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Lepton flavour violation at a future linear collider

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Summary. — We study the relation of the possible observation on the radiative decays $\mu \to e\gamma$ and $\tau \to \mu\gamma$ and LFV processes that could be detectable at a linear collider (LC) with a centre-of-mass energy in the TeV range. We use supersymmetric parameters consistent with cosmological considerations and with LHC searches for supersymmetry and the Higgs mass while we link the charged lepton flavor problem to the neutrino predictions in a $SU(5)$ GUT model, enhanced by an abelian flavour symmetry,

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PACS 11.30.Hv – Flavor symmetries.
PACS 14.80.Ly – Supersymmetric partners of known particles.

1. – Introduction

The link between neutrino oscillations and the violations of leptonic flavour (LFV) offers the possibility of observing processes such as $l_i \to l_j\gamma$ $(i \neq j)$ [1]. The present experimental upper limits constrain significantly the parameter space of theoretical models,

$$BR(\mu \to e\gamma) < 5.7 \times 10^{-12}, \tag{1}$$

$$BR(\tau \to \mu\gamma) < 4.4 \times 10^{-8}, \tag{2}$$

$$BR(\tau \to e\gamma) < 3.3 \times 10^{-8}. \tag{3}$$

In supersymmetric models, LFV can be observed in decays of the SUSY partners of the charged leptons. Examples are rare lepton decays [1-5] and slepton production at a LC [6-9].

The purpose of our study is to link the structure of model satisfying neutrino observation with prospects for detection of flavour violating slepton decays. We use constrained

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minimal supersymmetric standard model (CMSSM) framework supplemented with a see-saw mechanism to explain tiny neutrino masses. The structure of the Yukawa matrices is inspired by $SU(5)$ GUT models with Abelian flavour symmetries [10, 11].

In fist part of this presentation we introduce the model we used and discuss its predictions for neutrino observables, LFV in radiative decays and leptogenesis. The next two sections are dedicated to study LFV in slepton decays in colliders before finishing with the conclusions. Further details and a complete list of references are given in ref. [12].

2. – Predictions for neutrino observables

We choose a model inspired by a $SU(5)$ GUT combined with family symmetries [10, 11]. The $SU(5)$ structure of the model implies that the charged-lepton mass matrix is the transpose of the down-quark mass matrix, which relates the mixing of the left-handed leptons to that of the right-handed down-type quarks. The latest property implies that a large mixing can take place in the lepton sector while having a small mixing in the down quark sector, as suggested by a natural explanation of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Also the struture of the Yukawa coupling may influence the $b-\tau$ unification condition [13].

In ref. [12] we performed a large search for fits of of the model such that the ranges for the mixing angles satisfy the bounds of ref. [14] assuming a neutrino mass hierarchy with a mass splitting of the order of the neutrino masses and $m_{\nu_3} \sim 0.05\,\text{eV}$. The fit of the Yukawa textures selected for further analysis corresponds to

$$Y_\ell \propto \begin{pmatrix} \varepsilon^4 & 2\varepsilon^3 & -1.75\varepsilon \\ -0.5\varepsilon^3 & 1.9\varepsilon^2 & 0.5 \\ -0.5\varepsilon^3 & -0.7\varepsilon^2 & 1.25 \end{pmatrix}, \tag{4}$$

$$Y_\nu \propto \begin{pmatrix} \varepsilon^{|1\pm n_1|} & \varepsilon^{|1\pm n_2|} & 2\varepsilon^{|1\pm n_3|} \\ 0.75\varepsilon^{|n_1|} & \varepsilon^{|n_2|} & -0.5\varepsilon^{|n_3|} \\ \varepsilon^{|n_1|} & \varepsilon^{|n_2|} & 1.25\varepsilon^{|n_3|} \end{pmatrix},$$

$$M_N \propto \begin{pmatrix} \varepsilon^{2|n_1|} & \varepsilon^{|n_1+n_2|} & -\varepsilon^{|n_1+n_3|} \\ \varepsilon^{|n_1+n_2|} & \varepsilon^{2|n_2|} & \varepsilon^{|n_2+n_3|} \\ -\varepsilon^{|n_1+n_3|} & \varepsilon^{|n_2+n_3|} & -\varepsilon^{2|n_3|} \end{pmatrix}.$$

