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τ-flavour violation at the LHC

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Summary. — We study the conditions required for $\chi_2 \to \chi + \tau^\pm \mu^\mp$ decays to yield observable tau flavour violation at the LHC, for cosmologically interesting values of the neutralino relic density. These conditions can be achieved in the framework of a $SU(5)$ model with a seesaw mechanism that allows a possible coexistence of a LHC signal with a low prediction for radiative LFV decays.

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

1. – Introduction

Data from both atmospheric [1] and solar [2] neutrinos have by now confirmed the existence of neutrino oscillations with near-maximal $\nu_\mu - \nu_\tau$ mixing (Super-Kamiokande) and large $\nu_e \to \nu_\mu$ one (SNO). These observations would also imply violation of the corresponding charged-lepton numbers, which in supersymmetric theories might be significant and observable in low-energy experiments. Many signatures for charged-lepton-flavour violation have been considered [3, 4], including $\mu \to e\gamma$ decays and conversions, $\tau \to \mu\gamma$ and $\tau \to e\gamma$ decays. Other possibilities that have been considered are the decays $\chi_2 \to \chi + e^\pm \mu^\mp$ [5], and $\chi_2 \to \chi + \mu^\pm \tau^\mp$ [6, 7], where χ is the lightest neutralino, assumed here to be the lightest supersymmetric particle (LSP), and χ_2 is the second-lightest neutralino. We present the results from [8] where we found that a signal for τ flavour-violating χ_2 decays may be observable if the branching ratio exceeds about 10%. We consider the cosmologically preferred parameter space (as dictated by WMAP) of $b - \tau$ Yukawa-unified models with massive neutrinos [9, 10]. We find that, assuming general structures for the soft terms arising from a horizontal Abelian symmetry, $SU(5)$ RGEs efficiently suppress off-diagonal terms in the scalar soft matrices [11] as compared to the conventional case where the soft terms are postulated at the GUT scale, hence rendering the model compatible with current experimental bounds.

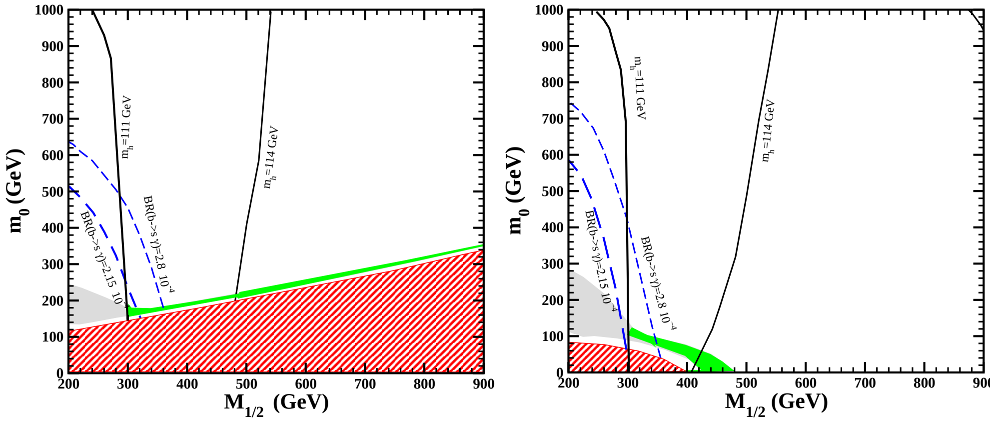

Fig. 1. – (Colour on-line) Cosmologically-favored areas (green) in the $(M_{1/2}, m_0)$-plane for $\tan\beta = 35$ and $A_0 = m_0$, assuming $SU(5)$ unification. In the left panel we assume universality at $M_X = M_{\rm GUT}$, whereas in the right panel we assume universality at $M_X = 2\times 10^{17}$ GeV. The red areas are excluded because $m_\chi > m_{\tilde\tau}$. We also display the contours for $m_h = 111$, 114 GeV (black solid and thin solid) and $BR(b\to s\gamma)\cdot 10^4 < 2.15$, 2.85 (blue dashed and thin dashed).

