Lepton flavor violating decays of Higgs bosons beyond the standard model

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We evaluate the lepton flavor violating (LFV) decays of Higgs bosons $H \to l_i^+ l_j^-$ in several extensions of the standard model (SM), including both the effective Lagrangian approach and several specific models. Within the effective Lagrangian case, we focus on the dimension-6 operators that induce LFV vertices for the Higgs and Z bosons. For those operators whose coefficients cannot be constrained by present data, we estimate a branching ratio (B.R.) of the order of $10^{-1}-10^{-2}$ for the LFV Higgs boson decays, which can be detected at future hadron colliders. For the other operators that are bounded by current limits on the LFV transition, there are strong bounds on $e-\mu$ transitions, which imply B.R.$(H \to e\mu) \simeq 10^{-9}$; however, even in this case the decay modes $H \to \tau\mu/\tau e$ are allowed to have a B.R. of the order 10^{-1}. In the case of the general two-Higgs-doublet model, we also obtain B.R.$(H \to \tau\mu/\tau e) \simeq 10^{-1}$, whereas for the SM with massive neutrinos and the minimal supersymmetric-SM, the B.R.'s of the corresponding LFV Higgs decays are strongly suppressed.

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I. INTRODUCTION

The separate conservation of the lepton number ($L_i = L_e, L_\mu, L_\tau$) can be considered one of the central features of the standard model (SM) of electroweak interactions. This result follows automatically from the assignment of quantum numbers to the fermions of the model. However, it is also known that the lepton number could be violated in many of its extensions; for instance by just providing neutrinos with a mass, either through dimension-5 operators or with Higgs triplets, one can violate the lepton number. In fact, the recent results presented by the Super-Kamiokande Collaboration [2], showing evidence for neutrino oscillations, indicate that the lepton number is not conserved in nature and that the lepton sector of the SM requires some modification to account for the pattern of neutrino mixing suggested by the data.

After the Kamiokande observations, it is almost mandatory to search for other processes where lepton flavor violation (LFV) can be present. Current experimental bounds on LFV transitions severely constrain most hypothetical sources of lepton flavor non-conservation [1]. However, since the Higgs boson is the only part of the SM that has not been detected [3], it interesting to ask if there could be a connection between the Higgs sector and the mechanism responsible for the non-conservation of lepton number, and to find out whether some remmant effect could show up in Higgs phenomenology, which may be detectable at present or future colliders.

In this paper, we are interested in studying the decays of the Higgs boson $H \to l_i^+ l_j^-$, as a possible signal of LFV. We shall work first within a model-independent approach, using the (linear) Effective Lagrangian extension of the SM. Our analysis for the dimension-six operators that induce LFV interactions of the Z and Higgs bosons is presented in Sec. II. Then, in Sec. III we consider several specific models where LFV Higgs decays may arise; namely, the standard model with massive neutrinos, the general two-Higgs-doublet model (THDM-III), and the minimal supersymmetric (SUSY) extension of the SM (MSSM). Our conclusions are presented in Sec. IV. The main result of this work concerns the decays $H \to \tau e/\tau\mu$, we find that it can reach a B.R. of order 0.1, for both the effective Lagrangian and THDM-III cases, which can be detected at Tevatron Run-II. The mode $H \to e\mu$ can reach a B.R. of order 10^{-3}, but only for some specific cases. We also find that LFV Higgs decays are highly suppressed for the SM with massive neutrinos and the MSSM.

II. MODEL-INDEPENDENT RESULTS

The effective Lagrangian approach has been used as a means to describe the effects of new physics in a model-independent fashion. These effects are parametrized through effective operators of a dimension higher than four [4]. The effective Lagrangian is conveniently written as

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{nij} \frac{\alpha_n^{ij}}{\Lambda^2} O_n^{ij}, \tag{1}$$

where i,j, $(=1,2,3)$ denote flavor indices, n runs over the number of independent operators of dimension-6. The scale Λ is associated with the onset of new physics. The coefficients α_n^{ij} are unknown, but should in principle be calculable from the fundamental theory; however for phenomenological purposes, it suffices to use the bounds implied by present experimental data.

The conservation of the lepton number, which is automatic in the SM, is lost in general with the inclusion of higher-dimensional operators. For instance, the dimension-5 operator: $O_{ij}^5 = \overline{\tilde{L}}_i \tau_a L_j \tilde{\Phi} \tau_a \Phi$, where L_i (Φ) denotes the lepton (Higgs) doublet, can generate neutrino masses of Majorana-type that violate the lepton number by two units; however, one can verify that this operator does not generate the LFV interaction of the neutral Higgs boson.