The light neutrinos mass matrix is, thanks to the see-saw mechanism,

$$m_{eff} \approx m_\nu^D \frac{1}{M_N} {m_\nu^D}^T. \tag{5}$$

Note that $Y_\ell Y_\ell^\dagger \sim m_{eff}$ at the lowest order, thus, given the following diagonalizations of the Dirac and Majorana mass matrices,

$$V_\ell^T (Y_\ell Y_\ell^\dagger) V_\ell^* = \text{diag}(y_e^2, y_\mu^2, y_\tau^2), \tag{6}$$

$$V_D^T (Y_\nu Y_\nu^\dagger) V_D^* = \text{diag}(y_{\nu_1}^2, y_{\nu_1}^2, y_{\nu_3}^2), \tag{7}$$

$$U_N^T M_N U_N = \text{diag}(M_1, M_2, M_3), \tag{8}$$

$$U_\nu^T m_{eff} U_\nu = \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}), \tag{9}$$

V_ℓ and U_ν diagonalize matrices with a similar structure. The Maki-Nakagawa-Sakata (MNS) matrix is given by

$$U_{MNS} \equiv U = V_\ell^\dagger U_\nu, \tag{10}$$

The predictions for the neutrino angels are, $\sin^2\theta_{13} = 0.019$, $\sin^2\theta_{12} = 0.28$, $\sin^2\theta_{23} = 0.40$. We observe no correlation between LFV and particular arrangements of neutrino parameters. However, LFV is maximized by large out-diagonal elements on V_ℓ and by the choice of charges n_i. Neutrino fits are independent of these charges because despite they affect Y_ν and M_N but not their combination in m_{eff}.

3. – SUSY and charged LFV

We need now to evaluate the SUSY spectrum and couplings using the CMSSM as general framework. The recent LHC measurement of the Higgs mass [15, 16] seems to point towards large SUSY masses in these scenarios. We use the global analysis of the CMSSM parameter space of ref. [17] and select two good fits to the available data ([1]):

$$\begin{aligned} &(a)\quad \tan\beta = 16, \quad m_0 = 300\,\text{GeV}, \quad M_{1/2} = 910\,\text{GeV}, \quad A_0 = 1320\,\text{GeV},\\ &(b)\quad \tan\beta = 45, \quad m_0 = 1070\,\text{GeV}, \quad M_{1/2} = 1890\,\text{GeV}, \quad A_0 = 1020\,\text{GeV}. \end{aligned} \tag{11}$$

Point (a) belongs to the region where the WMAP-favoured range of $\Omega_\chi h^2$ is achieved via $\chi - \tilde{\tau}$ coannihilation. Point (b) lies in the funnel region where the neutralino LSP annihilates rapidly via direct-channel H/A poles.

Even if we start with universal soft-terms at M_{GUT}, at the intermediate scale where the see-saw takes place, M_3 (taken as the mass of the heaviest Majorana neutrino), the slepton mass matrices and Y_ℓ cannot be diagonalized with a single superfield rotation. Thus, the interactions lepton-slepton-gaugino can mix flavours. To understand this mismatch of the leptons and sleptons rotations we can consider the soft masses evolution from M_{GUT} to M_3 in a basis such that Y_ν is diagonal, at M_3 the right handed neutrinos decouple and the REG can be rewritten in terms of Y_ℓ diagonal. In this basis the soft terms involving left slepton are not diagonal and can be written in terms of the matrix $V_{LFV} = V_D^\dagger V_\ell$:

$$m_{LL}^2 = V_{LFV}^\dagger (m_{LL}^2)_\text{d} V_{LFV} \tag{12}$$

while the A-terms become:

$$A_\ell = V_{LFV}^T (A_\ell)_\text{d}. \tag{13}$$

Here $(m_{LL}^2)_\text{d}$ and $(A_\ell)_\text{d}$ are the soft terms resulting from the RGE running of the universal soft terms at the GUT scale to M_3 with the fields written in a basis such that Y_ν is diagonal. The choice of right handed neutrino charges affects the matrix V_{LFV} and therefore the LFV predictions. Other potential sources of flavour violating entries in the soft terms are considered in ref. [18].

