Charged Lepton Flavor Violation $\mu \to e\gamma$ in $\mu$-$\tau$ Symmetric SUSY SO(10) Theories and LHC

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Charged Lepton Flavor Violation (cLFV) processes like $\mu \to e\gamma$ are rare decay processes, that are another signature of physics beyond Standard Model (BSM). These processes have been studied in various models, that could explain neutrino oscillations and mixings. In this work, we present bounds on cLFV decay $\mu \to e\gamma$ in a $\mu$-$\tau$ symmetric SUSY SO(10) theory, using type I seesaw mechanism. The updated constraints on BR($\mu \to e\gamma$) from MEG experiment, recently measured value of Higgs mass at LHC and value of $\theta_{13}$ from reactor data have been used. We present our results in mSUGRA, NUHM and NUGM models, and sensitivity to test these theories at next run of LHC is also discussed. cLFV in NUGM models is discussed in this work for the first time.

I. INTRODUCTION

The flavor changing neutral current (FCNCs) are forbidden in the standard Model (SM) of particle physics, at tree level. They are allowed beyond tree level, but highly suppressed by the GIM mechanism [1]. Flavor mixing in the standard model quark sector is well established, through processes like $K^0 - \bar{K}^0$ oscillations, $B_d - \bar{B}_d$ mixing etc. The phenomenon of neutrino oscillations, already proved by experiments, require to go beyond standard model. These neutrino oscillations, and hence mixings, are also expected to induce flavor violations in the charged leptonic sector. Theoretically, such cLFV processes could be induced in different theories with BSM particles such as SUSY GUT [2], SUSY See Saw [3-5], LHC Higgs Model [6] and models with extra dimension [7]. But since neutrino is the only BSM particle whose existence has been proved experimentally, in this work we consider cLFV decay $\mu \to e\gamma$, getting contributions from neutrino oscillations and mixings.

Many processes involving cLFV decays could be possible such as $\mu \to e$, $\tau \to \mu$ or $\tau \to e$ transitions. For $\mu \to eee$ decay, an improvement of upto 4 orders of magnitude is expected [8], and similarly for $\mu \to e$ conversions in atomic nuclei improvements are expected [9-13]. Improvements for $\mu \to e\gamma$ decay at next phase of MEG experiment is expected to reach BR ($\mu \to e + \gamma$) $\leq 6 \times 10^{-14}$ [14]. In this work, we have only considered the decay $\mu \to e + \gamma$, as this is best constrained by experiments. Such experimental searches, and theoretical studies on cLFV can help us constrain the new physics or BSM theories, that could be present just above the electroweak scale, or within the reach of next run of LHC. It is worth mentioning that in the next run of LHC, the center of mass energies are expected to go to 14 TeV [15].

In Non SUSY BSM theories, the cLFVs are highly suppressed, by the factor $\sim \left( \frac{m_\nu}{M_W} \right)$, where $m_\nu$ is the tiny neutrino mass of the order of eV and $M_W$ is the mass of W boson ($M_W \simeq 80$ GeV). But in SUSY GUTs, that naturally give rise to tiny neutrino masses via see saw mechanisms, significant contributions to these rare decay processes could come from flavor violations among heavy sleptons. The lepton flavor violation effects could become significant due to radiative corrections to Dirac Neutrino Yukawa Couplings (DNY), which might arise if the see saw
scale is slightly lower than the GUT scale [4,16-20]. Such studies in different seesaw mechanisms have been carried out in [4,16-21]. In [4], such studies were done in scenario when neutrino masses and mixings arise due to type I See Saw mechanism of SUSY SO(10) theory. In this work the Dirac neutrino Yukawa couplings were of the type- $Y_u = Y_u$ and $Y_e = Y_{ue}^{diag} U_{PMNS}$, where $Y_u = V_{CKM} Y_{u}^{diag} V_{CKM}^T$. Similar studies were done in [22] in type II See Saw scenario. Charged Lepton Flavor Violation in SUSY type II seesaw [23] models have also been studied earlier in [18,19-20].