Thus, our first task must be to find out which operators induce LFV for the Higgs sector. Most studies on LFV within the effective Lagrangian context, have focused on establishing bounds on the scale Λ, assuming for the coefficients the value $\alpha_n^{ij}=1$. Although it is tempting to associate a single scale $(=\Lambda_{LFV})$ with all LFV operators, one should not use this as the only criteria to judge the relative importance of some operator. The possible values of the coefficient α_n^{ij} should also be taken into account to estimate the strength of the corresponding operator. Moreover, it could be the case that the new physics associated with the scale Λ_{LFV}, could induce operators with very different coefficients α_n^{ij}. This already occurs in the SM, where the Glashow-Iliopoulos-Maiani (GIM) mechanism allows the flavor changing neutral current (FCNC) decay $b\to s+\gamma$ to be observable, but it strongly suppresses the top decay $t\to c+\gamma$ [5].

We are interested here in studying operators that can induce LFV interactions of the Higgs boson. In general, some of these operators will also induce LFV vertices for the Z boson $(Zl_i^+l_j^-)$. Present data on LFV transitions can be used to bound their coefficients, mainly from the decays $l_i\to l_j+\gamma, l_i\to l_j l_k l_k, Z\to l_i^+l_j^-, M\to l_i^+l_j^-$ (where $l_i=e,\ \mu,\ \tau$, and M denotes the light mesons) and electron-muon conversion in nuclei.

Following Ref. [6], one can specify whether some operator arises as a tree level or as a loop effect from the fundamental theory, and include in the last case the typical loop factor $1/16\pi^2$ to estimate its effect. At dimension-six there are a number of operators that can mix different lepton flavors, which can be classified according to the type of bosonic field that is involved (gauge bosons and Higgs bosons), as follows.

(1) Operators that generate LFV photon interactions. These operators appear in two types:

$$O_{LW}^{ij}=i(\overline{L}_i\tau^a\gamma_\mu D_\nu L_j)W^{a\mu\nu},$$

$$O_{LB}^{ij}=i(\overline{L}_i\gamma_\mu D_\nu L_j)B^{\mu\nu},$$

$$O_{lB}^{ij}=i(\overline{l}_{Ri}\gamma_\mu D_\nu l_{Rj})B^{\mu\nu} \tag{2}$$

and

$$O_{lW\phi}^{ij}=(\overline{L}_i\sigma^{\mu\nu}\tau^a l_{Rj})\Phi W_{\mu\nu}^a,$$

$$O_{lB\phi}^{ij}=(\overline{L}_i\sigma^{\mu\nu}l_{Rj})\Phi B_{\mu\nu}. \tag{3}$$

(2) LFV four-fermion operators:

$$O_{ijkl}^{(1)}=\frac{1}{2}(\overline{L}_i\gamma_\mu L_j)(\overline{L}_k\gamma^\mu L_l),$$

$$O_{ijkl}^{(3)}=\frac{1}{2}(\overline{L}_i\gamma_\mu\tau^a L_j)(\overline{L}_k\gamma^\mu\tau^a L_l). \tag{4}$$

(3) Operators that generate LFV interaction for the Z and Higgs bosons,

$$O_{D\phi}^{ij}=i(\phi^\dagger D^\mu\phi)(\overline{l}_{Ri}\gamma_\mu l_{Rj}),$$

$$O_{D\phi}^{(1)ij}=i(\phi^\dagger D^\mu\phi)(\overline{L}_i\gamma_\mu L_j),$$

$$O_{D\phi}^{(3)ij}=i(\phi^\dagger\tau^a D^\mu\phi)(\overline{L}_i\gamma_\mu\tau^a L_j), \tag{5}$$

$$O_{Dl}^{ij}=(\overline{L}_i D^\mu l_{Rj})D_\mu\Phi,$$

$$O_{DL}^{ij}=(\overline{D^\mu L}_i l_{Rj})D_\mu\Phi \tag{6}$$

(4) Yukawa-type operators that generate LFV interactions of the Higgs boson only,

$$O_{L\phi}^{ij}=(\Phi^\dagger\Phi)(\overline{L}_i l_{Rj}\Phi). \tag{7}$$

Several comments regarding these operators are in order.

The operators (2) and (3) must be generated as a loop-effect in the fundamental theory. In this case the constraints obtained from $e-\mu$ transitions are quite strong, because the resulting LFV transitions of the photon mediate the decays $\mu\to e\gamma$, eee, and electron-muon conversion. If one takes $\alpha^{ij}=1$, these processes imply a strong bound on the scale associated to LFV $[\Lambda_{LFV}>O(100)\ \text{TeV}]$. However, the bounds associated with LFV transitions of the tau lepton are significantly smaller.

