (E^c_{\tau L}, N^c_L) \sim (1, 2, \frac{1}{2}),
\]
\[
E_{\tau L} \sim (1, 1, -1),
\]
\[
N_L \sim (1, 1, 0).
\]

(33)

REFERENCES

1. T. Ibrahim and P. Nath, Phys. Rev. D 78, 075013 (2008) [arXiv:0806.3880 [hep-ph]].
2. H. Georgi, Nucl. Phys. B 156, 126 (1979).
3. F. Wilczek and A. Zee, Phys. Rev. D 25, 553 (1982).
4. G. Senjanovic, F. Wilczek and A. Zee, Phys. Lett. B 141, 389 (1984).
5. K. S. Babu, S. M. Barr and B. s. Kyae, Phys. Rev. D 65, 115008 (2002) [arXiv:hep-ph/0202178].
6. K. S. Babu, I. Gogoladze, P. Nath and R. M. Syed, Phys. Rev. D 74, 075004 (2006) [arXiv:hep-ph/0607244]; K. S. Babu, I. Gogoladze, P. Nath and R. M. Syed, Phys. Rev. D 74, 075004 (2006) [arXiv:hep-ph/0607244]; P. Nath and R. M. Syed, arXiv:0909.2380 [hep-ph].
7. I. Bars and M. Gunaydin, Phys. Rev. Lett. 45, 859 (1980).
8. S. L. Adler, Phys. Lett. B 533, 121 (2002) [arXiv:hep-ph/0201009].
9. H. Chavez and J. A. Martins Simoes, Nucl. Phys. B 783, 76 (2007) [arXiv:hep-ph/0610231]; P. Csikor and Z. Fodor, hep-ph/9205222; V. Elias and S. Rajpoot, Phys. Lett. B 134, 201 (1984); S. Rajpoot and J. G. Taylor, Phys. Lett. B 142, 365 (1984).
10. S. Nandi, A. Stern and E. C. G. Sudarshan, Phys. Rev. D 26, 2522 (1982).
11. P. Langacker and D. London, Phys. Rev. D 38, 886 (1988).
12. D. Choudhury, T. M. P. Tait and C. E. M. Wagner, Phys. Rev. D 65, 053002 (2002) [arXiv:hep-ph/0109097].
13. F. Csikor and I. Montvay, Phys. Lett. B 324, 412 (1994) [arXiv:hep-ph/9401290].
14. I. Montvay, arXiv:hep-ph/9708269.
15. G. Triantaphyllou, Int. J. Mod. Phys. A 15, 265 (2000) [arXiv:hep-ph/9906283].
16. K. S. Babu, I. Gogoladze, M. U. Rehman and Q. Shaﬁ, Phys. Rev. D 78, 055017 (2008) [arXiv:0807.3055 [hep-ph]].
17. K. S. Babu, I. Gogoladze and C. Kolda, arXiv:hep-ph/0410085.
18. V. Barger, J. Jiang, P. Langacker and T. Li, Int. J. Mod. Phys. A 22, 6203 (2007) [arXiv:hep-ph/0612206].
19. L. Lavoura and J. P. Silva, Phys. Rev. D 47, 1117 (1993).
20. N. Maekawa, Phys. Rev. D 52, 1684 (1995).
21. K. S. Babu, I. Gogoladze and C. Kolda, arXiv:hep-ph/0410085.
22. S. Martin, Talk at SUSY09. http://nuweb.neu.edu/susy09/talks/Talk742−Martin.pdf
23. G. D. Kribs, T. Plehn, M. Spannowsky and T. M. P. Tait, Phys. Rev. D 76, 075016 (2007) [arXiv:0706.3718 [hep-ph]]; R. Fok and G. D. Kribs, arXiv:hep-ph/0711.4353 [hep-ph].
24. P. Q. Hung and M. Sher, Phys. Rev. D 77, 037302 (2008) [arXiv:hep-ph/0606146]; JHEP 0703, 063 (2007) [arXiv:hep-ph/0702037].
25. B. Holdom, JHEP 0608, 076 (2006) [arXiv:hep-ph/0606146]; JHEP 0703, 063 (2007) [arXiv:hep-ph/0606146]; JHEP 0703, 063 (2007) [arXiv:hep-ph/0702037].