2. – Study of SUSY spectrum and parameter space

We pay particular attention to regions leading to large values of $\Gamma(\chi_2 \to \chi + \tau^\pm + \mu^\mp)$ via the on-shell slepton production mechanism:

$$BR(\chi_2 \to \chi\tau^\pm\mu^\mp) = \sum_{i=1}^{3}\Big[BR(\chi_2\to\tilde l_i\mu)BR(\tilde l_i\to\tau\chi) + BR(\chi_2\to\tilde l_i\tau)BR(\tilde l_i\to\mu\chi)\Big], \quad (1)$$

while satisfying all phenomenological and cosmological (relic density) constraints. The characteristic parameter region for the signal in the τ channel to be optimal is defined by the following: i) $m_{\chi_2} > m_{\tilde\tau} > m_\chi$; ii) one of the mass differences in i) is $> m_\tau$ and the other $> m_\mu$, $m_{\tilde\tau} > m_\chi$, so that the μ, τ and $\tilde\tau$ are all on-shell; iii) moderate values of m_χ (phase space and luminosity considerations).

Figure 1 is used to select points satisfying all phenomenological constraints for the event analysis of the next section. In particular, for $SU(5)$ unification and assuming universal soft terms at $M_X = 2\times 10^{17}$ GeV, $\tan\beta = 35$ is the smallest value of $\tan\beta$ such that the WMAP area in the plane $M_{1/2} - m_0$ is not excluded by the m_h bound [10, 9].

In table I we display parameters of the two reference points A and B. Point A is the CMSSM model used in [6]. Point B is a model with universality assumed at a scale $2\cdot 10^{17}$ GeV; for comparison with this point, we also present point C, a set of CMSSM parameters that leads to a similar sparticle spectrum and satisfies all the cosmological and phenomenological bounds. In all cases, we work with $\mu > 0$.

TABLE I.

Point	*Model type*	m_0	$M_{1/2}$	$\tan\beta$	A_0	$N_{\rm events}$	$\sigma_{\rm int}$	$L_{\rm int}$
A	CMSSM	100	300	10	300	757 K	25.3 pb	30 fb^{-1}
B	$SU(5)$	40	450	35	40	730 K	2.44 pb	300 fb^{-1}
C	CMSSM	220	500	35	220	536 K	1.79 pb	300 fb^{-1}

3. – SUSY lepton flavour violation

The flavour mixing entries are defined as

$$\delta^{ij}_{XX} = (M^2_{XX})^{ij}/(M^2_{XX})^{ii} \quad (X = L, R). \tag{2}$$

We take into account only 2–3 generation flavor mixing.

In order to have significant LFV signals, we need $\Gamma(\chi_2 \to \chi + \tau^\pm + \mu^\mp)/\Gamma(\chi_2 \to \chi + \tau^\pm + \tau^\mp) \sim 0.1$. Values of δ_{LL} leading to these ratios would imply a significant violation of the $\tau \to \mu\gamma$ bound. In fig. 2 we present the dependence of these decays on the flavour mixing parameters δ_{RR} and δ_{LL} for point B. We see that in this case we need large non-diagonal entries in the slepton mass matrix in order to achieve a branching ratio for $\tilde\chi_2 \to \tilde\chi_1 \tau^\pm\mu^\mp$ that is of interest for the LHC, *e.g.*, $\delta_{RR} \sim 0.15$ for $\delta_{LL} = 0$ or $\delta_{LL} \sim 0.35$ for $\delta_{RR} = 0$. We also see that $\tau \to \mu\gamma$ is very restrictive on the size of δ_{LL}, imposing a maximum value ~ 0.03. We see in the bottom-right panel that $\delta_{RR} \sim 0.15$ is allowed for $\delta_{LL} = 0$. Due to the strong bound imposed by $\tau \to \mu\gamma$, it is very difficult to obtain reasonable values of δ using only the LL and/or RL mixing found in seesaw models. However, significant FV entries on the RR sector can be generated only by using non-minimal models for the soft terms.