The set (4) is favored in composite models, and it also induces strong bounds on the scale Λ_{LFV} for $e\mu$ transitions.

The set of operators (5) and (6), which generate LFV interactions for both the Z and Higgs boson, provide a convenient framework to discuss LFV for the Higgs sector. In fact, one can use the bounds on the decays $Z\to l_i l_j$ and $l_i\to l_j l_k l_k$ to constrain their coefficients, and use them to predict the rates for the Higgs decays $H\to l_i l_j$. Operators (5) arise at tree-level, whereas Eq. (6) arise as one-loop effects from the underlying theory. It is interesting to note that the operators (5),(6),(7), which generate the vertices $Zl_i^+l_j^-$ and $Hl_i^+l_j^-$, do not induce the LFV photon vertex $Al_i^+l_j^-$, which in fact just follows from $\mathrm{U}(1)_{em}$ gauge invariance.

Operators (7) contribute to the fermion masses too; thus in order to derive the corresponding Feynman rules in a consistent manner, one should include their contribution to the fermion mass matrices, then perform their diagonalization, and finally write down the interaction Lagrangian in terms of mass eigenstates. However, we find that the effect of the diagonalizaing matrices can be reabsorbed into the (unknown) coefficients of the effective operators.[1]

[1]We have also verified, through a systematic use of the equations of motion, that other operators of the type $O_{ij}=i(\Phi^\dagger\Phi)\overline{L}_i\gamma^\mu D_\mu L_j$, which apparently can induce LFV interactions for photon, Z and Higgs boson, can be reduced to the form of Eq. (7).

Since the operators (2)–(4) do not generate LFV Higgs interactions, they willl not be discussed furthermore here. Their inclusion could strengthen the bounds on the coefficients of the operators (5)–(7) and, pending unnatural cancellations, it would allow larger values for the B.R. of the LFV Higgs decays. Since we want to retain only the essential physics of our problem, and to work within a conservative approach, our analysis will concentrate on the operators (5)–(7).

After SSB, one gets the LFV interactions of the Z and the remaining Higgs boson (H), which are described by the following Lagrangians:

$$L_{Zl_il_j}=-\frac{g}{4c_W}Z^{\mu}\Big\{\epsilon^{ij}_{D\phi}(\overline{l}_{Ri}\gamma_\mu l_{Rj})+(\epsilon^{(1)ij}_{D\phi}+\epsilon^{(3)ij}_{D\phi})\times(\overline{l}_{Li}\gamma_\mu l_{Lj})-\frac{1}{(4\pi)^2}\frac{2\sqrt{2}c_W}{gv}[\epsilon^{ij}_{Dl}(\overline{l}_{Li}\partial_\mu l_{Rj})+\epsilon^{ij}_{DL}(\partial_\mu\overline{l}_{Li}l_{Rj})]\Big\}+\text{H.c.},\tag{8}$$

$$L_{H^0l_il_j}=-g^2\epsilon^{ij}_{L\phi}H^0(\overline{l}_{Li}l_{Rj})+\frac{i}{2v}\partial^\mu H^0[\epsilon^{ij}_{D\phi}(\overline{l}_{Ri}\gamma_\mu l_{Rj})+(\epsilon^{(1)ij}_{D\phi}+\epsilon^{(3)ij}_{D\phi})(\overline{l}_{Li}\gamma_\mu l_{Lj})]+\frac{1}{(4\pi)^2}\frac{1}{\sqrt{2}v^2}\partial^\mu H^0[\epsilon^{ij}_{Dl}(\overline{l}_{Li}\partial_\mu l_{Rj})+\epsilon^{ij}_{DL}(\partial_\mu\overline{l}_{Li}l_{Rj})]+\text{H.c.},\tag{9}$$

where L denotes the standard left-hand lepton doublet under $SU(2)_L$ (but the subindices L,R are used to denote left- and right-handed fermion fields), $v=\sqrt{2}\langle\Phi\rangle_0$, $c_W=\cos\theta_W$, $s_W=\sin\theta_W$. In Eqs. (8),(9), we have introduced the dimensionless quantities $\epsilon^{ij}_n=(v/\Lambda_{LFV})^2\alpha^{ij}_n$, to absorb the dependence on the parameters Λ and α^{ij}_n into a single factor. We have also introduced explicitly the factor $1/(4\pi)^2$, for the coeffcients of the loop-induced operators (6). In fact, Eq. (9) describes the most general LFV interactions of a Higgs boson with terms of dimensions four, five, and six.

