Lepton flavor violating Higgs boson decay $H \rightarrow \mu\tau$ at muon colliders

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Abstract

We consider an effective nondiagonal coupling $H\bar{\mu}\tau$ and present the analysis of the Higgs boson mediated lepton-flavor violating (LFV) reaction $\mu^-\mu^+ \rightarrow \mu^\pm\tau^\mp$. For a Higgs boson mass around 115 GeV and convenient values of the strength of the coupling $H\bar{\mu}\tau$, which are within the bounds obtained from the experimental limits on the LFV decays $\tau^- \rightarrow \eta\mu^-$ and $\tau^- \rightarrow \mu^-\gamma$, we found that there would be up to a few hundreds of $\mu^\pm\tau^\mp$ events per year at a muon collider running with an integrated luminosity of 1 fb^{-1}. We paid special attention on the background for this LFV reaction, which arises from the standard model process $\mu^-\mu^+ \rightarrow \mu^\pm\tau^\mp\bar{\nu}_\mu\nu_\tau$, and discuss how it can be separated from the main signal.

Hopefully a Higgs boson will soon be detected, but it will still remain to determine several of its properties, whose study may shed light on the physics underlying the standard model (SM). One of the main tasks of the present and future particle accelerators is thus to perform a careful determination of the Higgs boson properties such as mass, decay width, couplings to other particles, and properties under the discrete symmetries C and P. This will be the goal of the CERN large hadron collider (LHC) but also of the next generation colliders, for which there are several alternatives such as a linear e^-e^+ collider and a muon collider. A major advantage of a muon collider is that it would operate as a Higgs boson factory [1], thereby offering great opportunities for the study of the Higgs boson properties and potential new physics effects in which this particle could play a relevant role.

Since lepton flavor violation (LFV) is forbidden in the SM, any observation of this class of effects would be a hint of new physics. This has brought considerable attention to LFV. The prospect of a muon collider, which would operate as

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a Higgs boson factory, opens up the possibility for the study of scalar mediated LFV processes. If the Higgs boson has nondiagonal couplings to the leptons, they may become evident through the reaction $\mu^- \mu^+ \to H \to \mu^\pm \tau^\mp$. LFV mediated by a neutral Higgs boson has long been studied in specific models such as two-Higgs doublet models (THDMs), suppersymmetry (SUSY) theories [2,3,4], and other beyond-the-SM scenarios [5]. Also, these interactions were recently studied in a model independent way within the framework of effective Lagrangians in Ref. [6]. The possible detection of the decay $H \to \mu \tau$ has already been considered at hadronic colliders [7], muon colliders [8], and $e^- e^+$ linear colliders [9]. As far as constraints on the nondiagonal coupling $H \bar{l}_i l_j$ $(l_i = e, \mu, \tau)$ are concerned, they have been obtained from the LFV decays $l_i \to l_j \bar{l}_k l_k$, $l_i \to l_j \gamma$, $l_i \to l_j \eta$, and the muon anomalous magnetic moment [10]. All these studies have focused mainly on the most general THDM. In this work we will present the study of LFV at a muon collider via $\mu^- \mu^+ \to \mu^\pm \tau^\mp$ scattering mediated by the Higgs boson. The analysis will be performed within the framework of the effective Lagrangian approach (ELA), which is tailored for the study of new physics effects in a model independent fashion [11].

The $Hl_i l_j$ coupling is induced by the following Yukawa-like operator of dimension six [6]:

$$O_{L_\phi}^{ij} = \phi^\dagger \phi \, \bar{L}'_i \phi \, l'_{Rj}, \tag{1}$$

where L'_i and l'_{Rj} represent the left-handed doublet and right-handed singlet of the electroweak group, ϕ is the Higgs doublet and the subscripts i and j stand for distinct lepton families, whereas the prime denotes gauge eigenstates. Although the coupling $H\bar{l}_i l_j$, and also the $Z\bar{l}_i l_j$ one, is induced at the tree-level by another set of dimension six operators [12], the contribution of such effective operators is suppressed by the factor $m_{i,j}/m_Z$ and will be neglected from now on.