([1]) Note that our A_0 values have opposite sign with respect to those of ref. [17] where the authors use a definition for the trilinear scalar coupling that differs from the one in standard codes like Suspect and SoftSusy.

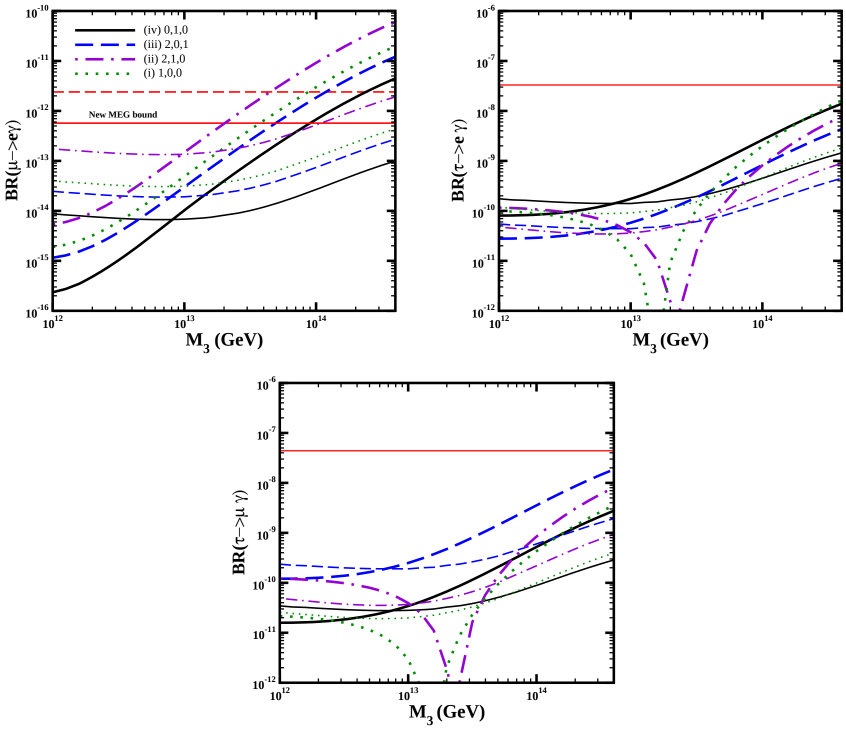

Fig. 1. – Predictions for the rare LFV decays $\ell_i \to \ell_j \gamma$ as a function of the right-handed neutrino mass M_N, for the benchmark points displayed in (11) (a) (thick line), (b) (thin line), using the neutrino mixing fits with several choices right-handed neutrino charges. The horizontal solid lines indicate the current experimental upper bounds, while the dashed line correspond to the previous MEG limit on $BR(\mu \to e\gamma)$.

In fig. 1 we show numerical predictions for the LFV branching ratios. We can see the effect of varying M_N from 6×10^{14} GeV down to 10^{12} GeV for several choices of right-handed neutrino charges. The branching ratios are larger for the lower-mass scenario with $\tan\beta = 16$, due to the lighter spectrum. The new MEG bound on $BR(\tau \to \mu\gamma)$ imposes constraints on the "see-saw" scale for all for all the charge choices of n_i's charges at point (a) while the predictions of point (b) are in the range of the experimental searches.

4. – LFV and leptogenesis

Since LFV is related to the see-saw parameters in our framework, there can be interesting consequences for LFV in charged lepton decays and elsewhere [19]. We have used real parameters to fit the Yukawa couplings, but small phases that would not alter our LFV considerations could induce significant contributions to the lepton and baryon asymmetries of the universe.