From the interactions contained in Eqs. (8) and (9), we can derive the expressions for the decay widths of the processes $l_i\to l_j+l_k+l_k$ and $Z\to l_i^+ + l_j^-$, which will be used to constrain the parameters ϵ^{ij}_n. We shall be working to first order in the parameters ϵ^{ij}_n. On the other hand, although there are strong experimental bounds on the radiative decays $\mu\to e+\gamma,\tau\to e+\gamma,\mu+\gamma$, it happens that they receive contributions from the operators (5)–(7) only to second order in the parameters ϵ^{ij}_n, and the resulting constraints are rather weak and can be neglected in the present analysis. The results for the decay widths are

$$\Gamma(Z\to l_i^+l_j^-)=\frac{\alpha m_Z}{96s_W^2c_W^2}\left[|\epsilon^{ij}_{D\phi}|^2+|\epsilon^{(1)ij}_{D\phi}+\epsilon^{(3)ij}_{D\phi}|^2+\frac{1}{4(4\pi)^4}|\epsilon^{ij}_{DL}-\epsilon^{ij}_{Dl}|^2\right],\tag{10}$$

$$\Gamma(l_i\to l_jl_k^+l_k^-)=\frac{\alpha^2(g_V^{k2}+g_A^{k2})m_i}{2048\pi s_W^4c_W^4}\left(\frac{m_i}{m_Z}\right)^4\times\Big\{\frac{2}{3}[|\epsilon^{ij}_{D\phi}|^2+|\epsilon^{(1)ij}_{D\phi}+\epsilon^{(3)ij}_{D\phi}|^2]+\frac{1}{(4\pi)^4}\frac{m_i^2}{5m_Z^2}|\epsilon^{ij}_{Dl}+\epsilon^{ij}_{DL}|^2+\frac{1}{(4\pi)^2}\frac{\sqrt{2}}{3}\frac{m_i}{m_Z}Im\,\epsilon^{ij*}_{D\phi}(\epsilon^{ij}_{Dl}+\epsilon^{ij}_{DL})\Big\},\tag{11}$$

where g_V^k,g_A^k denote the vector and axial-vector couplings of lepton k with the Z boson; α denotes the fine structure constant, θ_W is the electroweak (EW) mixing angle. In deriving these expressions, we have neglected the lepton masses of the final states. For the decay $l_i\to l_jl_kl_k$, we have included only the Z-mediated contributions, because we are assuming that the diagonal Higgs-fermion terms are of similar strength to the SM values, thus their contribution to the decay amplitude can be neglected. One can see from the above expressions that the effects coming from the operator (5) will be dominant, whereas the one coming from the loop-induced operator (6) will be more suppressed.

Then, we can evaluate the width for the LFV Higgs decays from the Lagrangian (9), the result is given by

$$\Gamma(H^0\to l_i^+ + l_j^-)=\frac{\pi\alpha^2m_{H^0}}{s_W^4}[|A_L^{ij}|^2+|A_R^{ij}|^2],\tag{12}$$

where

$$A_L^{ij}=\epsilon^{ij}_{L\phi}-\frac{s_W}{8c_W\sqrt{\pi\alpha}}\left[\frac{m_i}{m_Z}(\epsilon^{(1)ij}_{D\phi}+\epsilon^{(3)ij}_{D\phi})-\frac{m_j}{m_Z}\epsilon^{ij}_{D\phi}\right]-\frac{\sqrt{2}}{c_W^2}\frac{1}{(4\pi)^2}\left(\frac{m_{H^0}}{m_Z}\right)^2[\epsilon^{ij}_{DL}+\epsilon^{ij}_{Dl}],\tag{13}$$

$$A_R^{ij}=\frac{s_W}{8c_W\sqrt{\pi\alpha}}\left[\frac{m_i}{m_Z}\epsilon^{ij}_{D\phi}-\frac{m_j}{m_Z}(\epsilon^{(1)ij}_{D\phi}+\epsilon^{(3)ij}_{D\phi})\right].\tag{14}$$

In order to present results for the branching ratios of the Higgs boson into the LFV modes, we could choose many combinations for the ϵ parameters that satisfy the experimen-

TABLE I. Bounds on the LFV parameters ϵ_n^{ij} for the effective Lagragian scenarios considered in this paper.

