Lepton Flavour Violating Heavy Higgs Decays
Within the $\nu$MSSM and Their Detection at the LHC

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Abstract
Within the $\nu$MSSM, a Minimal Supersymmetric neutrino See-saw Model, Lepton Flavour Violating Higgs couplings are strongly enhanced at large $\tan \beta$ ($\gtrsim 30$), which can lead to $\text{BR}(H^0/A^0 \rightarrow \tau\mu) \simeq 10^{-4}$, for $M_{H^0/A^0} \gtrsim 160$ GeV. Enhancements on the production of Higgs bosons, through the gluon fusion mechanism, $gg \rightarrow H^0/A^0$, and the associated production channel $gg, q\bar{q} \rightarrow b\bar{b}H^0/A^0$, whose rates grow with $\tan \beta$, as well as the mass degeneracy that occurs between the $H^0$ and $A^0$ states in this regime, also contribute to further the possibilities to detect a heavy Higgs signal into $\tau\mu$ pairs. We show that the separation of $\tau\mu$ Higgs events from the background at the upcoming CERN Large Hadron Collider could be done for Higgs masses up to about 600 GeV for 300 fb$^{-1}$ of luminosity, for large $\tan \beta$ values. However, even with as little as 10 fb$^{-1}$ one can probe $H^0/A^0$ masses up to 400 GeV or so, if $\tan \beta = 60$. Altogether, these processes then provide a new Higgs discovery mode as well as an independent test of flavour physics.
1 Introduction

It is possible that some of the most exciting times in particle physics will come soon, as the upcoming Large Hadron Collider (LHC) will enable us to probe the mechanism of Electro-Weak Symmetry Breaking (EWSB). The standard picture contains a single Higgs state that couples to the other fundamental particles with an intensity proportional to their masses [1]. In the case of fermions, the Standard Model (SM) Higgs couplings are diagonal in flavour space, due to the fact that the Higgs couplings and the fermion mass matrices are both diagonalised by the same bi-unitary rotations. However, this picture ceases to remain valid in many extensions of the SM. For instance, in the general Two Higgs Doublet Model of Type III (THDM-III), where both Higgs doublets couple to both types of up- and down-type fermions, there appear non-diagonal Higgs couplings, which lead to interesting Lepton Flavour Violating/Flavour Changing Neutral Current (LFV/FCNC) Higgs phenomenology [2]. In turn, even though the Minimal Supersymmetric Standard Model (MSSM) is a Type II Two-Higgs Doublet Model (THDM-II) at tree level – with additional mass and coupling relations enforced by Supersymmetry (SUSY) – this structure is not protected by any symmetry, so that loop effects can effectively render it a THDM-III. In addition, the detection of neutrino oscillations [3, 4] seem to suggest that there is a large mixing between the second and third families in the lepton sector, which could also appear in new scenarios that are contained in some extensions of the SM [5]. In particular, within SUSY models, the pattern of LFV effects at the Planck or Grand Unification Theory (GUT) scales could be reflected in the structure of the soft SUSY-breaking terms, i.e., in the slepton mass matrices, which in turn can communicate these to the Higgs sector through radiative effects [6].

Detectable effects of LFV Higgs couplings could show up in the decay $\tau \rightarrow 3\mu$, which is a particularly sensitive probe at large $\tan \beta$ [7] (the ratio of the two Higgs vacuum expectation values in the MSSM), with a Branching Ratio (BR) scaling as $\tan^6 \beta$, a phenomenon which may render this mode detectable at the LHC. The relevance of the LFV Higgs decay $\phi \rightarrow \tau \mu$\(^1\) for Higgs phenomenology at the LHC was discussed in Ref. [8]\(^2\), within the context of several extensions of the SM. In particular, it was shown that a large BR($\phi \rightarrow \tau \mu$) (of order 0.001–0.01) could easily be achieved in the THDM-III. Moreover, it was shown there that large LFV Higgs couplings were not in conflict with any low energy constraints, such as LFV decays of $\tau$’s. Calculations of the SM Higgs BR($\phi \rightarrow \tau \mu$) showed it to be be very suppressed ($< 10^{-15}$) whilst in the (constrained) MSSM the corresponding rates could be enhanced for some of the Higgs states.