In this work we carry out studies on cLFV decay ($\mu \rightarrow e \gamma$) using type I see saw mechanism in $\mu$-$\tau$ symmetric SUSY SO(10) theories [24], and hence check the sensitivity to test the observation of sparticles at next run of LHC [15], in mSUGRA, NUHM, and NUGM [25] models. Such studies in NUGM models are done for the first time in this work. It may be noted that $\mu$-$\tau$ symmetric SUSY SO(10) theory provides good fit to observed neutrino oscillations and mixings. The analysis have been done for $\tan \beta = 10$, and $M_{GUT} = 2 \times 10^{16}$ GeV. The form of Dirac neutrino Yukawa couplings is used from [24]. The value of Higgs mass as measured at LHC [15] and global fit values of reactor mixing angle $\theta_{13}$ as measured at Daya Bay, Reno [26] have been used in this work. Also, after the improved constraints on BR($\mu \rightarrow e \gamma$) at MEG experiment [27], this is the first study in type I See Saw scenario. Such studies in type II See Saw have been carried out in [22] also, using CKM or PMNS like Dirac neutrino Yukawa couplings. In [4], such studies were done using type I see saw formula, using older value of BR($\mu \rightarrow e \gamma$) [27].

It is well known that SUSY can be broken by soft terms of type $-A_0, m_0, M_{1/2}$, where $A_0$ is the universal trilinear coupling, $m_0$ is the universal scalar mass, and $M_{1/2}$ is the universal gaugino mass. Strict universality between Higgs and matter fields of mSUGRA models can be relaxed in NUHM (Non Universial Higgs Mass) [28] models. As shown in our results in Sec.IV in mSUGRA, the spectrum of $M_{1/2}$ and $m_0$ is found to lie towards heavy side, as allowed by MEG constraints on BR($\mu \rightarrow e \gamma$), though in NUHM, lighter spectra is possible (due to partial cancellations in flavor violating term). So it motivated us to investigate cLFV decay $\mu \rightarrow e \gamma$ in NUGM (Non Universal Gaugino Mass Models) [25]. Non Universality of gaugino masses can be realised in various scenarios, including grand unification [29]. In these models, gaugino masses are non universal at GUT scales, unlike in mSUGRA/NUHM models. From [25] we have used

$$M_1 : M_2 : M_3 = -1/2 : -3/2 : 1$$

(1)

for SO(10) theory.Here, $M_1, M_2$ and $M_3$ are the gaugino masses at GUT scale. In NUGM, an increase in allowed SUSY soft parameter space is observed, as compared to mSUGRA and NUHM that lies within BR($\mu \rightarrow e \gamma$) limits of MEG 2013. The BR($\mu \rightarrow e \gamma$) is found to increase with increase of $m_0$ here, which is opposite to mSUGRA and NUHM models. In NUGM model, the $|A_0|$ is found to shift towards large value side, as compared to mSUGRA and NUHM models.

From above it is seen that signatures of cLFV could be tested at next run of LHC, if SUSY sparticles are observed within few TeV range, as discussed in more detail in next sections. It is worth mentioning here that, during last run of LHC, no SUSY partner of SM has been observed, and this could point to a high scale SUSY theory. The LHC has stringent limits on sparticles, which could imply a tuning of EW symmetry at a few percent level [30-35]. And hence some alternatives to low scale SUSY theories have been proposed. Some of them are — minisplit SUSY [36] and maximally natural SUSY [37]. In the former the scalar sparticles are heavier than the sfermions (gauginos and
higgsinos), so that sfermions could be observed at LHC. Scalar particles could be anywhere in the range \((10^{-1} - 10^{5})\) TeV. In maximally natural SUSY, the 4D theories arise from 5D SUSY theory, with Scherk-Schwarz SUSY breaking at a Kaluza-Klein scale \(\sim \frac{1}{\pi}\) of several TeV [37]. Charged Lepton Flavor Violation in these models would be studied in our future works.

| LFV Processes | Present Bound | Near Future Sensitivity Of Ongoing Experiments |
|---------------|---------------|-----------------------------------------------|
| \(BR(\mu \to e\gamma)\) | \(5.7 \times 10^{-13}\) | \(6 \times 10^{-14}\) |
| \(BR(\tau \to e\gamma)\) | \(3.3 \times 10^{-8}\) | \(10^{-9}\) |
| \(BR(\tau \to \mu\gamma)\) | \(4.4 \times 10^{-8}\) | \(3 \times 10^{-9}\) |
| \(BR(\mu \to eee)\) | \(1.0 \times 10^{-12}\) | \(10^{-15}\) |
| \(BR(\tau \to eee)\) | \(3.0 \times 10^{-8}\) | \(10^{-9}\) |
| \(BR(\tau \to \mu\mu\mu)\) | \(2.0 \times 10^{-8}\) | \(3 \times 10^{-9}\) |

Table I: Expected present and future sensitivities from the current generation experiments on various LFV processes [22].