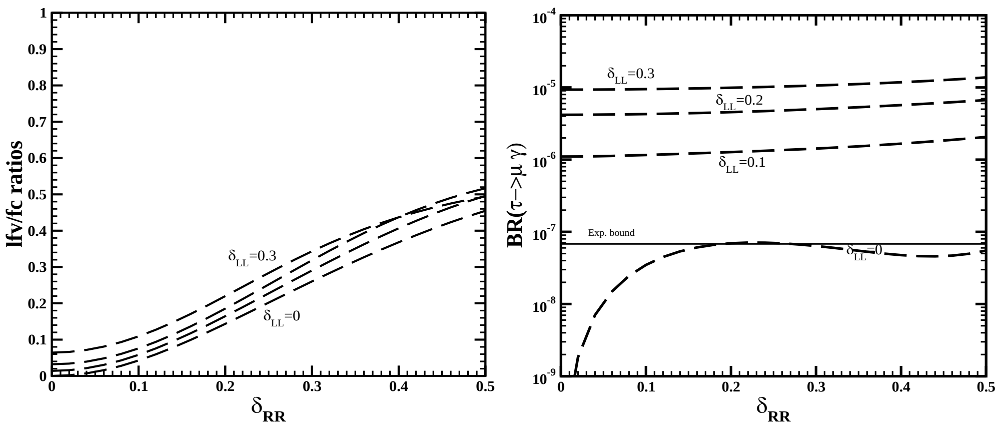

Fig. 2. – Branching ratios for point B as functions of δ_{RR} for certain discrete choices of δ_{LL}.

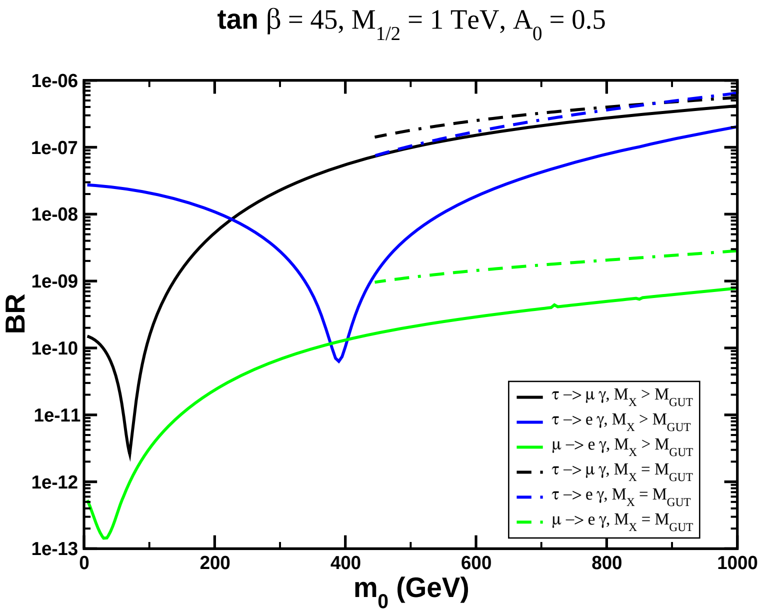

Fig. 3. – Prediction for the charged-lepton flavour violating branching ratios showing the difference of taking either M_X or $M_{\rm GUT}$ as the high scale.

4. – $SU(5)$ unification and GUT soft masses

The introduction of non-trivial flavour structures for the slepton soft terms at $M_{\rm GUT}$, although being reasonable as an implication of the family symmetry responsible for the Yukawa texture, typically results on a large violation of the bounds on $l_j \to l_i\gamma$ [12, 13]. This picture may be remedied if we assume that SUSY is broken with universal soft terms at a scale $M_X > M_{\rm GUT}$. In this case, the cosmological requirement of having a neutral particle as the LSP imposes low values on m_0, such that $m_{\tilde\tau} > m_\chi$ [9, 10], since diagonal terms of the soft masses have a large RGE growth, while non-diagonal elements remain almost unaffected by the runs. Thus, even assuming non-diagonal soft terms with matrix elements of the same order of magnitude at M_X, the corresponding matrix at $M_{\rm GUT}$ exhibits dominant diagonal elements. To some extent, the RGE effect is similar to the action of closing an umbrella: the general non- universal soft terms at M_X resemble an open umbrella that approaches a diagonal matrix at the GUT scale.

In fig. 3, we show the differences respect considering: i) $SU(5)$ RGE evolution of the soft terms from the high scale M_X down to $M_{\rm GUT}$ and then the MSSM with seesaw neutrinos (solid lines), ii) Soft SUSY breaking terms given at $M_{\rm GUT}$ and then the MSSM with seesaw neutrinos (dashed lines). In case ii) we stop the lines at the value of m_0 below which $m_{\tilde\tau}$ becomes the LSP. In contrast, m_0 can even vanish at M_X in case i). We used the same textures and soft terms as in ref. [13]. However, unlike these authors, we decouple the right-handed neutrinos below $M_{\rm GUT}$. As a result, the predicted BR's do not vanish in the limit $m_0 = 0$.