The effective operator (1) induces the following Lorentz structure for the LFV coupling $Hl_i l_j$:

$$\mathrm{L}^{Hl_i l_j} = \frac{i \, g \, \xi_{ij}}{2} \bar{l}_i \, l_j, \tag{2}$$

where ξ_{ij} is an unknown coefficient that parametrizes our ignorance of the new physics inducing LFV. Of course, when a particular model is considered, ξ_{ij} takes a particular form. For instance, in the most general THDM [13], dubbed model III, where scalar LFV couplings are allowed at the tree-level, it is usual to consider the parametrization introduced by Cheng and Sher [14]: $\xi_{ij} = \lambda_{ij} \sqrt{m_i m_j}/m_W$, where λ_{ij} is a free parameter to be constrained by low-energy experiments. This parametrization, which is suited for models with

multiple Higgs doublets, suggests that LFV couplings involving the electron are naturally suppressed, whereas LFV transitions involving the muon and the tau are much less suppressed and can have a sizeable strength, which may be able to give rise to effects that could be observed at particle colliders. It has been suggested that $\lambda_{\mu\tau} \sim O(1)$ [14], though current constraints on this parameter from experimental data are very weak and allow much larger values for $\lambda_{\mu\tau}$ [10]. Instead of considering a specific model, we will pursue a model independent approach and consider the most stringent bounds on $\xi_{\mu\tau}$ as obtained from the most recent experimental data on LFV processes.

We will consider two possibilities for LFV in the Higgs sector. In the SM there is only one Higgs doublet and the diagonalization of the mass matrix simultaneously diagonalizes the matrix of Yukawa couplings. LFV can arise when the Higgs sector is comprised by more than one Higgs doublet or a more complex set of Higgs multiplets. In the simplest case, the mere addition of only one Higgs doublet can give rise to tree-level scalar LFV couplings such as occurs in the model III. Nevertheless, it is well known that any tree-level LFV couplings of the Higgs boson can be eliminated by invoking a discrete symmetry [15]. In this scenario, this class of effects can still arise at the one-loop level via the virtual effects of new particles. A simple example of this scenario is given by SUSY models, in which the LFV arises at the one-loop level by the exchange of SUSY particles [2,4]. Instead of choosing a particular model, effective Lagrangians allow one to study LFV in a general fashion. In our analysis we will assume that there is a relatively light Higgs boson whose behavior deviates marginally from that predicted by the SM, i.e. we will consider LFV effects mediated by a SM-like Higgs boson.

In order to be able to make predictions it is necessary to give a numerical value to the coefficient $\xi_{\mu\tau}$. According to the effective Lagrangian philosophy, this parameter is to be bounded from the current experimental limits on LFV processes such as the decays $\tau^- \to \mu^-\mu^+\mu^-$, $\tau^- \to \mu^-\gamma$, and $\tau^- \to \eta\mu^-$. The branching ratio of the one-loop process $\tau^- \to \mu^-\gamma$ reads, in the $m_\mu \to 0$ limit:

$$Br(\tau^- \to \mu^-\gamma) = \frac{\alpha^3 \, |F(m_\tau, m_H)|^2 \, m_\tau^3 \, \xi_{\mu\tau}^2}{512 \, \pi^2 \, s_W \, c_W \, m_Z^2 \, \Gamma_\tau}, \tag{3}$$

where Γ_τ is the full τ width, and $F(m_\tau, m_H)$ is given by

$$F(m_\tau, m_H) = \frac{1}{2} + \left(2 - \frac{m_H^2}{m_\tau^2}\right) \left(B_0(m_\tau^2, m_\tau^2, m_H^2) - B_0(0, m_\tau^2, m_H^2)\right)$$
$$+ 2 \, m_\tau^2 C_0(0, 0, m_\tau^2, m_H^2, m_\tau^2, m_\tau^2). \tag{4}$$

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with C_0 and B_0 the usual Passarino-Veltman scalar functions. The experimental bound on this decay is [16]: $Br_{exp}(\tau^- \to \mu^-\gamma) \leq 1.1 \times 10^{-6}$.