The paper has been organised as follows. In section II, we give connections of cLFV with type I See Saw mechanism in \(\mu - \tau\) symmetric SO(10) theories. In section III, the values of various parameters used in our analysis has been presented. We have used software SuSeFLAV [38] to compute \(BR(\mu \to e\gamma)\). Section IV contains our results and their analysis. Section V summarises the work.

II. CHARGED LFV \(\mu \to e\gamma\) DECAY IN SUSY SO(10) IN CONNECTION WITH TYPE I SEE SAW

Neutrino oscillations and mixings are now a proved phenomenon, and through a neutrino oscillation, a cLFV process could be induced as

\[ l_i \xrightarrow{W} \nu_i \rightarrow \nu_j \xrightarrow{W} l_j \] (2)

Here \(W\) means a vertex involving a W boson. The process requires neutrino mass insertion at two points. In type I See Saw mechanism, \(\Delta L = 2\) majorana neutrino masses arise from tree level exchange of a heavy right handed neutrino. The SUSY SO(10) theory naturally incorporates the seesaw mechanism. The presence of heavy RH neutrinos at an intermediate scale leads to the running and generate flavor violating entries in the left-handed slepton mass matrix at the weak scale [4]. These entries in the Leading Log Estimates in mSUGRA are [39]

\[ (m^2_L)_{i\neq j} = (\Delta_{i\neq j})_{\text{LL}} = \frac{-3m_0^2 + A_0^2}{8\pi^2} \sum_k (Y^*_{\nu})_{ik} (Y^\nu)_{jk} \log \left( \frac{M_X}{M_{R_k}} \right) \] (3)

here \(M_X\) is the GUT scale, \(M_{R_k}\) is the scale of the \(k^{th}\) heavy RH majorana neutrino, \(m_0\) and \(A_0\) are universal soft mass and trilinear terms at the high scale. \(Y^\nu\) are the Dirac neutrino Yukawa couplings. The fermion masses can
be generated by renormalisable Yukawa couplings of the $10 \oplus 126 \oplus \bar{120}$ representation of scalars of SO(10) GUTs. We have used the Dirac neutrino Yukawa couplings $Y_\nu$ at the high scale in SO(10) GUTs in our work from [24].

$$Y_\nu = \frac{1}{\sin \beta} M_D$$  \hspace{1cm} (4)

$M_D$ is the Dirac neutrino mass matrix. The flavor violating off-diagonal entries at the weak scale in eq. (3) are then completely determined by using $Y_\nu$ from eq. (4).

Possibly the finest way to understand the lepton flavour violating entries in the SO(10) SUSY GUT framework is in terms of the low energy parameters. We employ the so called Mass Insertion (MI) [40] notation to represent the various flavour violating entries of the slepton mass matrix. These flavour violating entries are zero at the high scale, where SUSY breaking soft scalar masses are universal. At the weak scale, the universality is broken by the RG evolution and the $6 \times 6$ slepton squared-masses matrix $M_{\tilde{l}}^2$ takes the following form

$$M_{\tilde{l}}^2 = \begin{pmatrix}
m_{\tilde{l}}^2 (1 + \delta_{LL}) + Y_e Y_e^\dagger \nu^2 + O(g^2) & v_d (A^\dagger_\tau - Y_\nu^\dagger \mu \tan \beta) + \delta_{LR} \tilde{m}_d^2 \\
v_d (A_d - Y_\nu \mu \tan \beta) + \delta_{RL} \tilde{m}_d^2 & m_{\tilde{l}}^2 (1 + \delta_{RR}) + Y_e Y_e^\dagger \nu^2 + O(g^2)
\end{pmatrix}$$  \hspace{1cm} (5)

where the flavour violation is parameterized in terms of the quantity $\delta_{ij} = \frac{\Delta_{ij}}{m_{\tilde{l}}^2}$. Here $\tilde{m}_d^2$ is the geometric mean of the slepton squared masses [41], and $\Delta_{i\neq j}$ are flavour non diagonal entries of the slepton mass matrix induced at the weak scale due to RG evolution. The mass insertions are branched into the LL/LR/RL/RR types [42], according to the chirality of the corresponding SM fermions.