We can explore what sizes of the phases in Y_ν can predict a value for the baryon asymmetry Y_B compatible with the observation [20]

$$Y_B = (6.16 \pm 0.16) \times 10^{-10}. \tag{14}$$

TABLE I. – *Baryon asymmetry predictions based on four representative fits. Here,* Y_B^{max} *is the value obtained using eq.* (17)*, and* Y_B^* *is the prediction for* Y_B *computing* ϵ_1 *with its full expression and inserting a phase of* 0.1 rad *in the* (12) *element of* Y_ν*. In each row the upper value corresponds to* $M_3 = 5 \cdot 10^{13}$ GeV *and the lower to* $M_3 = 10^{12}$ GeV.

	(i)	(ii)	(iii)	(iv)
M_1 (GeV)	$4.3 \cdot 10^{12}$ $8.6 \cdot 10^{10}$	$2.6 \cdot 10^{11}$ $5.3 \cdot 10^{9}$	$5.4 \cdot 10^{11}$ $1.1 \cdot 10^{10}$	$2.3 \cdot 10^{12}$ $4.7 \cdot 10^{10}$
$\tilde{m}_1$ (eV)	0.19 0.11	0.78 0.48	5.17 3.18	1.19 0.7
Y_B^{max}	$1.0 \cdot 10^{-8}$ $3.6 \cdot 10^{-10}$	$1.2 \cdot 10^{-10}$ $4.3 \cdot 10^{-12}$	$2.8 \cdot 10^{-11}$ $9.7 \cdot 10^{-13}$	$6.6 \cdot 10^{-10}$ $2.3 \cdot 10^{-11}$
Y_B^*	$1.3 \cdot 10^{-10}$ $2.8 \cdot 10^{-12}$	$3.5 \cdot 10^{-11}$ $7 \cdot 10^{-13}$	$1.2 \cdot 10^{-12}$ $2.6 \cdot 10^{-14}$	$3.2 \cdot 10^{-12}$ $6.9 \cdot 10^{-14}$

For hierarchical heavy neutrinos in a supersymmetric see-saw model, one has [21],

$$Y_B \simeq -10^{-2} \kappa \epsilon_1, \tag{15}$$

where ϵ_1 is the CP-violating asymmetry in the decay of the lightest Majorana neutrino and κ an efficiency factor parametrizing the level of washout of the generated asymmetry by inverse decay and scattering interactions. ϵ_1 depends on the mass of the decaying neutrino M_1 and the effective mass parameter

$$\tilde{m}_1 = \frac{v_u^2}{M_1} (\lambda_\nu^\dagger \lambda_\nu)_{11}, \tag{16}$$

where λ_ν is the Dirac neutrino Yukawa matrix in the basis where the Majorana masses are diagonal, and v_u is the vev of the Higgs field that couples to up-quarks and neutrinos.

The value of the CP asymmetry depends on the details of the model, but a model-independent upper bound exists, given by [22]

$$|\epsilon_1| \leq \frac{3}{8\pi} \frac{M_1}{v_u^2} (m_3 - m_1), \tag{17}$$

where the m_i are the masses of the light neutrinos.

Some typical results are presented in table I, where fits (i)-(iv) correspond to the choices of charges given in fig. 1. We see that fit (i) can accommodate comfortably the observed baryon asymmetry Y_B with phases of $\mathcal{O}(0.1)$ rad, which would not change the LFV predictions. The remaining three models, if the phases are small, would under-produce Y_B. Therefore, overproduction of baryons is not a problem in the scenarios presented here.