As far as the decay $\tau^- \to \eta\mu^-$ is concerned, its branching ratio is related to that of the decay $\tau^- \to \mu^-\mu^+\mu^-$ as follows $Br(\tau^- \to \eta\mu^-) = 8.4 Br(\tau^- \to \mu^-\mu^+\mu^-)$. Considering the leading term in m_μ we have

$$Br(\tau^- \to \mu^-\mu^+\mu^-) = \frac{1}{\Gamma_\tau} \frac{\alpha^2 \, m_\tau^5}{1536 \, \pi \, s_W^4 \, m_H^4} \left(\frac{m_\mu}{m_W}\right)^2 \xi_{\mu\tau}^2, \tag{5}$$

whereas the experimental limit on $\tau^- \to \eta\mu^-$ is [17]: $Br_{exp}(\tau^- \to \eta\mu^-) \leq 3.4 \times 10^{-7}$.

The limits on $\xi_{\mu\tau}$ obtained via these decays are shown in Table 1 for different values of m_H. These values are much less stringent than those that are obtained via the Cheng-Sher ansatz, which is only appropriate for models with multiple Higgs doublets [14]. Nevertheless, our study is focused on a broader class of models inducing LFV, including that class of models in which the Cheng-Sher ansatz applies but also those theories in which the LFV arise at the one-loop level. Below we will take a conservative approach and consider the values in the range 10^{-3}-10^{-1} for $\xi_{\mu\tau}$.

Table 1
Bounds on the LFV parameter $\xi_{\mu\tau}$ as a function of the Higgs boson mass from the decays $\tau^- \to \mu^-\mu^+\mu^-$ (first row) and $\tau^- \to \mu^-\gamma$ (second row).

m_H (GeV)	120	130	140	150	200
$\xi_{\mu\tau} \leq$	1.75	2.05	2.38	2.73	4.87
$\xi_{\mu\tau} \leq$	1.61	1.85	2.10	2.37	3.91

We turn now to the calculation of scalar mediated $\mu^-\mu^+ \to \mu^\pm\tau^\mp$ scattering. We will neglect the lepton masses everywhere except in the term associated with the $H\bar{\mu}\mu$ coupling. It is straightforward to obtain the unpolarized cross section after averaging over initial polarizations and integrating over the scattering angle:

$$\sigma(\mu^-\mu^+ \to \mu^\pm\tau^\mp) = \frac{\pi^2 \, \alpha^2 \, m_\mu^2 \, \xi_{\mu\tau}^2}{16 \, s_W^4 \, m_W^2 \, \pi s}(A_s + A_t + A_{st}), \tag{6}$$

with

$$A_s = \frac{\hat{s}^2}{(\hat{s} - 1)^2 + \hat{\Gamma}_H^2},$$
$$A_t = \frac{2(1 + \hat{s}) \log(1 + \hat{s}) - \hat{s}(2 + \hat{s})}{\hat{s}(1 + \hat{s})},$$