A. LL Insertions From The Running

To calculate the $\delta s$ from the RGEs, we use the leading log approximation. Assuming the soft masses to be flavour universal at the input scale, off diagonal entries in the LL sector are induced by right handed neutrinos running in the loops. To use the leading log expression (eq. (3)) we need the mass of the heaviest right handed neutrino, which we have used from [24] by diagonalising matrix $M_R$, and found to be $\sim 10^{16}$ GeV. The induced off-diagonal entries relevant to $l_i \rightarrow l_j + \gamma$ are of the order of (putting $A_0$ to 0)

$$\left(\delta_{LL}\right)_{\mu\nu} = \frac{-3}{8 \pi^2} (Y_\nu^*)_{13} (Y_\nu)_{23} \ln \left( \frac{M_X}{M_{R_3}} \right)$$  \hspace{1cm} (6)

$$\left(\delta_{LL}\right)_{\tau\mu} = \frac{-3}{8 \pi^2} (Y_\nu^*)_{23} (Y_\nu)_{33} \ln \left( \frac{M_X}{M_{R_3}} \right)$$  \hspace{1cm} (7)

$$\left(\delta_{LL}\right)_{\tau e} = \frac{-3}{8 \pi^2} (Y_\nu^*)_{13} (Y_\nu)_{33} \ln \left( \frac{M_X}{M_{R_3}} \right)$$  \hspace{1cm} (8)
Lake Vertical Flavor (LFV) contributions from USD options are given in Table II:

| LFV contributions | From USD option |
|-------------------|-----------------|
| $\Delta_{12}$     | $1.801 \times 10^{-3}$ |
| $\Delta_{23}$     | $7.94 \times 10^{-4}$  |
| $\Delta_{31}$     | $1.706 \times 10^{-3}$ |

Table II: Values (dominant) of $\Delta_{ij}$ that enter eqs. (6,7,8) for user defined options (USD) which we have used from [24]

The branching ratio of a charged LFV decay $l_i \rightarrow l_j$ is [4]

$$\text{BR} \left( l_i \rightarrow l_j + \gamma \right) \approx \alpha^3 \frac{\left| \delta_{ij}^{LL} \right|^2}{G_F^2 M_{\text{SUSY}}^4} \times \tan^2 \beta \text{BR} \left( l_i \rightarrow l_j \nu_i \tilde{\nu}_j \right) \quad (9)$$

where $M_{\text{SUSY}}$ is the SUSY breaking scale. In NUHM models, the term $(-3m_0^2 + A_0^2)$ of mSUGRA models in Eq.(3) is replaced by $(-2m_0^2 + A_0^2 + m_{H_u}^2)$. Here, $m_{H_u}$ is the soft mass terms of the up type Higgs at the high scale. We consider the NUHM1 case (at the GUT scale)

$$m_{H_u} = m_{H_d} \quad (10)$$

Moreover, there can be a relative sign difference between the universal mass terms for the matter fields and the Higgs mass terms at the GUT scale. This can clearly lead to cancellations for

$$m_{H_u}^2 \approx -2m_0^2 \quad (11)$$

Or enhancements for

$$m_{H_u}^2 \geq m_0^2 \quad (12)$$

compared to mSUGRA in the flavor violating entries at the weak scale.

III. CALCULATION OF BR($\mu \rightarrow e\gamma$) IN MSUGRA, NUHM AND NUGM

In this section we present our calculations and results on the charged LFV constraints in $\mu$-$\tau$ symmetric SO(10) SUSY theory, using type I Seesaw mechanism with mSUGRA, NUHM and NUGM like boundary conditions through detailed numerical analysis. For mSUGRA we scan the soft parameter space in the following ranges.

$$M_{\text{SUSY}} = 1 \text{ TeV}, \tan \beta = 10$$

$$m_h \in [122.5, 129.5] \text{ GeV}$$
\[ \Delta m_H \in 0 \]

\[ m_0 \in [0, 7] \text{ TeV} \]

\[ M_{1/2} \in [0.3, 3.5] \text{ TeV} \]

\[ A_0 \in [-3m_0, +3m_0] \]

\[ \text{sgn} (\mu) \in \{-, +\} \quad (13) \]

We perform random scans for the following range of parameters in NUGM model with non universal and opposite sign gaugino masses at \( M_{\text{GUT}} \), with the sfermion masses assumed to be universal maintaining the ratio between the non universal gaugino masses \([25]\).