In this paper we are interested in discussing further aspects of LFV phenomenology entering the Higgs sector of the MSSM, by investigating the possibility of a new detection mode for heavy $H^0/A^0$ Higgs bosons ($M_{H^0/A^0} \gtrsim 2M_{W^\pm}$ GeV) at the LHC. In particular, we shall demonstrate that the decays of the heavy neutral Higgs bosons of the MSSM to $\tau \mu$ pairs are sizable and represent a very sensitive probe of LFV physics. We calculate

\(^{1}\text{Hereafter, unless otherwise specified, the label } \phi \text{ will refer to a generic Higgs state.}\)

\(^{2}\text{However, a calculation of the actual LFV Higgs decay rates was presented first in [9].}\)
the rates for the BR($H^0/A^0 \rightarrow \tau \mu$), involving the heavy neutral MSSM CP-even Higgs state and the CP-odd one, and find that they can be as large as $10^{-4}$, for high values of $\tan \beta$, while those for the BR($h^0 \rightarrow \tau \mu$), involving the light neutral MSSM CP-even Higgs state, remain rather small in comparison. Furthermore, it should be recalled that MSSM Higgs production at hadron colliders is enhanced for large $\tan \beta$, both via gluon fusion and in association with $b\bar{b}$ pairs. Moreover, in this $\tan \beta$ regime, there appears a degeneracy for the masses of the $H^0$ and $A^0$ states, which essentially doubles the event rate of the overall Higgs signal. All such effects enable one then to reach detectable levels at the LHC for $H^0/A^0 \rightarrow \tau \mu$ signals. Finally, by extending previous studies on the signal-to-background separation at the LHC, we show that detection of $H^0/A^0$ LFV Higgs decays into tau-muon pairs could be achieved for Higgs masses as high as 600 GeV. In short, these LFV decay modes can provide a new detection channel for the heavy Higgs bosons of the MSSM, which would in turn give not only important evidence for SUSY but also, along with the modes $B^0 \rightarrow \mu \mu$, $\tau \rightarrow 3\mu$, $\tau \rightarrow \mu \gamma$ and $\mu \rightarrow e\gamma$, probe the form of the neutrino Yukawa mass matrix.

The plan of the paper is as follows. The underlying aspects of the model and the calculation are laid out in Sect. 2. The LFV Higgs signals are characterised in Sect. 3. The numerical calculation of the cross sections and decays for the relevant Higgs modes is pursued in Sect. 4, including the determination of signal-to-background event rates and the proof of detectability of LFV Higgs signals at the LHC. Summary and conclusions are found in Sect. 5.

2 Slepton Mixing and LFV in the Higgs Sector

One of the most attractive explanations for the observed neutrino masses [3, 4] is the “see-saw” mechanism [10], which includes Dirac masses ($m_D$) as well as Majorana masses ($M_R$). Atmospheric neutrino data favours a $\nu_\tau$ mass of about 0.04 eV [11]. Thus, for Dirac neutrino masses of the order of the corresponding up-quark masses, i.e. $(m_D)_{\nu_\tau} \approx 100 - 200$ GeV, as predicted in a GUT such as SO(10), one finds that the right-handed Majorana mass, $M_R$, needs to be of order $10^{14}$ GeV. Majorana neutrino masses imply LFV within the Minimal Supersymmetric see-saw Model, which is defined as the Minimal Supersymmetric Standard Model augmented by three heavy right-handed neutrinos, $\nu_R^3$, LFV interactions can be communicated directly from $\nu_R$’s to the sleptons and from these to the charged leptons and Higgs bosons. The initial communication takes place through renormalisation group flow of the slepton mass matrices at energies between $M_{\text{Planck}}$ and $M_R$. The presence of $\nu_R$ states at scales above $M_R$ leaves an imprint on the mass matrices of the sleptons, which propagates down to the Electro-Weak (EW) scale. This effect has been used to predict large BRs for $\tau \rightarrow \mu \gamma$ and $\mu \rightarrow e\gamma$ within the MSSM [12, 13, 14].