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$$A_{st} = \frac{(\hat{s}-1)\,(\hat{s}-\log{(1+\hat{s})})\,\hat{s}}{(\hat{s}-1)^2 + \hat{\Gamma}_H^2}, \tag{7}$$

where $\hat{s} = s/m_H^2$ and $\hat{\Gamma}_H = \Gamma_H/m_H$, with s the square of the center of mass energy of the muon collider, and Γ_H the total Higgs boson decay width. In Fig. 1 we show the numerical evaluation of (6) for different values of $\xi_{\mu\tau}$. We have assumed that Γ_H is approximately given by the total decay width of the SM Higgs boson, which was evaluated via the HDECAY program [18]. As expected, we can see that the $\mu^-\mu^+ \to \mu^\pm\tau^\mp$ cross section is only relevant in the resonance region, where it takes the familiar form:

$$\sigma(\mu^-\mu^+ \to \mu^\pm\tau^\mp) = \frac{4\pi}{m_H^2} Br(H \to \mu^-\mu^+) Br(H \to \mu^\pm\tau^\mp), \tag{8}$$

with

$$Br(H \to \mu^-\mu^+) = \frac{\alpha\, m_H\, m_\mu^2}{8\, s_W^2\, m_W^2\, \Gamma_H}, \tag{9}$$

and

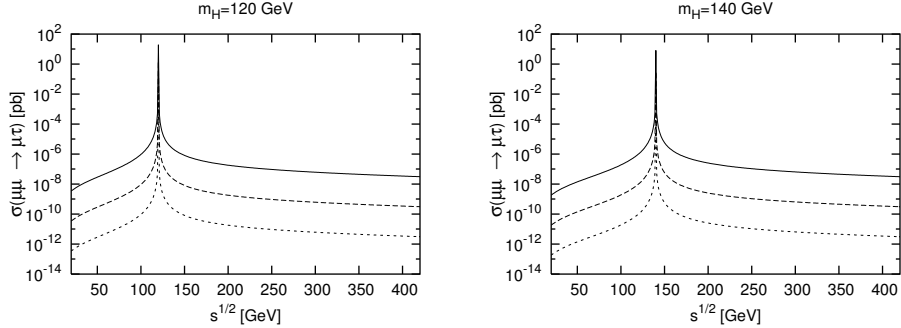$$Br(H \to \mu^\pm\tau^\mp) = \frac{\alpha\, m_H\, \xi_{\mu\tau}^2}{8 s_W^2 \Gamma_H}. \tag{10}$$

Fig. 1. Unpolarized $\mu^-\mu^+ \to \mu^\pm\tau^\mp$ cross section as a function of the energy of the center of mass frame for two values of m_H and distinct values of $\xi_{\mu\tau}$: 10^{-1} (line), 10^{-2} (dashes) and 10^{-3} (points.)

We will now concentrate on the scenario in which the muon collider operates as a Higgs boson factory. In Fig. 2 we show the cross section for $\mu^-\mu^+ \to \mu^\pm\tau^\mp$ scattering as a function of the Higgs boson mass. Although we only show the $\mu^-\mu^+ \to \mu^\pm\tau^\mp$ cross section for $\xi_{\mu\tau} = 10^{-2}$, which is a moderate value if we consider the bounds given in Table 1, the corresponding curve is only shifted upwards (downwards) for larger (smaller) values of this parameter. For comparison purposes, we also include the most important decay channels of the Higgs boson. A future muon collider is expected to work with an integrated

luminosity of about 1 fb^{-1} [1]. From Figure 2 we conclude that there would be up to a few hundred of $\mu^{\pm}\tau^{\mp}$ events in a year for a Higgs boson with a mass ranging between 100 and 140 GeV. For a heavier Higgs boson, the cross section drops dramatically as more decay channels ($H \to WW$ and $H \to ZZ$, with both particles on-shell) become opened. These results are in agreement with those presented in Ref. [8] for the case of the THDM-III.
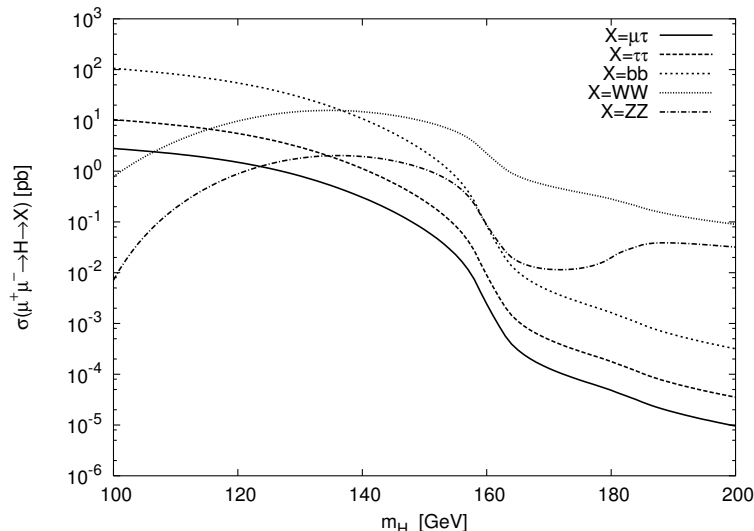

