α-Flavour Violation at the LHC

M.E. Gómez(1), E. Carquin(2), P. Naranjo(1) and J. Rodríguez-Quintero(1)

(1) Departamento de Física Aplicada, University of Huelva, Spain
(2) Departamento de Física y Centro de Estudios Subatómicos, Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile

Summary. — We study the conditions required for $\chi_2 \rightarrow \chi + \tau^\pm \mu^\mp$ 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 see-saw mechanism that allows a possible coexistence of a LHC signal with a low prediction for radiative LFV decays.

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 $\nu_e \rightarrow \nu_\mu$ 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 $\mu \rightarrow e\gamma$ decays and conversions, $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$ decays. Other possibilities that have been considered are the decays $\chi_2 \rightarrow \chi + e^\pm \mu^\mp$ [5], and $\chi_2 \rightarrow \chi + \mu^\pm \tau^\mp$ [6, 7], where $\chi$ is the lightest neutralino, assumed here to be the lightest supersymmetric particle (LSP), and $\chi_2$ is the second-lightest neutralino. We present the results from [8] where we found that a signal for $\tau$ flavour-violating $\chi_2$ 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. – 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 \(M_X = M_{\text{GUT}}\), 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 \(\Gamma(\chi_2 \to \chi + \tau^\pm + \mu\bar{\tau})\) via the on-shell slepton production mechanism:

\[
BR(\chi_2 \to \chi \tau^\pm + \mu\bar{\tau}) = \sum_{i=1}^{3} \left[ BR(\chi_2 \to \tilde{l}_i\mu)BR(\tilde{l}_i \to \tau\chi) + BR(\chi_2 \to \tilde{l}_i\tau)BR(\tilde{l}_i \to \mu\chi) \right],
\]

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

Fig. 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 1 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 \(2 \times 10^{17}\) 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 \(\mu > 0\).

3. – SUSY Lepton Flavour Violation

The flavour mixing entries are defined as:

\[
\delta_{XX}^{ij} = (M_{XX}^2)^{ij}/(M_{XX}^2)^{ii} \quad (X = L, R).
\]
We take into account only 2–3 generation flavor mixing.

In order to have significant LFV signals, we need $\Gamma(\chi_2 \to \chi + \tau^\pm + \mu \bar{\tau})/\Gamma(\chi_2 \to \chi + \tau^\pm + \tau^\mp) \sim 0.1$. Values of $\delta_{LL}$ 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 with the flavour mixing parameters $\delta_{RR}$ and $\delta_{LL}$ 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 $\tilde{\chi}_2 \to \tilde{\chi}_1 \tau^\pm \mu \bar{\tau}$ 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 $\delta_{LL}$, imposing a maximum value $\sim 0.03$. 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 $\delta$ 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.

4. – SU(5) Unification and GUT soft masses

The introduction of non-trivial flavour structures for the slepton soft terms at $M_{GUT}$, 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 $M_X > M_{GUT}$. 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].
\[ \tan \beta = 45, \quad M_{1/2} = 1 \text{ TeV}, \quad A_0 = 0.5 \]

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

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 \( M_{GUT} \) 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 \( M_{GUT} \) and then the MSSM with see-saw neutrinos (solid lines), ii) Soft SUSY breaking terms given at \( M_{GUT} \) and then the MSSM with see-saw neutrinos (dash-lines). In case ii) we stop the lines at the value of \( m_0 \) below which \( m_{\tau} \) 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 \( M_{GUT} \). 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 \( 0 < m_0 < 100 \text{ GeV} \) region. In the area of the parameter space where WMAP bounds are satisfied due to \( \tau - \chi \) coannihilations, we find that \( m_{1/2} \) obeys a linear function of \( m_0 \), \( m_{1/2} \sim a_1 + a_2 m_0 \), 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:

\[
(3) \quad m_{S_i}^2 \simeq C_i^2 (m_0) m_0^2.
\]
where we have defined

\[
C_2^2 (m_0) = \frac{144}{20\pi} \alpha_5 \left( \left( \frac{a_1}{m_0} \right)^2 + 2a_1a_2 \right) \ln \left( \frac{M_X}{M_{GUT}} \right)
\]

and \( S_i \) stands for the supermultiplets \( 10 \) and \( \bar{5} \). 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 \( m_0 \approx 60 - 80 \) GeV at \( M_X \) such an enhancement at the GUT scale is as large as \( \approx 100 \). As a consequence, the soft mass matrices \( \bar{m}_{10}^2 \) and \( \bar{m}_{\bar{5}}^2 \) at GUT scale read as

\[
\bar{m}_{10}^2 = \begin{pmatrix} 1 & \varepsilon^3 & \varepsilon^5 \\ \varepsilon^3 & 1 & \varepsilon^4 \\ \varepsilon^5 & \varepsilon^4 & 1 \end{pmatrix} C^2 (m_0) m_0^2, \quad \bar{m}_{\bar{5}}^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & \varepsilon^3 \\ 0 & \varepsilon^3 & 1 \end{pmatrix} C^2 (m_0) m_0^2
\]

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 1 were calculated using ISAJET 7.78 [14] and then interfaced into PYTHIA 6.418 [15]. The SUSY-LFV decays described in the previous sections give a \( \mu^\pm \tau^\mp \) pair and produce an asymmetry between \( \mu^\pm \tau^\mp \) and \( \mu^\pm \tau^\pm \) final states that would not be observable in the case of charged lepton number conservation. In Fig. 5, an excess of OS \( l^\mp \tau^\pm_{R_h} \) 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 fb\(^{-1}\) (100 fb\(^{-1}\)). The observable numbers, \( N_{\mu^\pm \tau^\pm_{R_h}} \), of \( \mu^\pm \tau^\pm_{R_h} \) 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 $M_{\ell\tau}$ masses between 30 and 110 GeV. We obtain

$$\begin{align*}
\text{Point A} & : N_{\mu\tau_h}^{\ell\nu} = 470 \pm 39 \ (12 \ \sigma) \\
\text{Point B} & : N_{\mu\tau_h}^{\ell\nu} = 308 \pm 30 \ (10 \ \sigma)
\end{align*}$$

(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 $10\sigma$ for point A and $9\sigma$ 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 $\Gamma(\chi_2 \rightarrow \chi_1 \tau^{\pm} \mu^{\mp}) / \Gamma(\chi_2 \rightarrow \chi_1 \tau^{\pm} \tau^{\mp}) \sim 0.1$. 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 $\tau \rightarrow \mu\gamma$ 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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