We can provide one explicit example of the growth of the diagonal terms of the slepton mass matrix in models with interesting predictions for both LFV and $\Omega_\chi h^2$. Let us consider the $0 < m_0 < 100$ GeV region. In the area of the parameter space where

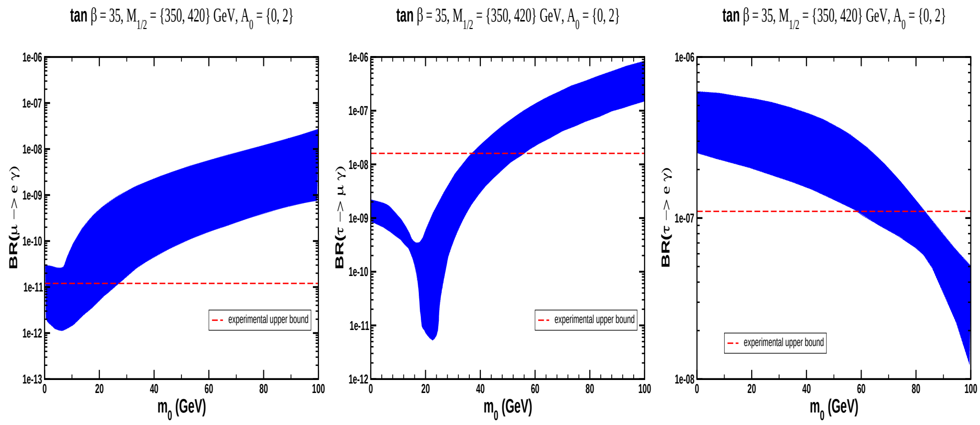

Fig. 4. – Prediction for the $l_j \to l_i \gamma$ branching ratios for the cosmologically preferred area of values of $M_{1/2}$, A_0, for choice of $U(1)_F$ charges in ref. [11] leading to the matrices of eq. (5).

WMAP bounds are satisfied due to $\tau - \chi$ coannihilations, we find that $m_{1/2}$ obeys a linear function of m_0, $m_{1/2} \sim a_1^i + a_2^i m_0$, where i runs over the multiplets. It turns out that, taking into account that the radiative corrections to the off-diagonal entries of the soft mass matrices are subdominant as compared with those of the diagonal ones, these diagonal elements can be expressed as follows:

$$m_{S_i}^2 \simeq C_i^2(m_0) m_0^2, \tag{3}$$

where we have defined

$$C_i^2(m_0) \equiv \frac{144}{20\pi}\alpha_5 \left(\left(\frac{a_1^i}{m_0} \right)^2 + \frac{2a_1^i a_2^i}{m_0} + a_2^2 \right) \ln \left(\frac{M_X}{M_{\rm GUT}} \right) \tag{4}$$

and S_i stands for the supermultiplets $\mathbf{10}$ and $\bar{\mathbf{5}}$. As stated, eq. (3) implies a large enhancement only of the diagonal entries of the soft matrices, thus further suppressing the off-diagonal elements. It turns out indeed that for values of $m_0 \simeq 60$–$80\,\mathrm{GeV}$ at M_X such an enhancement at the GUT scale is as large as $\simeq 100$. As a consequence, the soft mass matrices $\bar{m}_{10}^2$ and $\bar{m}_5^2$ at GUT scale read as

$$\bar{m}_{10}^2 = \begin{pmatrix} 1 & \varepsilon^3 & \varepsilon^5 \\ \varepsilon^3 & 1 & \varepsilon^4 \\ \varepsilon^5 & \varepsilon^4 & 1 \end{pmatrix} C^2(m_0) m_0^2, \qquad \bar{m}_5^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & \varepsilon^3 \\ 0 & \varepsilon^3 & 1 \end{pmatrix} C^2(m_0) m_0^2 \tag{5}$$

which clearly exhibit the suppression on the off-diagonal terms (compare with textures). The corresponding predictions for LFV radiative decays at $\tan\beta = 35$ are displayed in fig. 4.