To derive the effective Lagrangian for the LFV lepton-Higgs interactions, we begin

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3Henceforth, we will use the notation $\nu\text{MSSM}$ to indicate such an extension of the MSSM.
with the Yukawa Lagrangian:

$$-\mathcal{L} = \bar{Y}_l l_R L + \bar{Y}_\nu \nu_R H_u + \frac{1}{2} \mu \nu_R H_u,$$

where $l_R$, $L$ and $\nu_R$ represent the right-handed charged leptons, left-handed lepton doublets and right-handed neutrinos, respectively, while $H_u, H_d$ denote the Higgs doublets of the MSSM. $Y_l, Y_\nu$ and $M_R$ are $3 \times 3$ matrices in flavour space. We shall work in a basis in which both $Y_l$ and $M_R$ have been diagonalised, but where $Y_\nu$ remains an arbitrary complex matrix. Lepton number is violated in this Lagrangian due to the presence of the $\nu_R$ Majorana mass term.

Furthermore, the $6 \times 6$ slepton mass matrix is written in terms of $3 \times 3$ blocks, as follows:

$$M^2_{\tilde{L}} = \begin{pmatrix} M^2_{LL} & M^2_{LR} \\ M^2_{RL} & M^2_{RR} \end{pmatrix},$$

where

$$M^2_{LL} = M^2_{\tilde{L}} + M^2_{\tilde{l}} + M^2_{Z_0} \cos 2\beta (T^3_{\tilde{L}} - Q_{\tilde{L}} \sin^2 \theta_W)$$

$$M^2_{RR} = M^2_{\tilde{L}} + M^2_{\tilde{l}} + M^2_{Z_0} \cos 2\beta Q_{\tilde{L}} \sin^2 \theta_W$$

$$M^2_{LR} = A_l \nu \cos \beta / \sqrt{2} - M_l \mu \tan \beta$$

Here $v = 246$ GeV, $\theta_W$ is the weak/Weinberg angle while $\mu$ and $A_l$ denote the higgsino mass parameter and trilinear slepton couplings, respectively. $M_{W^\pm, Z^0}$ are the masses of the $W^\pm, Z^0$ gauge bosons and $M_l$ the lepton mass matrix. We will work in a basis where $M_l$ is diagonal.

When the SUSY-breaking slepton mass matrix $(M^2_{\tilde{L}})_{ij}$ evolves from the scale $M$ at which flavour-blind SUSY-breaking is communicated to the visible sector, down to the slepton mass scale $M_{\tilde{L}}$ (assuming $M > M_R$), one obtains a flavour-mixing piece that corrects the slepton soft mass terms, i.e., $M^2_{\tilde{L}} \to M^2_{\tilde{L}} + \Delta M^2_{\tilde{L}}$, with the latter given by:

$$(\Delta M^2_{\tilde{L}})_{ij} \simeq -\frac{\log(M/M_R)}{16\pi^2} \left(6m^2_0(Y^\dagger_\nu Y_\nu)_{ij} + 2(A^\dagger_\nu A_\nu)_{ij} \right),$$

where $m_0$ is a common scalar mass evaluated at the scale $Q = M$ and $i \neq j$. If one assumes that the $A$-terms are proportional to Yukawa matrices, then:

$$(\Delta M^2_{\tilde{L}})_{ij} \simeq \xi (Y^\dagger_\nu Y_\nu)_{ij},$$

where

$$\xi = -\frac{\log(M/M_R)}{16\pi^2}(6 + 2a^2)m^2_0$$

and $a$ is $O(1)$. In the simplest SUSY-breaking scenarios, gravity plays the role of messenger and $M = M_{\text{Planck}}$. Global fits to neutrino data favour large mixing between $\nu_\mu$ and
\( \nu_r \) and also between \( \nu_e \) and \( \nu_\mu \) \cite{11}. Thus, we shall consider here a form for \( m_\nu \) with \( O(1) \) entries in the 23 and 32 elements \ [15]. If we further assume that \( (M_R)_{ij} \) is an identity matrix, then \( (Y_\nu^0 Y_\nu)_{23} \) will also be of \( O(1) \).