Fig. 2. Unpolarized cross section for $\mu^{-}\mu^{+} \to H \to X$ as a function of m_H at a muon collider running as a Higgs boson factory. For $m_H < 2\,m_V$ ($V = W, Z$), the curves for $X = VV$ correspond to the production of an on-shell V boson accompanied by a virtual one.

It is worthwhile to examine carefully the potential background for the LFV process $\mu^{-}\mu^{+} \to \mu^{\pm}\tau^{\mp}$. In this reaction the final leptons always emerge back to back and carrying a constant energy which is one half the center of mass energy. The main background would arise from the SM process $\mu^{-}\mu^{+} \to \mu^{\pm}\tau^{\mp}\bar{\nu}_{\mu}\nu_{\tau}$, whose signature is a pair $\mu^{\pm}\tau^{\mp}$ plus missings. There are 24 Feynman diagrams contributing to this process, with exchange of the photon, the Z boson, the W boson and the Higgs boson itself. We have explicitly calculated the contribution of these diagrams via the CALCHEP package [19]. To discard those final leptons emerging outside the detector coverage, we imposed the following cut $|\cos\theta| \leq 0.99$, where θ is the scattering angle. It turns out that on the Higgs boson resonance the dominant contribution comes from the diagrams shown in Fig. 3, whereas the remaining diagrams give a negligible contribution. For instance, those diagrams in which the photon and the Z boson are exchanged in the s channel are suppressed by an inverse factor of m_H^4 and $(m_H^2 - m_Z^2)^2$, respectively. On the other hand, the cross section of the diagrams in which the photon couples directly to the initial and final muons is inversely proportional to $m_H^4 \sin^4(\theta/2)$ when the muon mass is neglected and so it is considerably suppressed by the cut $|\cos\theta| \leq 0.99$. In these diagrams the final muon emerges predominantly with low energy. Therefore, the main

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contribution to the background comes from the diagram with Higgs boson exchange [Fig. 3 (a)]. The cross section arising from the background process is shown in Fig. 4 as a function of m_H. It reaches a peak around $m_H = 130$ GeV, where it may be larger than the LFV cross section, and then drops quickly.
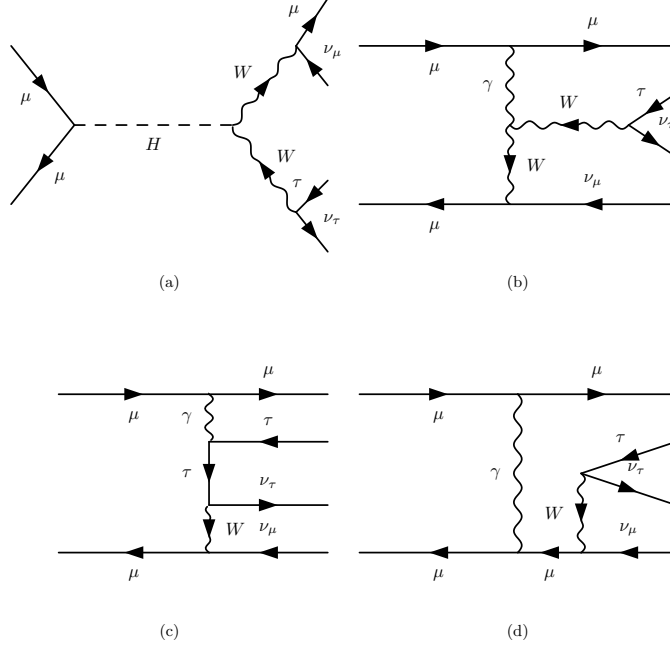