5. – LFV in χ_2 decays at the LHC

A promising channel to search for LFV at the LHC is the production and decay of the second lightest neutralino, $\chi_2 \to \chi + \tau^\pm \mu^\mp$. In [23-25] it was shown that in order to

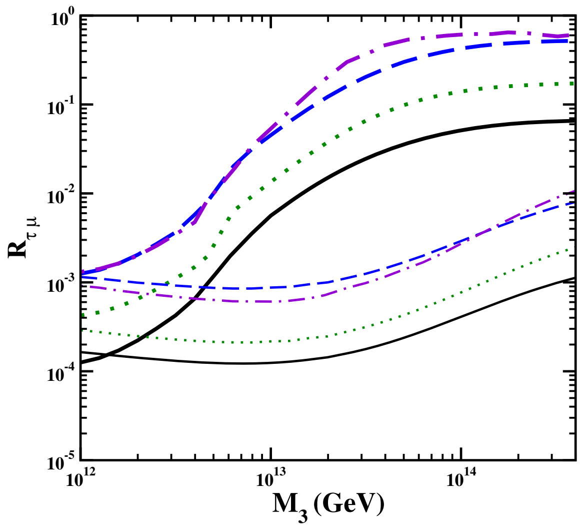

Fig. 2. – The ratio defined in eq. (18) is presented for the CMSSM points (a) (thick line) and (b) (thin line) (in eq. (11)), with the same notation as in fig. 1.

have a signal that could be distinguished from the background, the ratio

$$R_{\tau\mu} = \Gamma(\chi_2 \to \chi + \tau^\pm + \mu^\mp)/\Gamma(\chi_2 \to \chi + \tau^\pm + \tau^\mp) \tag{18}$$

should be of the order of 10%. For $A_0 = 0$, due to the absence of cancellations suppressing rare charged lepton decays, one had to go beyond the CMSSM to find solutions compatible with all experimental and cosmological data [25]. Here, we extend this study to large values of A_0, noting that the cancellations that can arise in the branching ratios of radiative decays do not occur in $R_{\tau\mu}$.

In fig. 2 we present the predictions for the branching ratio (18) as a function of M_3. For point (a), our predictions are within the reach of the LHC for values of M_3 that are compatible with the MEG limit. For point (b), the predictions are below the expected experimental sensitivity.

6. – LFV at a linear collider

If the flavour mixing is introduced in the left-left slepton sector, as is the case for the models under consideration here, the dominant channels are slepton-pair production and LFV decays, such as

$$\begin{aligned} e^+e^- &\to \tilde{\ell}_i^- \tilde{\ell}_j^+ \to \tau^\pm \mu^\mp \tilde{\chi}_1^0 \tilde{\chi}_1^0, \\ e^+e^- &\to \tilde{\nu}_i \tilde{\nu}_j^c \to \tau^\pm \mu^\mp \tilde{\chi}_1^+ \tilde{\chi}_1^-. \end{aligned} \tag{19}$$

In the CMSSM benchmark points introduced above, the channel mediated by charged sleptons clearly dominates over the sneutrino-pair production process, and may lead to a cross section of the order of 1 fb; this is the reference value of [6], for a LFV signal of