This source of LFV interactions can be transmitted to the Higgs sector as well, because radiative effects could induce flavour mixing in the Higgs couplings. These corrections allow the neutral Higgs bosons to mediate FCNCs, in particular \( B^0 \to \mu \mu \) \cite{6} can reach BRs at large \( \tan \beta \) that can be probed by Run II of the Tevatron \cite{16}. For the leptonic sector, the Feynman graphs that induce such corrections involve loops of sleptons and charginos-neutralinos, which are transmitted further to induce LFV Higgs couplings. To derive the SUSY-induced THDM-III, one can write an effective Lagrangian for the couplings of the charged leptons to the neutral Higgs fields, namely:

\[
-\mathcal{L} = \bar{\ell} R Y_1 E_L H_0^0 + \bar{\ell} R Y_1 \left( \epsilon_1^1 + \epsilon_2 Y_\nu^0 \right) E_L H_0^0 + h.c.
\]  

(9)

where \( \epsilon_{1,2} \) include the slepton radiative effects. LFV couplings results from our inability to simultaneously diagonalise the term \( Y_1 \) and the non-holomorphic loop corrections, \( \epsilon_2 Y_\nu^0 Y_\nu \). The contributions from higgsinos and gauginos, which are approximated as mass eigenstates, can be written as follows,

\[
\epsilon_{2i} \simeq \frac{\alpha_i}{8\pi} \xi \mu M_i f_i \left( \frac{\mu^2}{\xi^2}, m_{\tilde{\ell}}^2, m_{\tilde{\mu}}^2, M_i^2 \right),
\]

(10)

in which \( \tilde{\ell} = \tilde{\mu}, \tilde{\tilde{e}}, \tilde{\nu}_l \), and \( \tilde{\ell} = \tilde{\tau}, \tilde{\nu}_r \). \( M_1 = M_{1,2} \) are the \( U(1) \) and \( SU(2) \) gaugino masses, while \( \xi \) is defined in eq. (8). For our purposes, the function \( f_i \) can be evaluated in the limit \( a = b = c = d \), for which \( f_i(a, a, a, a) = 1/(6a^2) \).

Since the charged lepton masses cannot be diagonalised in the same basis as the Higgs couplings, this will allow neutral Higgs bosons to mediate LFV processes, with rates proportional to \( \epsilon_2^2 \). The term proportional to \( \epsilon_1 \) will generate a mass shift for the charged leptons that will appear as a second-order effect \cite{17}.

Then, the LFV interactions relevant for the Higgs sector phenomenology can be written in terms of Higgs mass eigenstates as follows \( (\phi_0^n_h = h^0, H^0, A^0) \):

\[
-\mathcal{L}_{\phi_k l_l l_j} = \left[ \frac{g m_\tau \eta_\phi}{2M_{W^\pm} \cos \beta} \right] \left( \chi_{ij} \bar{\ell}_R l_l \phi_0^0 + h.c. \right),
\]

(11)

where

\[
\chi_{ij} \simeq \frac{-\epsilon_2 \tan \beta \rho_0 \left( Y_\nu^0 Y_\nu \right)_{ij}}{\sin \beta \eta_0}
\]