Mode	''Democratic'' scenario $\lvert\epsilon^{ij}\rvert^2<$	''Loop'' scenario $\lvert\epsilon_{Dl}^{ij}-\epsilon_{DL}^{ij}\rvert^2<$	''Yukawa'' scenario
$Z\to\mu e$	1.1×10^{-5}	5.4	
$Z\to\tau e$	6.2×10^{-5}	31.2	
$Z\to\tau\mu$	1.1×10^{-4}	54.2	
Mode	$\lvert\epsilon^{ij}\rvert^2<$	$\lvert\epsilon_{Dl}^{ij}+\epsilon_{DL}^{ij}\rvert^2<$	$\lvert\epsilon_{L\Phi}^{ij}\rvert^2/m_H^4<$
$\mu\to eee$	4.4×10^{-12}	1.4	3.42×10^{-9}
$\tau\to eee$	8.1×10^{-5}	9.3×10^4	6.3×10^{-2}
$\tau\to\mu ee$	8.1×10^{-5}	9.6×10^4	6.5×10^{-2}
$\tau\to\mu\mu\mu$	8.1×10^{-5}	5.4×10^4	8.5×10^{-7}

tal bounds on LFV processes. However, in order to simplify the analysis, we shall only consider three scenarios, which illustrate the possibilities to detect LFV through Higgs decays.

(1) The ''Democratic'' scenario, where we simply assume that all the parameters ϵ that appear in Eqs. (10), (11) are equal, i.e., $\epsilon_{D\phi}^{ij}=\epsilon_{D\phi}^{(1)ij}=\epsilon_{D\phi}^{(3)ij}=\epsilon_{DL}^{ij}=\epsilon_{Dl}^{ij}=\epsilon^{ij}$, which is probably the most conservative case. The resulting bounds arising from the $Z\to l_i^+l_j^-$ and $l_i\to l_j l_k l_k$, are shown in the first column of Table I. We can see that the 3-body decay $\mu\to eee$ provides the strongest bound for $e-\mu$ transitions, whereas the Z-decays gives slightly better bounds for tau transitions. To evaluate the B.R. of the Higgs boson in this ''democratic'' scenario we also take $\epsilon_{L\phi}^{ij}=\epsilon^{ij}$; the results are shown in Fig. 1, and we can see that the modes $H\to\tau\mu/\tau e$ reach a B.R. of order 0.1 that seems to be at the reach of Tevatron for intermediate Higgs boson masses (95 GeV $<m_H<2m_W$), whereas the decay $H\to\mu e$ can be at most of order 10^{-9}.

(2) The ''Loop-dominated'' scenario, where we assume that only the loop-induced operators (6) contribute to LFV. In this case we find that the present data do not impose strong bounds on the coefficients of these operators, as it is shown in Table I (column 2). Moreover, in this case the bounds do not distinguish among the different LFV modes. However, even if we assume that the respective coefficients α_n^{ij} are of order 1, it is found that the B.R. of the LFV Higgs decays are of order 10^{-3}. Figure 2 shows the values of the B.R. for the LFV modes assuming several values of the parameter $\epsilon_{DL,Dl}^{ij}$, namely 0.06,0.005,0.0005 (the first value corresponds to the values $\Lambda_{LFV}=1$ TeV and $\alpha_{DL,Dl}^{ij}=1$).

(3) The ''Yukawa-dominated'' scenario; in this case it is assumed that the operator (7) is the only operator responsible for LFV Higgs interactions. This scenario is weakly constrained by low-energy bounds, and in fact the resulting bounds are not significant. Thus, we choose to present the B.R. for the Higgs LFV modes as a function of the parameter $\epsilon_{L\phi}^{ij}$. However, in order to introduce a criterion to discriminate among the different decay modes, we shall also include a factor that takes into account the breaking of the flavor symmetries, which would be respected in the absence of fermion masses. The flavor-dependent factor used here is similar to

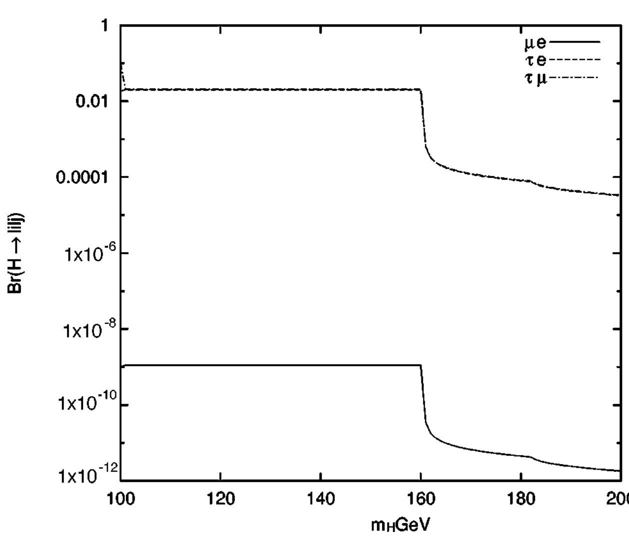

FIG. 1. B.R. of LFV Higgs decays for the effective Lagrangian approach in the ''democratic scenario.'' The splitting between the $\tau\mu$ and τe curves is about 10^{-4}.