5. – SUSY-LFV events at the LHC

The spectra for points of table I were calculated using `ISAJET 7.78` [14] and then interfaced into `PYTHIA 6.418` [15]. The SUSY-LFV decays described in the previous

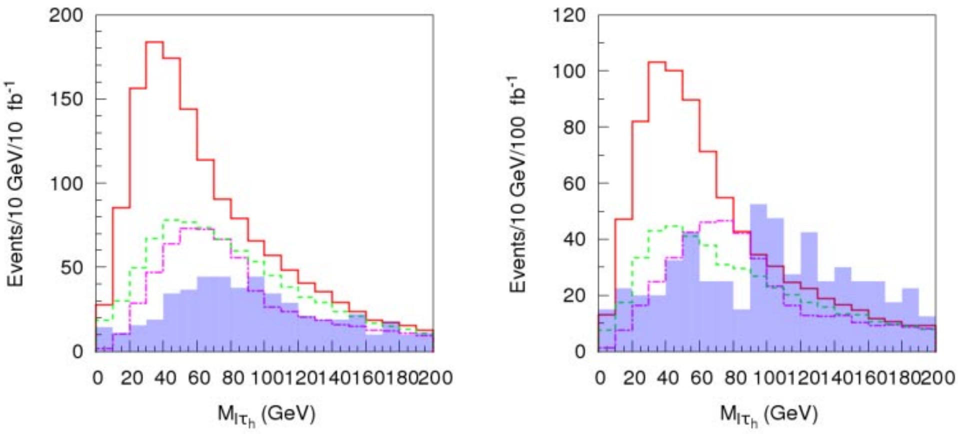

Fig. 5. – (Colour on-line) Visible $l\tau_h$ mass distributions with OS (red solid lines), SS (green dashed lines), and OS Standard Model backgrounds (shaded). The LFV OS $\mu\tau_h$ pairs are also shown (pink-dot-dashed). Left plot is for case A and right plot for case B.

sections give a $\mu^\pm\tau^\mp$ pair and produce an asymmetry between $\mu^\pm\tau^\mp$ and $e^\pm\tau^\mp$ final states that would not be observable in the case of charged lepton number conservation. In fig. 5, an excess of OS $l^\mp\tau_h^\pm$ pairs over the SS pairs can be seen. The left (right) plot corresponds to point A (B) and shows the numbers of events normalized to a reference luminosity of $10\,\text{fb}^{-1}$ ($100\,\text{fb}^{-1}$). The observable numbers, $N_{\mu\tau_h}^{\text{LFV}}$, of $\mu^\mp\tau_h^\pm$ LFV pairs are obtained by summing the counts in the subtracted $\mu^\mp\tau_h^\pm - e^\mp\tau_h^\pm$ distributions in the interval of $M_{l\tau}$ masses between 30 and 110 GeV. We obtain

$$\begin{aligned} &\text{Point A}: \ N_{\mu\tau_h}^{\text{LFV}} = 470 \pm 39 \ (12\ \sigma), \\ &\text{Point B}: \ N_{\mu\tau_h}^{\text{LFV}} = 308 \pm 30 \ (10\ \sigma), \end{aligned} \tag{6}$$

where we quote only the statistical errors for the signal samples. If we estimate an efficiency of 70% for the jet-tau matching, the signal is reduced to 10σ for point A and 9σ for point B. Therefore, LFV signal has a good likelihood of being observable, as long as its branching ratio exceeds about 10%.

6. – Conclusions

The observation of LFV in neutralino decays at the LHC can be possible if $\Gamma(\chi_2 \to \chi_1\tau^\pm\mu^\mp)/\Gamma(\chi_2 \to \chi_1\tau^\pm\tau^\mp) \sim 0.1$. The LFV signal remains observable at points which are favoured in the usual CMSSM framework. Finally, we conclude that the search for this decay at the LHC is interesting and complementary to the parallel searches for $\tau \to \mu\gamma$ decays, for non-minimal GUTs. Furthermore, linear colliders will allow to explore complementary parameter space [16].

As a final remark, let us stress that the phenomenological analysis performed in this work can naturally be embedded within a $SU(5)$ GUT model featuring non-universal soft terms at the high scale M_X, whose origin can be traced back to a $U(1)_F$ family symmetry [11].

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