(12)

and \( (\eta_h, \eta_H, \eta_A) = (\sin \alpha, -\cos \alpha, \sin \beta), \rho_h, \rho_H, \rho_A = (\cos(\beta - \alpha), -\sin(\beta - \alpha), -i) \), with \( \alpha \) denoting the Higgs mixing angle. Constraints on the LFV \( (\bar{\tau}_R \mu_L) \)–Higgs interaction can be obtained from the LFV \( \tau \)-decays (e.g., \( \tau \to 3\mu \)), which can be generated via exchange of \( h^0, H^0 \) and \( A^0 \). For instance, for the case in which \( \mu = M_1 = M_2 = m_{\tilde{\ell}} = m_\nu, M_R = 10^{14} \) GeV and \( (Y_\nu^0 Y_\nu)_{32} = 1 \), Ref. \cite{7} finds that \( \epsilon_2 \simeq 4 \times 10^{-4} \), which is stable with respect to changes in the SUSY spectrum. Then \( \text{BR}(\tau \to 3\mu) \simeq (1 \times 10^{-7}) \times (\tan \beta/60)^6 \times \)
(100 GeV/$M_{A^0}$)\(^4\), which puts the $\tau \to 3\mu$ mode into a regime that is experimentally accessible at current B-factories. At the LHC and SuperKEKB, limits in the region of $10^{-9}$ should be achievable [18], allowing an even deeper probe into the model parameter space. On the other hand, Tevatron has already constrained the large tan $\beta$ domain, from the search for the decay $B_s \to \mu\mu$ [19], that seems to exclude the value tan $\beta = 60$, which is preferred by the requirement of Yukawa unification. However, it is possible to evade such constraints, for instance in SUSY breaking scenarios where slepton and squark masses do not have any strong correlation. In any case, given that such limits depend on multiple MSSM parameters, which makes it difficult to draw a general conclusion, it is certainly preferable to test the resulting LFV Higgs couplings directly at the LHC, as it is discussed in the next section.

3 The LFV Higgs Decays $H^0/A^0 \to \tau\mu$

LFV Higgs decays have been evaluated within the general MSSM with a particular ansatz for the trilinear $A$ terms in [5], where was found that a BR($h^0 \to \tau\mu$) $\approx 10^{-4} - 10^{-7}$ could well be achieved. Subsequently, Refs. [20, 21] and [22] presented a more detailed calculation of the BR($h^0 \to \tau\mu$), within the MSSM, which was essentially in agreement with the previous result. In fact, Ref. [22] also reported a complete one-loop calculation of the LFV Higgs decay within the SM extension with massive neutrinos, using a realistic pattern of neutrino masses and mixings, which resulted in very suppressed LFV Higgs decays (with BR of order $10^{-30}$ or less). Afterwards, [23] presented a detailed study of the prospects to detect LFV Higgs decays at the Tevatron and LHC, concluding that it
is certainly possible to detect such decays in the THDM-III within the Higgs mass range 114–160 GeV, approximately. Later on, Ref. [24] presented a more realistic study of the signal and backgrounds, essentially reaching the same conclusions. Subsequently, it was also studied in detail the mass-matrix ansatz used in the THDM-III, by Ref. [25], while the evaluation of the corresponding LFV Higgs decays was presented in [26]. Mixing of the SM fermions with other exotic fermions was also shown to be a possible source of LFV in the Higgs sector [27], resulting in BRs of the order 0.01-0.001 again, which could clearly be detectable too. Bounds on LFV Higgs decays at the Tevatron were reported by the CDF collaboration in [28].

In this paper we shall concentrate on the LFV heavy Higgs decays to $\tau\mu$, which has a very small BR within the context of the SM with light neutrinos, so that this channel is potentially an excellent window for probing new physics. Although the previously mentioned works have studied LFV Higgs decays within the $\nu$MSSM, the specific evaluation of the BRs of the LFV decays for $H^0/A^0$ in the heavy mass range has not been studied. Hence a discussion of the corresponding detectability at the LHC has not been presented so far either. To remedy this is our aim in the present paper.