\[ m_h \in [122.5, 129.5] \text{ GeV} \]

\[ m_0 \in [0, 7] \text{ TeV} \]

\[ M_1 \in [-3, -2.8] \text{ TeV} \]

\[ M_2 \in [-9, -8.4] \text{ TeV} \]

\[ M_3 \in [6, 5.6] \text{ TeV} \]

\[ \tan \beta = 10 \]

\[ A_0 \in [-3m_0, +3m_0] \quad (14) \]

Here \( m_0 \) is the universal SSB mass parameter for sfermions, and \( M_1, M_2, \) and \( M_3 \) denote the gaugino masses for \( U(1)_Y, SU(2)_L \) and \( SU(3)_C \) respectively. \( A_0 \) is the trilinear scalar interaction coupling, \( \tan \beta \) is the ratio of the MSSM Higgs vacuum expectation values (VEVs).
We have done the numerical analysis using the publicly available package SuSeFLAV [38]. We also study cLFV for the non universal Higgs model without completely universal soft masses at high scale. Range of scan of various SUSY parameters, used by us, in NUHM are:

\[ m_h \in [122.5, 129.5] \text{ GeV} \]

\[ 30 \text{ GeV} \leq m_0 \leq 6 \text{ TeV} \]

\[ 30 \text{ GeV} \leq M_{1/2} \leq 2.5 \text{ TeV} \]

\[ -8.5 \text{ TeV} \leq m_{H_u} \leq +8.5 \text{ TeV} \]

\[ -8.5 \text{ TeV} \leq m_{H_d} \leq +8.5 \text{ TeV} \]

\[ -18 \text{ TeV} \leq A_0 \leq +18 \text{ TeV} \]  \hspace{1cm} (15)

\( \Delta_{i \neq j}^{LL} \) due to non universal Higgs and \( m_h \geq 125 \text{ GeV} \) puts a strong constraint on SUSY parameter space. Also, because of partial cancellations in the entries of \( \Delta_{i \neq j}^{LL} \) in NUHM case large region of parameter space can be explored by MEG. The masses of the heavy neutrinos used in our calculations are \( M_{R_1} = 10^{13} \text{ GeV}, M_{R_2} = 10^{14} \text{ GeV}, \) and \( M_{R_3} = 10^{16} \text{ GeV} \). For \( \Delta m_{\text{sol}}^2, \Delta m_{\text{atm}}^2 \) and \( \theta_{13} \), we use the central values from the recent global fit of neutrino data [26]. The present limits on different LFV observables are summarized in Table 1.

IV. ANALYSIS AND DISCUSSION ON RESULTS

In this section, we will present analysis and discussion on results obtained in section III.

A. Complete Universality - cMSSM (mSUGRA)

In mSUGRA at the high scale, the parameters of the model are \( m_0, A_0 \) and unified gaugino mass \( M_{1/2} \). In addition to these, there is the Higgs potential parameter \( \mu \) and the undetermined ratio of the Higgs VEVs, \( \tan \beta \). The entire supersymmetric mass spectrum is determined once these parameters are given. We find that, the updated MEG limit [22] together with a large \( \theta_{13} \) [26] puts significant constraints on SUSY parameter space in mSUGRA. As can be seen from fig 1a, only small part of the parameter space survives for \( \tan \beta = 10 \) in mSUGRA allowed by future MEG limit for \( \text{BR}(\mu \to e\gamma) \). This leads to the conclusion that the parameter space \( M_{1/2} \geq 1 \text{ TeV} \) is allowed by present MEG...
bounds on $\text{BR}(\mu \to e\gamma)$, while future MEG limit excludes small $M_{1/2}$ space $\leq 3.5$ TeV. The allowed regions in fig 1b require very heavy spectra, i.e. $m_0 \geq 6$ TeV for small $M_{1/2}$ or $M_{1/2} \geq 2$ TeV for small $m_0$. In fig 1c, 1d we plot the lightest Higgs mass $m_h$ as a function of $m_0$, $M_{1/2}$ in the mSUGRA case. We see that for the range of Higgs mass as given by the data at LHC, i.e. $122.5$ GeV $\leq m_h \leq 129.5$ GeV, $m_0 \geq 1$ TeV is allowed by present MEG bounds on $\text{BR}(\mu \to e\gamma)$. The space $M_{1/2} \geq 1$ TeV is allowed as can be seen from fig 1d. In fig 1e we have presented results for the decay $\mu \to eee$. In SUSY (with conserved R-parity) the dominant contribution to this process arises from the same dipole operator responsible for $\mu \to e\gamma$. Such prediction is consistent with our results shown in fig 1e for $\tan\beta = 10$.