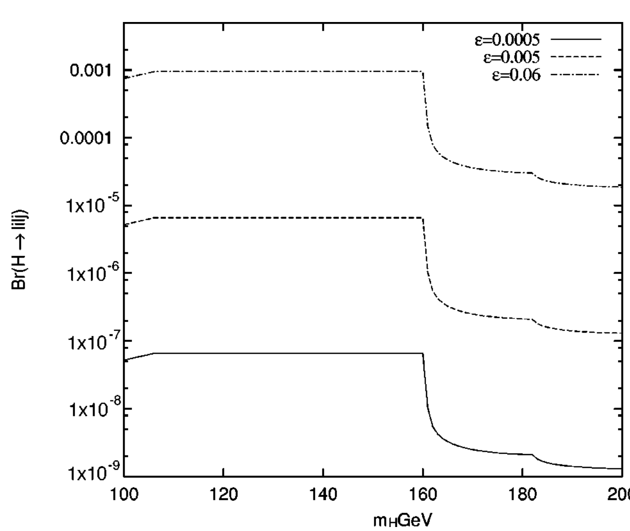

FIG. 2. B.R. of LFV Higgs decays for the effective Lagrangian approach in a ''radiative-dominated'' scenario. In this case all the LFV Higgs decay modes have the same B.R.

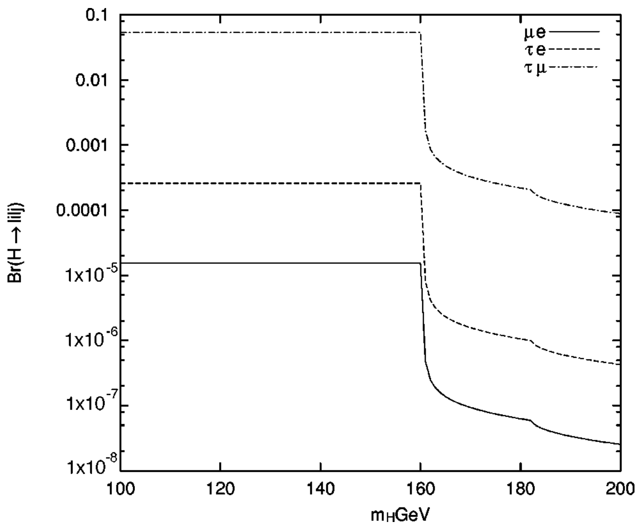

FIG. 3. B.R. of LFV Higgs decays for the effective Lagrangian approach in a ''Yukawa-dominated'' scenario.

the ansatz introduced in the general two-Higgs doublet model to suppress FCNC, which will be discussed in the next section, namely, we take $\epsilon_n^{23}=0.06(m_\mu/m_\tau)^{1/2}$, $\epsilon_n^{13}=0.06(m_e/m_\tau)^{1/2}$, $\epsilon_n^{12}=0.06[(m_e m_\mu)^{1/2}/m_\tau]$. The factor 0.06 corresponds to the value of $\epsilon_{L\Phi}^{ij}$ that is obtained for $\Lambda_{LFV}=1$ TeV and $\alpha_{L\phi}^{ij}=1$. The results for the B.R. are shown in Fig. 3; we find that the mode $H\to\tau\mu$ can also reach a B.R. of order 0.1, which can be easily tested at Tevatron Run-II for intermediate Higgs masses.

III. RESULTS FOR SPECIFIC MODELS

In this section we shall evaluate the LFV Higgs decays for three specific models, namely, for the SM with massive neutrinos, the THDM-III and the MSSM.

A. LFV with massive neutrinos

The SM with massive neutrinos provides the simplest example where LFV decays of the Higgs boson appear. It is well known that the existence of massive neutrinos requires the inclusion of physics beyond the SM [7,8]. Assuming that the low-energy effect of the physics responsible for neutrino masses can be parametrized by the neutrino mass eigenvalues (m_{ν_i}) and the leptonic mixing matrix (V_{ij}), the leading contributions of massive neutrinos to the 1-loop decay $H\to l_i^+ l_j^-$ can be estimated by just evaluating the loop with two internal W's, which give the finite result:

$$\Gamma(H\to l_i^+ l_j^-)=\frac{\alpha^3}{32\pi^3\sin^6\theta_W}\frac{m_i^2 m_W^2}{m_H^3}|A_{ij}|^2, \tag{15}$$

where m_i, m_W, m_H denote the mass of the heavier (charged) lepton, W and Higgs boson, respectively. The factor A_{ij} is given by $A_{ij}=V_{ik}^* V_{kj}\,\log(m_{\nu k}/m_W)$.