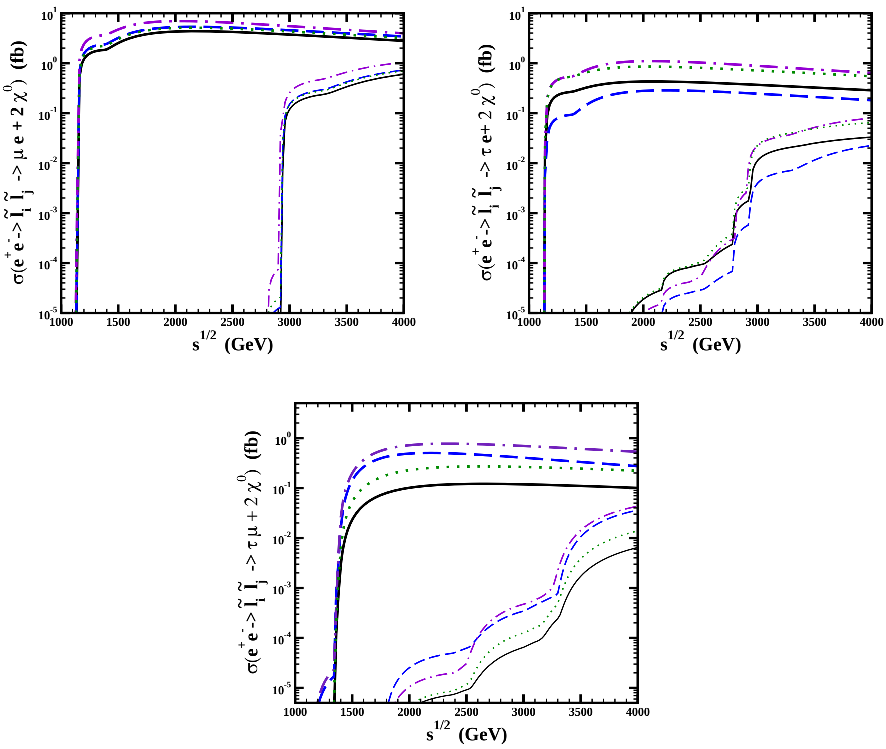

Fig. 3. – Values of the cross sections $\sigma(e^+e^- \to \tilde{\ell}_i^- \tilde{\ell}_j^+ \to \ell_a^\pm \ell_b^\mp + 2\chi^0)$ ($\ell_a \neq \ell_b$ as indicated in each panel) as functions of $\sqrt{s}$. The line styles are the same as those in fig. 1. For point (a) we use $M_3 = 2 \times 10^{13}$ GeV, while for the point (b) we work with $M_3 = 10^{14}$ GeV.

$\mu^\pm\tau^\pm$ pairs that can be distinguished from the background. Complete expressions for the LFV cross sections are given in ref. [7] and used in our work.

In fig. 3 we present the expected cross sections $\sigma(e^+e^- \to \tilde{\ell}_i^- \tilde{\ell}_j^+ \to \ell_a^\pm \ell_b^\mp + 2\chi^0)$ as a function of $\sqrt{s}$ for the same choice of parameters as in figs. 1 and 2.

The cross sections in the case of point (a) are larger because sleptons and gauginos are much lighter than in the spectrum of point (b). In the case of point (b), the heavy spectrum implies a threshold around 3 TeV and cross sections below 10^{-1} fb.

According to fig. 1, at the selected value of $M_3 = 2 \times 10^{13}$ GeV, $BR(\tau \to \mu\gamma)$ and $BR(\tau \to e\gamma)$ are suppressed. Since these cancellations do not occur for the LFV LC signals, it is possible to observe slepton flavor oscillations at the LC, in cases where LFV would be undetectable in rare charged lepton decays (as it could also happen at the LHC). It is worth to remark that the CLIC project for a linear collider has as nominal centre-of-mass energies the values 1.4 TeV and 3 TeV [26,27], with the option of reaching 5 TeV. The value $\sqrt{s} = 1.4$ TeV is optimal for point (a) where the LFV cross sections are nearly maximal.

7. – Conclusions

In our presentation, we revisited the signatures of charged LFV in theoretically-motivated scenarios, studying the correlations arising in CMSSM models with parameter values that are favoured by the LHC and cosmological considerations. We have explored these issues using updated experimental input from neutrino data, particularly recent measurements of θ_{13}, MEG and the LHC.

In the cases we studied, it was possible to establish correlations between the expected rates for radiative LFV decays, the LFV decay of the second lightest neutralino χ_2 at the LHC and LFV in slepton decay at a future LC, for different possibilities for the structure of the heavy Majorana neutrino masses. The absence of a supersymmetry signal at the LHC data and the discovery of a neutral Higgs weighing $\sim 125\,\text{GeV}$ imply that observation of slepton flavour violation at the LHC would be difficult but possible, for points with a lighter spectrum. Observation of LFV at the LC is also possible for the centre of mass energies above 1 TeV that are compatible with the nominal energies of CLIC.

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