In SUSY with conserved R-Parity the two processes $\mu \to e\gamma$ and $\mu \to eee$ are correlated. This correlation is clearly seen in fig 1e as $\text{BR}(\mu \to e\gamma) \sim \alpha_{\text{em}} \text{BR}(\mu \to 3e)$. Here $\alpha_{\text{em}}$ is the electromagnetic dipole operator. Asymmetry in the value of $A_0$, can be seen in fig 1f.

**B. Non Universal Higgs Model (NUHM1)**

Next, we present our results obtained in NUHM1 case. In fig. 2a we have shown $M_{1/2}$ [GeV] Vs Log[BR($\mu \to e + \gamma$)] and the fig. 2b in the right panel shows $m_0$ [GeV] Vs $M_{1/2}$[GeV]. Different horizontal lines in fig. 2a correspond to present and future bounds on $\text{BR}(\mu \to e + \gamma)$. We can see from the figs. 2a and 2b that even in the presence of partial cancellations, most of the NUHM1 parameter space is going to be explored by present and future bound of MEG.

In figs. 2c and 2d, the SUSY parameter space $M_{1/2} - m_h$ and $m_0 - m_h$ is presented, as allowed by present MEG bounds. For Higgs mass around 126 GeV, almost all values of $M_{1/2}$ are allowed in the range (100 GeV– 2500 GeV). Similarly for $m_h$ around 126 GeV, region 3 TeV $\leq m_0 \leq 6$ TeV are mostly favoured. In $\delta_{i\neq j}^{LL}$ due to cancellations between $m_{H_u}^2$ and $m_{H_d}^2$ large region of soft parameter space is allowed which would be easily accessible at the next run of LHC satisfying the current cLFV constraints. Fig 2e shows $A_0$ [GeV] Vs $m_h$ [GeV]. $A_0$ is slightly more symmetric compared to mSUGRA.

**C. NON UNIVERSAL GAUGINO MASS MODELS (NUGM)**

From the studies in mSUGRA and NUHM model in above subsections, we see that the SUSY parameter space, as allowed by future MEG bounds on $\text{BR}(\mu \to e + \gamma)$ shifts to heavier side. And hence, we are motivated to do such studies in NUGM models. In this section we discuss the scenario with non universal and opposite sign gaugino masses at $M_{GUT}$, with the sfermion masses assumed to be universal. We perform random scans for ranges of the parameters given in eq. (14). We concentrate on the specific model 24 of [25] with the gaugino masses having the ratios $M_1 : M_2 : M_3 = -1/2 : -3/2 : 1$. In fact the non-universality of the gaugino masses is by no means a peculiar phenomenon, rather it is realized in various scenarios, including some approaches to grand unification [29]. Fig 3a reveals that light spectrum accessible at LHC can be explored by current and future bound of MEG Limit. The resulting preference for light sparticle masses renders detection of NUGM at the LHC operating at 14 TeV collision energy positive.
Figure 1: The results of our calculations are presented for mSUGRA case. In fig 1a, different horizontal lines represent the present (MEG 2013) and future MEG bounds for BR($\mu \rightarrow e + \gamma$). In figs (b-e) we have shown SUSY parameters space allowed by MEG 2013 bound.

From fig. 3a, we find that the branching ratio Log[BR($\mu \rightarrow e + \gamma$)] increases with increase in scalar masses (in contrast to mSUGRA and NUHM). This could be due to some strong cancellations occurring because of the particular ratios of gaugino masses in NUGM model.

In fig 3b, the SUSY parameter space $m_0 - M_3$ as allowed by MEG 2013 bound on BR($\mu \rightarrow e\gamma$) is presented. We
Figure 2: The results of our calculations are presented for NUHM case. In fig 2a, different horizontal lines represent the present (MEG 2013) and future MEG bounds for $\text{BR}(\mu \to e + \gamma)$. Figs. 2b-2e show the allowed space for different parameters, that is allowed by MEG 2013 bound.

find that $M_3 \geq 2$ TeV is allowed for almost the whole range of $m_0$; while for low $M_3 \leq 2$ TeV, smaller values of $m_0$ are favoured. The region below the curve line is excluded by SUSY.