In order to derive the formulae for the LFV Higgs decay widths, we notice that the quantity inside the square brackets in eq. (11) corresponds to the Higgs-lepton coupling $\phi_k\tau\bar{\tau}$, which will be denoted by $g_{\phi\tau\bar{\tau}}$. Thus, we can write the LFV Higgs coupling $\phi_k\tau\mu$ as

$$g_{\phi\tau\mu} = g_{\phi\tau\bar{\tau}}\lambda_{ij}^\phi.$$  

The decay width for the generic process $\phi_k \rightarrow \tau\mu$ (in which we add both final states $\tau^+\mu^-$ and $\tau^-\mu^+$) can then be written in terms of the Higgs decay width $\Gamma(\phi \rightarrow \tau\tau)$, as follows:

$$\Gamma(\phi \rightarrow \tau\mu) = 2|\lambda_{\phi\mu}^\phi|^2\Gamma(\phi \rightarrow \tau\tau),$$  

so that the LFV Higgs BR can in turn be approximated by $\text{BR}(\phi \rightarrow \tau\mu) = 2|\lambda_{\phi\mu}^\phi|^2\text{BR}(\phi \rightarrow \tau\tau)$.

We are interested in studying the large $\tan\beta$ domain (i.e., $\beta \rightarrow \pi/2$), where the LFV Higgs couplings are enhanced. It is also simpler to work in such so-called decoupling regime of the MSSM Higgs sector, which in fact is quite general since it is reached even for moderate values of $M_{A^0} (\simeq 200 \text{ GeV})$. In this case we have that $\lambda_{\phi\mu}^\phi \rightarrow 0$, $\epsilon_2\tan\beta$, $\epsilon_2\tan\beta$ for $\phi_k = h^0, H^0, A^0$, respectively. Therefore, the LFV decays of the light Higgs boson ($h^0$) are suppressed for most regions of parameter space. Conversely, for the above mentioned choices of SUSY parameters yielding $\epsilon_2 = 4 \times 10^{-4}$ (which we call set A) and with $M_{H^0, A^0} \approx 160 \text{ GeV}$, one obtains $\text{BR}(H^0/A^0 \rightarrow \tau\mu) \simeq 0.12$, which in turn gives $\text{BR}(H^0/A^0 \rightarrow \tau\mu) \simeq 2.9 \times 10^{-5}$ for $\tan\beta = 30$. For another set of parameters with a large $\mu$ limit, i.e. $\mu >> M_{1,2}$ (which we call set B), one gets $\epsilon_2 \simeq 8 \times 10^{-4}$, which will produce a larger BR for $H^0/A^0 \rightarrow \tau\mu$. More in general, we calculate the LFV Higgs decay rates in the channels $H^0/A^0 \rightarrow \tau\mu$ – by appropriately modifying the HDECAY program [29] and using the formula in eq. (14) – as a function of the Higgs masses and corresponding LFV Higgs couplings.
Figure 2: The dependence of number of events of the LFV Higgs signals at the LHC on the degenerate Higgs masses $M_{H^0}$ and $M_{A^0}$, including the sum of production cross sections $\sigma(gg \rightarrow H^0) + \sigma(gg \rightarrow A^0)$ times the corresponding decay rates $\text{BR}(H^0 \rightarrow \tau \mu)$ and $\text{BR}(A^0 \rightarrow \tau \mu)$, for two representative values of $\tan \beta = 30$ (+set A) and 60 (+set B). We are assuming a detection efficiency of 3% and two values of integrated luminosities $30 \text{ fb}^{-1}$ and $100 \text{ fb}^{-1}$.

It is appropriate to mention at this point that reference [24] did include a discussion of the LFV $H^0/A^0$ decays. However, the authors concentrated on the mass range below $2M_{W\pm} \approx 160$ GeV. They hint in fact that above this mass range the modes $H^0/A^0 \rightarrow \tau \mu$ will be suppressed because the channels $W^+W^-$ and $Z^0Z^0$ would be open and dominate the total decay width. However, this is not true. The reason is twofold. Firstly, the $A^0$ – being a CP-odd state – does not couple to vector boson pairs. Secondly, although the $H^0$ state does couple to $W^+W^-$ and $Z^0Z^0$ pairs, in the heavy Higgs mass limit such coupling is considerably suppressed. Our calculation takes correct care of these aspects.