The present bounds on the mixing angles and the neutrino masses [2], indicate that $A_{\tau\mu}\simeq O(1)$ [9]. Thus, for $m_H=100$ GeV the resulting B.R. for the mode $H\to\mu\tau$ is B.R.$\simeq 6\times10^{-7}$; whereas the mode $H\to e\mu$ is expected to be even more suppressed because present data suggest $A_{e\mu}\ll A_{\mu\tau}$. These rates are clearly beyond experimental reach.

B. LFV in the general two-Higgs doublet model

We are also interested in studying the LFV Higgs decays in the general two-Higgs doublet extension of the SM (THDM). This model has potential problems with FCNC, which were solved in its early versions (the so-called Models I and II) [10] by requiring a discrete symmetry that restricted each fermion to couple at most to one Higgs doublet; and flavor changing neutral scalar interactions (FCNSI) are absent at the tree-level. Later on, it was found that FCNSI could be suppressed at acceptable rates, with relatively light Higgs bosons, by impossing a more realistic pattern on the Yukawa matrices, which in principle can be associated with some family symmetry [11].

The phenomenological predictions of this model (called model III in the literature [12]) have been studied to some extent. In this paper we use the Higgs mass-eigenstate basis, which is more appropriate when one is interested in the detection of direct Higgs signatures. In this basis the LFV interactions of the neutral Higgs boson H^0 of model III take the form:

$$\mathcal{L}_{LFV}=\xi_{ij}\cos\alpha\,\overline{l}_i l_j H^0+\text{H.c.}, \tag{16}$$

where α denotes the mixing angle of the neutral Higgs sector, and ξ_{ij} denotes the Yukawa coupling of the second doublet. In order to satisfy the low-energy data on FCNC, Cheng and Sher [13] proposed the following ansatz:

$$\xi_{ij}=\lambda_{ij}\frac{(m_i m_j)^{1/2}}{v} \tag{17}$$

where $v=246$ GeV and the lepton mass factor gives the order of magnitude of the interaction. The coefficients λ_{ij} are dimensionless parameters that can be constrained by comparing the prediction for relevant processes with present experimental bounds on FCNC and LFV transitions. The strongest bound for the parameters λ_{ij} are obtained from muon anomalous magnetic moment [14], namely: $\lambda_{\mu\tau}<10$, which involves only one coupling. Other interesting bounds are $(\lambda_{e\mu}\lambda_{\mu\tau})^{1/2}<5$, which are obtained from the decay $\mu\to e+\gamma$. We have also studied the decay $\mu\to eee$, and find the result: $(\lambda_{ee}\lambda_{e\mu})^1/2<200$, which is not as good as the one obtained from the muon anomalous magnetic moment.

Then, the corresponding decay width for $h^0\to l_i^+ l_j^-$ is given by

$$\Gamma(H^0\to l_i^+ l_j^-)=\frac{\xi_{ij}^2}{8\pi}\cos^2\alpha\, m_H. \tag{18}$$

The dominant decay mode of the Higgs boson in the intermediate mass range is expected to be $H\to b\overline{b}$, which will be proportional to $\sin^2\alpha$.

TABLE II. B.R. of LFV Higgs decays for the THDM-III. Results are shown for $\sin\alpha=0.1$, and the numbers in parenthesis correspond to $\sin\alpha=0.9$.

m_H GeV	B.R.$(H\rightarrow\mu\tau)$	B.R.$(H\rightarrow e\mu)$
100	0.7 (0.1)	1.3×10^{-5} (2.0×10^{-6})
130	0.7 (0.1)	1.2×10^{-5} (2.1×10^{-6})
170	0.3 (1.2×10^{-3})	5.5×10^{-6} (2.3×10^{-8})
200	0.1 (3.5×10^{-4})	2.2×10^{-6} (6.4×10^{-9})

Then, if we include the present bounds for λ_{ij}, the resulting upper limit on the B.R. of the mode $H\rightarrow e\mu$ is of the order 10^{-5} for $\sin\alpha=0.1$, which does not seem to be in the reach of future experiments. On the other hand, the mode $H\rightarrow\mu\tau$ is allowed to have a B.R. of order 0.1, which seems in the reach of future colliders. In fact, the direct search for this mode at Run-II of Tevatron could be used to improve the limits on the values of $\lambda_{\mu\tau}$. Results for $\sin\alpha=0.1$ (0.9) are shown in Table II.