In figs. 4a, 4c, 4e we present the constraints from $\text{BR}(\mu \to e + \gamma)$ on NUGM parameter space for $\tan \beta = 10$. As can be seen, large part of the parameter space survives for $\tan \beta = 10$ in NUGM, as compared to NUHM and mSUGRA. From fig. 4b we find that for Higgs mass $m_h$ around 125.9 GeV, the whole parameter space $m_0 \geq 1.5$ TeV is allowed. Squark masses $m_0 \geq 1.5$ TeV corresponding to 126 GeV Higgs are mostly favoured which would be
In Fig 3a we have shown the plot $m_0$ [GeV] Vs Log [BR($\mu \rightarrow e + \gamma$)]. Fig 3b represents parameter space of $m_0$ and $M_3$, for NUGM model. Different horizontal lines represent present and future bounds on BR($\mu \rightarrow e\gamma$).

accessible at next run of LHC (satisfying the current MEG limit $BR(\mu \rightarrow e + \gamma) \leq 5.7 \times 10^{-13}$). From fig. 4d, we see that for Higgs mass around 126 GeV $M_1$ lies between $-2.8 \text{ TeV} \leq M_1 \leq -1 \text{ TeV}$. The constraints imposed on the soft SUSY breaking parameters, in NUGM space, is found to be less severe compared to NUHM and mSUGRA. The plot of $A_0$[GeV] Vs $m_h$[GeV] is shown in fig. 4f. The patches in the plot are due to cancellation in the entries of the left handed slepton mass matrices $\delta^{LL}_{i\neq j}$ between the soft universal mass terms.

We find that in CMSSM/mSUGRA like models, the present experimental limit on $BR(\mu \rightarrow e\gamma)$ disfavors the soft SUSY breaking parameters $m_0 \leq 6 \text{ TeV}$ and $M_1/2 \leq 2$ TeV if the Dirac neutrino Yukawas are used from [24]. LFV constraint on SUSY spectrum is relaxed if NUHM model is considered and we find that interesting cancellation in the magnitude of charged LFVs arise if the universality condition is relaxed for the soft mass of up type Higgs $m^2_{H_u}$.

As a result of this, as compared to mSUGRA, relatively soft parameter space is allowed in NUHM, by $BR(\mu \rightarrow e\gamma)$ bounds. In mSUGRA if the seesaw scale is slightly lower than the GUT scale, mixings among the sleptons of different generation get induced at the seesaw scale through (i) renormalization group evolution (RGE) effects and (ii) lepton flavor violating Yukawa couplings. As a result, slepton mass matrices no longer remain diagonal at the seesaw scale.

At the weak scale, the off-diagonal entries in the slepton mass matrices generate large rate of LFV decays. These effects have been studied in the literature in all three variants of the seesaw mechanisms [4, 18-20].

In Tables III and IV we have summarised the comparison of our study with [4]. The new results in NUGM which we find in our work are the following:

1. Lighter $m_0$ is also allowed as compared to mSUGRA.
2. A wider SUSY parameter space is allowed.
3. $A_0$ range in this work is shown in the Table V.
4. $BR(\mu \rightarrow e\gamma)$ increases with increase of masses.
Figure 4: The results of our calculations are presented for NUGM case. In fig 4a,4c,4e different horizontal lines show the present (MEG 2013) and future MEG bounds for BR(µ → e + γ). Fig 4b,4d,4f shows the allowed space for different parameters, that is allowed by MEG 2013 bound.