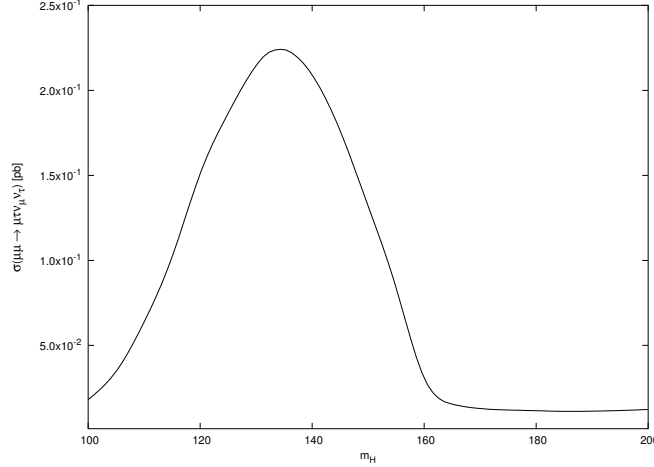Fig. 3. The dominant contributions to the SM background $\mu^-\tau^+ \to \mu^\pm\tau^\mp\bar{\nu}_\mu\nu_\tau$.

Fig. 4. Cross section for $\mu^-\tau^+ \to \mu^\pm\tau^\mp\bar{\nu}_\mu\nu_\tau$ scattering at $\sqrt{s} = m_H$.

We turn to some kinematical distributions that may be helpful to separate the background from the signal. Since the background signal is a $2 \to 4$ process, the energy distribution of the final μ and τ would be essentially different from what would observed in the $2 \to 2$ reaction $\mu^-\tau^+ \to \mu^\pm\tau^\mp$: while the energy distribution of the μ and τ leptons emerging from the latter process is peaked at $\sqrt{s}/2 = m_H/2$, the μ and τ emerging from the background process have a smaller and nonuniform energy, which reach its maximal value at $m_H/2$.

The respective distribution is illustrated in Fig. 5 for various values of m_H, where we considered the dominant contributions to $\mu^-\tau^+ \to \mu^\pm\tau^\mp\bar{\nu}_\mu\nu_\tau$. We can thus impose a hard cut on the energy of the final particles and get rid of most of the background events. We also show in Fig. 6 the $\theta_{\mu\tau}$ distribution, with $\theta_{\mu\tau}$ the angle between the spatial momenta of the μ and τ emerging from the background, for three values of m_H. This distribution is peaked at $\cos\theta_{\mu\tau} = -1$ in the LFV process. We can see that the $\cos\theta_{\mu\tau}$ distribution arising from the background is very different to that of the LFV signal. These and other kinematical distributions along with appropriate cuts can be used to separate the signal from the background. Furthermore, the use of polarized beams can be helpful to separate those contributions coming essentially from Higgs boson exchange to those coming from other sources such as an extra Z' boson.
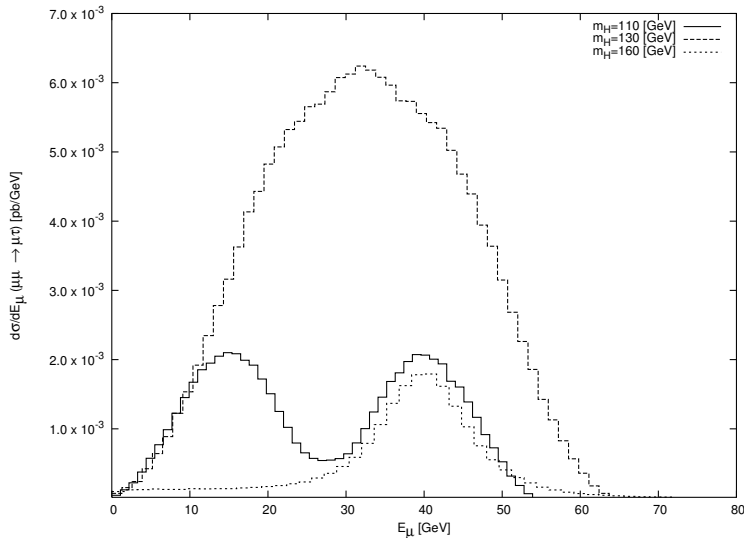