4 Signal-to-Background Analysis

Once one folds in the values of LFV Higgs BRs with the main heavy neutral Higgs production modes at the LHC, it is clear that LFV Higgs decays into $\tau \mu$ pairs may be detectable at the CERN hadron collider. As a benchmark, according to previous studies [24], with SM-like cross sections and $m_\phi \lesssim 160$ GeV, one could detect at the LHC the aforementioned LFV Higgs decays with a BR of order $8 \times 10^{-4}$. We intend to push forward the region of detectability into higher mass values within the MSSM, by exploiting the aforementioned $\tan \beta$ enhancement and the fact that our LFV Higgs BRs become almost constant for heavier Higgs masses. Besides, for heavier Higgs masses one should expect a much larger background reduction, as compared to the lower Higgs mass case, owing to the much harder energy spectra for the emerging $\tau$- and $\mu$-leptons.

As already mentioned, high values of $\tan \beta$ are also associated with a large $b$-quark
Figure 3: The dependence of number of events of the LFV Higgs signals at the LHC on the degenerate Higgs masses $M_{H^0}$ and $M_{A^0}$, including the sum of production cross sections $\sigma(pp \to b\bar{b}H^0) + \sigma(pp \to b\bar{b}A^0)$ times the corresponding decay rates $\text{BR}(H^0 \to \tau\mu)$ and $\text{BR}(A^0 \to \tau\mu)$. Other parameters are the same as in Figure 2.

Yukawa coupling, which in turn can produce an enhancement of the Higgs production cross sections at hadron colliders via both gluon fusion and associated production with $b$-quark pairs: i.e., $gg \to H^0/A^0$ (via triangle loops at lowest order) and $gg, q\bar{q} \to b\bar{b}H^0/A^0$ (at tree-level), respectively. (We calculate these two production processes here by using the HIGLU and HQQ programs in default configurations [30].) Figure 1 shows the relevant LFV Higgs BRs as a function of $M_{A^0}$. The LFV BR is basically the same for both $H^0$ and $A^0$ and its variation with $M_{A^0}$ is very mild. In Figures 2 and 3 we present the expected LFV Higgs event rates as a function of degenerate Higgs mass $M_{A^0}$ for two values of $\tan\beta = 30$ and 60 and two values of LHC luminosities, $L = 30 \text{ fb}^{-1}$ and 100 $\text{ fb}^{-1}$, respectively. It is clear from these two plots that LFV Higgs rates can be substantial even at large Higgs masses.

In Ref. [23] it was proposed a series of cuts to reconstruct the hadronic and electronic $\tau$ decays from $\phi \to \tau\mu$ and separate the signal from the background, which is dominated by $\tau$-pair production via Drell-Yan modes (i.e., $q\bar{q} \to \gamma^*, Z^* \to \tau^+\tau^-$) and $q\bar{q}, gg \to W^+W^- \to \tau^+\nu_\tau\tau^-$/$\overline{\nu}_\tau$. In fact, it should be recalled that the decay product distributions of $\tau$-leptons generated in the decay of Higgs bosons are notably different from those emerging in gauge boson decays, because of the different spin of the primary objects. A more realistic search strategy for the LHC based on the cuts of Ref. [23] was presented in Ref. [24], where one can find detection efficiencies in the Higgs mass range 120–160 GeV. The typical figure goes from about 2% for $M_{h^0} = 120$ GeV up to about 3% for $M_{h^0} = 160$ GeV, where it starts stabilising. Although one expects that this detection efficiency will increase for heavier Higgs masses, in order to use a conservative estimate, we shall use the 3% figure throughout in our estimates in the remainder of the paper.
Figure 4: The 95% CL exclusion and 5σ discovery reaches for the LFV Higgs signals at the LHC as a function of the degenerate Higgs masses $M_{H^0}$ and $M_{A^0}$ and the integrated luminosity, including the sum of production cross sections $\sigma(gg \rightarrow H^0)$ and $\sigma(gg \rightarrow A^0)$ plus $\sigma(pp \rightarrow b\bar{b}H^0)$ and $\sigma(pp \rightarrow b\bar{b}A^0)$ times the corresponding decay rates $\text{BR}(H^0 \rightarrow \tau\mu)$ and $\text{BR}(A^0 \rightarrow \tau\mu)$, for $\tan\beta = 30$ (+set A) (dashed lines) and 40 (+set A) (solid lines).