V. CONCLUSION

To conclude, in this work we have studied the rare cLFV decay µ → eγ in µ – τ symmetric SUSY SO(10) theories, using type I see saw mechanism, in mSUGRA, NUHM and NUGM models. We have used the value of Higgs mass
as measured at LHC, latest global data on the reactor mixing angle $\theta_{13}$ for neutrinos, and latest constraints on $\text{BR}(\mu \to e\gamma)$ as projected by MEG [14]. We find that in mSUGRA very heavy $M_{1/2}$ region is allowed by future MEG bound of $\text{BR}(\mu \to e\gamma)$, though in NUHM case a low $M_{1/2}$ is also allowed. Hence we further studied the non universal gaugino mass model (NUGM). In mSUGRA, the $m_0$ values as allowed by MEG 2013 bound, shifts toward heavier spectrum, as compared to allowed $m_0$ of [4] (which was allowed by a less stringent bound of MEG 2011). As compared to mSUGRA, in NUHM, a wider parameter range is allowed. For Higgs mass central value 125.4 GeV, our analysis allows a slightly lower value of $m_0$ than [4], both in mSUGRA and NUHM (as can be seen from Tables III and IV). In NUGM, these calculations are presented for the first time here in this work. We find that NUGM allows in general, a wider parameter space, as compared to both mSUGRA and NUHM. Here $\text{BR}(\mu \to e\gamma)$ is found to increase with increase in $m_0$ which could be due to particular ratios of gaugino masses. In NUGM, we find that allowed values of $|A_0|$ are shifted towards heavier side (compared to mSUGRA and NUHM). Hence any observation of heavy particles at next run of LHC, could help us understand to discriminate among these models, in reference to constraints put by cLFV decays. This in turn could contribute towards a better understanding of theories beyond standard model (BSM).

| Table III: Masses in this table are comparison between [4] and this work for mSUGRA. |
|---------------------------------------------------------------|
| **Range of parameters allowed by** | **Range of parameters allowed by** |
| $\text{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ | $\text{BR}(\mu \to e\gamma) < 2.4 \times 10^{-12}$ |
| [MEG 2013](From this work) | [MEG 2012](L. Cabbibibi et al [4]) |
| 1. Fig 1a: | 1. For MEG 2011, $M_{1/2} \geq 0.5$ TeV |
| $M_{1/2} \geq 1$ TeV by MEG 2013, and very heavy $M_{1/2} \geq 3.5$ TeV | $M_{1/2} \geq 1.5$ TeV for $\text{BR}(\mu \to e\gamma) < 10^{-13}$ |
| by future MEG bound [14] | |
| 2. Fig 1b (MEG 2013): | 2. For MEG 2011 |
| $m_0 \geq 6$ TeV for small $M_{1/2}$ | $m_0 \geq 4$ TeV for small $M_{1/2}$ |
| $M_{1/2} \geq 2$ TeV for small $m_0$ | $M_{1/2} \geq 2$ TeV for small $m_0$ |
| ($M_0$ shifts to slightly heavier side) | |
| 3. Fig 1c | 3. $m_0 \geq 4$ TeV for $m_h = 125.9$ GeV |
| $m_0 \geq 3$ TeV for $m_h = 125.9$ GeV | |
| 4. Fig 1f | 4. $-11$ TeV $< A_0 < -6$ TeV |
| $-12$ TeV $< A_0 < -6$ TeV for $m_h = 125.9$ GeV | for $m_h = 125.9$ GeV |

Table III: Masses in this table are comparison between [4] and this work for mSUGRA.
Range of parameters allowed by BR($\mu \rightarrow e\gamma$) $< 5.7 \times 10^{-13}$

[MEG 2013](From this work)

1. Fig 2a:
   Almost whole $M_{1/2}$ space allowed

2. Fig 2b: (MEG 2013)
   $m_0 \geq 1.5$ TeV for $M_{1/2} \geq 500$ GeV
   (wider space is allowed in this work)

3. Fig 2d:
   $m_0 \geq 2.3$ TeV for
   $m_h = 125.9$ GeV

4. Fig 2e:
   $-13 \text{ TeV} < A_0 < -7 \text{ TeV}$
   for $m_h = 125.9$ GeV

Range of parameters allowed by BR($\mu \rightarrow e\gamma$) $< 2.4 \times 10^{-12}$

[MEG 2012](L. Cabbibibi et al [4])

1. Only $M_{1/2} \geq 0.5$ TeV

2. $m_0 \geq 3$ TeV for small $M_{1/2}$
   $M_{1/2} \geq 1$ TeV for small $m_0$

   by MEG 2011

3. $m_0 \geq 3.2$ TeV for
   $m_h = 125.9$ GeV

4. Almost same as in ours

| $A_0$ (mSUGRA) | $A_0$ (NUHM) | $A_0$ (NUGM) |
|----------------|--------------|--------------|
| TeV            | TeV          | TeV          |
| $-12 < A_0 < -6$ | $-13 < A_0 < -7$ | $-15 < A_0 < -10$ |

**Table IV**: Comparison between [4] and this work for NUHM

**Table V**: Comparison of $A_0$ between mSUGRA, NUHM and NUGM (this work)

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