Fig. 5. Energy distribution of the final muon in $\mu^-\tau^+ \to \mu^\pm\tau^\mp\bar{\nu}_\mu\nu_\tau$ scattering for $\sqrt{s} = m_H$ and three values of m_H. The muons emerging from the LFV process $\mu^-\tau^+ \to \mu^\pm\tau^\mp$ are monoenergetic, with an energy half the Higgs boson mass, so their energy distribution exhibits a sharp peak at $m_H/2$.

We have presented an analysis of lepton flavor violation within the effective Lagrangian approach. We have considered the reaction $\mu^-\tau^+ \to \mu^\pm\tau^\mp$, which could be at the reach of a future muon collider. We only have considered the scenario in which the LFV arises from the Higgs boson. For the strength of the effective coupling $H\bar{\mu}\tau$, we assumed some values that are within the constraints obtained from the LFV decays $\tau^- \to \mu^-\gamma$ and $\tau^- \to \mu^-\eta$. From our analysis we can conclude that a future muon collider may be useful to detect LFV mediated by the Higgs boson. Our study also shows that the main background could be separated from the signal through appropriate cuts and the study of some kinematical distributions.
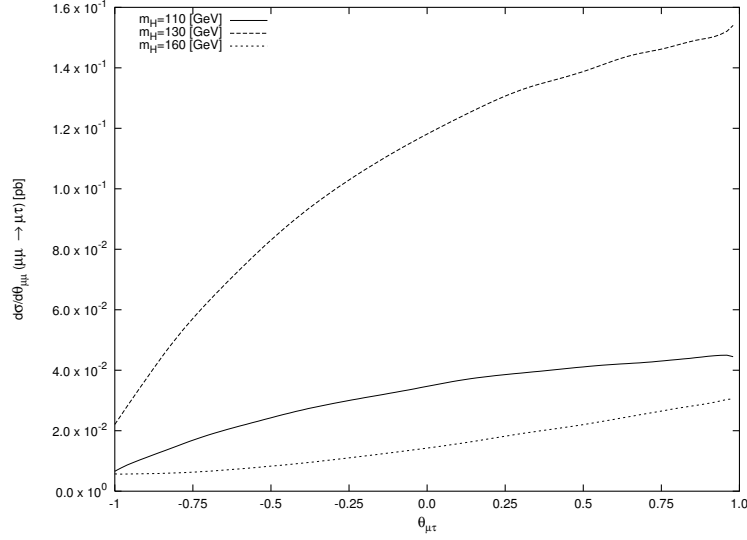
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Fig. 6. $\cos\theta_{\mu\tau}$ distribution of $\mu^-\tau^+ \to \mu^\pm\tau^\mp\bar{\nu}_\mu\nu_\tau$ scattering for $\sqrt{s} = m_H$ and three values of m_H. The μ and τ from the LFV process emerge back to back and so its $\cos\theta_{\mu\tau}$ distribution exhibits a sharp peak at $\cos\theta_{\mu\tau} = -1$.

Acknowledgements

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