C. The minimal SUSY SM (MSSM)

LFV interaction can also arise at 1-loop in the minimal SUSY standard model (MSSM) [15]. The MSSM has become one the most preferred extension of the SM; it predicts new signatures associated with the superpartners, although it reproduces the SM agreement with data. The most general Lagrangian for the MSSM has problems with FCNC. In the supergravity (SUGRA) inspired models [16], potential FCNC problems are solved by assuming that the sfermion masses are degenerated and the cubic A-terms are proportional to the mass of the corresponding fermion. However, these conditions only hold at a heavy [grand unified theory (GUT)] scale, and once these parameters are evolved down to the EW scale ($M_{EW}=246$ GeV), some detectable FCNC effects may arise. To illustrate the rates that arise in the MSSM, we shall evaluate the LFV effects that arise from the Higgs-slepton vertex in the minimal SUSY SU(5) model. Then, we can use the results of [17], which give the following expression for the off-diagonal A-terms:

$$A^l_{ij}=-\frac{9}{16\pi^2}[V^{3i}_{CKM}V^{3j*}_{CKM}Y^2_tY_i]a_0m_0\log\frac{M_{EW}}{M_{GUT}}, \quad (19)$$

where V^{ij}_{CKM} denotes the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix, whereas Y_f, a_0, m_0 correspond to the Yukawa, trilinear and universal scalar mass, respectively.

To estimate the decay width $H^0\rightarrow l^+_i l^-_j$ for the light Higgs boson H^0, one could evaluate the graph that includes only sleptons and bino inside the loop, which gives the following finite result:

$$\Gamma(H^0\rightarrow l^+_i l^-_j)=\frac{9\alpha^3}{6400\pi^2c^2_W}\left[\frac{A^{l2}_{ij}m^3_H}{\tilde{m}_0{}^3}\right]. \quad (20)$$

Then, if we include the corresponding lepton masses and take $a_0=\tilde{m}_0=100$ GeV, the resulting B.R. for $H\rightarrow e\mu$ is of the order 10^{-11}, whereas for $H\rightarrow\tau\mu/\tau e$ it can be of order 10^{-6}, which are much smaller than the ones obtained with the effective Lagrangian and THDM III.

IV. DISCUSSION OF RESULTS AND CONCLUSIONS

We have studied the lepton flavor violating (LFV) decays of Higgs bosons $H\rightarrow l^+_i l^-_j$, in several extensions of the SM. Results for the Effective Lagrangian approach and the general two-Higgs doublet model (THDM-III) are presented in detail, whereas for the SM with massive neutrinos and the minimal SUSY-SM, some estimates are given. In the effective Lagrangian case, it is found that for those operators whose coefficients cannot be constrained by present data, the LFV Higgs decays could have a branching ratio (B.R.) of order 10^{-1}, which could be detected at hadron colliders (Tevatron or LHC). Those cases when current bounds on LFV transition apply, induce strong bounds for $e-\mu$ transitions, and the resulting B.R. for the decay $H\rightarrow e\mu$ is of order 10^{-9}; however, the bounds involving the tau are considerably weaker, and allow the mode $H\rightarrow\tau\mu/\tau e$ to have a B.R. of the order 10^{-1} too. Similar results are obtained for THDM-III; whereas the corresponding decays in the SM with massive neutrinos and the minimal SUSY-SM are much smaller.

Thus, we found that the LFV Higgs decays $H\rightarrow\tau\mu/\tau e$ can have large branching ratios, of order 0.1 in some cases. It is important to estimate whether such rates can be detected at future colliders. At the next run-II of Tevatron, it is possible to use the gluon-fusion mechanism to produce a single Higgs boson; assuming that the production cross-section is of similar strength to the SM case, about 1.2 pb for $m_H=100$ GeV, it will allow us to produce 12,000 Higgs bosons with an integrated luminosity of 10 fb^{-1}. Thus, for B.R.$(H\rightarrow\tau\mu/\tau e)\simeq10^{-1}$ Tevatron can produce 1200 events. Since it has been shown that it is possible to identify the hadronic decays of the tau lepton at Tevatron [18], it seems logical to study the LFV Higgs into $\tau\mu/\tau e$ by imposing a cut on the invariant-mass of the final state, which should allow us to identify the signal. On the other hand, since the mode $H\rightarrow\mu e$ can reach at most a B.R. of order 10^{-3}, then it will require a higher luminosity to be detected. For instance, if we have an integrated luminosity of 30 fb^{-1}, then we get 18 events, after including a detection efficiency of 50%. Although the rate seems quite low, the signal is so distinctive that using a cut on the invariant mass should allow us to eliminate the SM backgrounds.

In summary, we have found several cases where the LFV Higgs decays may be at the reach of the Run II of Tevatron, which should be considered as a motivation, or starting point, to search for LFV Higgs decays at present and future colliders.

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