26. J. E. Dubicki and C. D. Froggatt, Phys. Lett. B 567, 46 (2003) [arXiv:hep-ph/0305007].
27. V. A. Novikov, L. B. Okun, A. N. Rozanov and M. I. Vysotsky, JETP Lett. 76, 127 (2002) [Pisma Zh. Eksp. Teor. Fiz. 76, 158 (2002)] [arXiv:hep-ph/0203132].
28. Z. Murdock, S. Nandi and Z. Tavartkiladze, arXiv:0806.2064 [hep-ph].
29. O. Cakir, H. Duran Yildiz, R. Melahiyan and I. Turk Cakir, arXiv:0801.0236 [hep-ph].
30. I. T. Cakir, H. D. Yildiz, O. Cakir and G. Unel, arXiv:0908.0123 [hep-ph].
31. C. Liu, arXiv:0907.3011 [hep-ph].
32. J. L. Hewett and T. G. Rizzo, Phys. Rev. D 35, 2194 (1987).
33. R. L. Arnowitt and P. Nath, Phys. Rev. D 36 (1987) 3423.
34. V. D. Barger, J. L. Hewett and T. G. Rizzo, Mod. Phys. Lett. A 5, 743 (1990).
35. P. H. Frampton, P. Q. Hung and M. Sher, Phys. Rept. 330, 263 (2000) [arXiv:hep-ph/9903387].
36. S. Singh and N. K. Sharma, Phys. Rev. D 36, 160 (1987); S. Singh and N. K. Sharma, Phys. Rev. D 36, 3387 (1987).
37. M. T. Dova, J. Swain and L. Taylor, Nucl. Phys. Proc. Suppl. 76 (1999) 133 [arXiv:hep-ph/9811209].
38. M. Jezebek and J. H. Kuhn, Phys. Lett. B 329, 317 (1994) [arXiv:hep-ph/9403366].
39. C. A. Nelson, B. T. Kress, M. Lopes and T. P. McCauley, Phys. Rev. D 56, 5928 (1997) [arXiv:hep-ph/9707211].
40. V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 100, 062004 (2008) [arXiv:0711.0032 [hep-ex]].
41. Yu. Kobzarev, L.B. Okun and I. Ya. Pomeranchuk, Sov. J. of Nucl. Phys. 3, 837 (1966).
42. R. N. Mohapatra, S. Nasri and S. Nussinov, Phys. Lett. B 627, 124 (2005) [arXiv:hep-ph/0508109].
43. J. Maalampi and M. Roos, Phys. Rept. 186, 53 (1990).
44. J. Maalampi, J.T. Peltoniemi, and M. Roos, PLB 220, 441 (1989).
45. T. Ibrahim and P. Nath, Rev. Mod. Phys. 80, 577 (2008) [arXiv:hep-ph/0210251].
46. D. N. Spergel et al. [WMAP Collaboration], Astrophys. J. Suppl. 170 (2007) 377 [arXiv:astro-ph/0603449].
47. L. G. Cabrera, J. Bernabeu, J. Vidal and A. Zepeda, Eur. Phys. J. C 12, 633 (2000) [arXiv:hep-ph/9907249].
48. M. Dvornikov and A. Studenikin, Phys. Rev. D 69, 073001 (2004) [arXiv:hep-ph/0305206].
49. S. N. Gninenko, Phys. Lett. B, 452, 414 (1999).
50. A. H. Chamseddine, R. Arnowitt and P. Nath, Phys. Rev. Lett. 49 (1982) 970.
51. P. Nath and R. Arnowitt, Mod. Phys. Lett. A 2, 331 (1987); H. Baer, C. h. Chen, F. Paige and X. Tata, Phys. Rev. D 50, 4508 (1994); V. D. Barger, C. Kao and T. j. Li, Phys. Lett. B 433, 328 (1998).
52. T. Ibrahim, Phys. Rev. D 77, 065028 (2008) [arXiv:0803.4134 [hep-ph]].
53. D. Feldman, Z. Liu and P. Nath, Phys. Rev. Lett. 99, 251802 (2007); Phys. Lett. B 662, 190 (2008); JHEP 0804, 054 (2008).