Figure 5: Same as Figure 4, but for $\tan\beta = 50$ (+set B) (dotted-dashed lines) and 60 (+set B) (solid lines).
Adopting the background rates estimated in Ref. [24] for Higgs masses up to 200 GeV and trivially extrapolating them to heavier Higgses, we are then in a position to compare the yield of our signals (see Figures 2–3) with that of the total background, thereby estimating both a 95% Confidence Level (CL) exclusion limit and a 5σ discovery reach. The scope of the LHC in both respects, as a function of the Higgs masses and machine luminosity, is then well described by Figures 4 and 5. To display our results, we have chosen the combinations $\tan \beta = 30$ and 40 with SUSY parameters of set A, and $\tan \beta = 50$ and 60 with SUSY parameters of set B. (Other combinations should lay within these results.) Clearly, with an integrated luminosity of 300 fb$^{-1}$, for $\tan \beta = 30$, one can detect a signal for Higgs masses up to about 260 GeV, which is already significantly above the $2M_{W^\pm}$ mark of Ref. [24], while, for $\tan \beta = 60$, Higgs masses up to even 600 GeV can be probed. However, since for $\tan \beta = 60$ one is dangerously close to the bounds from $B \to \mu\mu$, the reader may well refer instead to those for $\tan \beta = 40$ (with SUSY parameters of set A) and $\tan \beta = 50$ (with SUSY parameters of set B). In these cases too we find that it will be possible to extract a LFV Higgs signal at the LHC for heavy Higgs masses, up to about 300(500) GeV for $\tan \beta = 40(50)$ with 300 fb$^{-1}$ of luminosity.

5 Summary and Conclusions

We have demonstrated that LFV effects in the slepton sector of the νMSSM can generate LFV couplings between leptons and neutral Higgs bosons leading to large BRs for LFV Higgs decays into lepton pairs. In particular, we have calculated the BRs of the processes $H^0/A^0 \to \tau\mu$ and found that they can be as large as $3 \times 10^{-4}$, while the BR($h^0 \to \tau\mu$) is only about $\simeq 10^{-8}$. Furthermore, these rates occur for large values of $M_{H^0/A^0}$ and $\tan \beta$, a configuration also responsible for a strong degeneracy between the masses (and couplings) of the $H^0$ and $A^0$ states, producing an overall Higgs event rate which is double the one of either Higgs state alone. These LFV Higgs modes can be extracted at the LHC for Higgs masses slightly beyond 600 GeV, provided $\tan \beta = 60$. For smaller values of this parameter though the LHC scope greatly diminishes, reducing to just above 260 GeV in Higgs mass for $\tan \beta = 30$. These values can only be reached at 300 fb$^{-1}$ of luminosity. However, even with a modest 10 fb$^{-1}$, one could probe Higgs masses up to 400(415) GeV, provided $\tan \beta = 50(60)$. Besides, in view of the assumptions made on detection efficiencies for the signal, we believe these conclusions to be rather conservative. Altogether, these novel channels complement the modes $B^0 \to \mu\mu$, $\tau \to 3\mu$, $\tau \to \mu\gamma$ and $\mu \to e\gamma$ in order to provide evidence for SUSY and key insights into the form of the neutrino Yukawa mass matrix. More detailed experimental simulations are now awaited.

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