Lepton flavor violating Higgs decays and unparticle physics

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Abstract

We predict the branching ratios of the lepton flavor violating Higgs decays $H^0 \rightarrow e^{\pm} \mu^{\pm}$, $H^0 \rightarrow e^{\pm} \tau^{\pm}$ and $H^0 \rightarrow \mu^{\pm} \tau^{\pm}$ in the case that the lepton flavor violation is carried by the scalar unparticle mediation. We observe that their branching ratios are strongly sensitive to the unparticle scaling dimension and they can reach to the values of the order of 10^{-4} , for the heavy lepton flavor case and for the small values of the scaling dimension.

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The hunt of the Higgs boson H^0 in Large Hadron Collider (LHC) is one of the main goals of physicists to test the standard model (SM), to get strong information about the mechanism of the electroweak symmetry breaking, the Higgs mass and to determine the scale of the new physics beyond. From theoretical point of view, the couplings of Higgs boson with the fundamental particles are well defined and the branching ratios (BRs) of its various decays have been estimated as a function of the Higgs boson mass. There are predictions on the Higgs mass limits from coupling to $Z/W_{\pm} m_{H^0} > 114.4 \, CL\%95$ and, indirect one, from electroweak analysis $m_{H^0} = 129^{+74}_{-49}$ [1] ($m_{H^0} = 114^{+69}_{-45}$ [2]).

The present work is devoted to the analysis of the lepton flavor violating (LFV) Higgs boson decays in an appropriate range, 110 - 150 (GeV), of the Higgs boson mass. There are various analysis done on LFV Higgs boson decays in the literature. In [3, 4] $H^0 \rightarrow \tau \mu$ decay has been studied in the framework of the 2HDM. In [3], large BR, of the order of magnitude of 0.1 - 0.01, has been obtained and in [4], the BR was obtained in the interval 0.001 - 0.01 for the Higgs mass range 100 - 160 (GeV), for the LFV parameter $\lambda_{\mu\tau} = 1$. [5] is devoted to the observable CP violating asymmetries in the lepton flavor (LF) changing H^0 decays with BRs of the order of $10^{-6} - 10^{-5}$. The LFV $H^0 \rightarrow l_i l_j$ decay has been studied also in [6], in the framework of the two Higgs doublet model type III. In these works the LF violation is carried by the leptonlepton-new Higgs boson couplings which are free parameters of the model used. In our analysis we consider that the LF violation is carried by the scalar unparticle (U)-lepton-lepton vertex and the scalar unparticle appears in the internal line in the loop.

The unparticle idea, which is based on the interaction of the SM and the ultraviolet sector, having non-trivial infrared fixed point at high energy level, is introduced by Georgi [7, 8]. Georgi considers that the ultraviolet sector comes out as new degrees of freedom, called unparticles, being massless and having non integral scaling dimension d_u , around, $\Lambda_U \sim 1 TeV$. The interactions of unparticles with the SM fields in the low energy level is defined by the effective lagrangian

$$\mathcal{L}_{eff} \sim \frac{\eta}{\Lambda_U^{d_u+d_{SM}-n}} O_{SM} O_U \,, \tag{1}$$

where O_U is the unparticle operator, the parameter η is related to the energy scale of ultraviolet sector, the low energy one and the matching coefficient [7, 8, 9] and n is the space-time dimension.

In literature, the unparticle effect in the processes, which are induced at least in one loop level, is studied in various works [11]-[23]. The process we study exists at least in one loop level and the effective interaction lagrangian, which drives the LFV decays in the low energy effective theory, reads

$$\mathcal{L}_1 = \frac{1}{\Lambda_U^{du-1}} \Big(\lambda_{ij}^S \,\bar{l}_i \,l_j + \lambda_{ij}^P \,\bar{l}_i \,i\gamma_5 \,l_j \Big) O_U \,, \tag{2}$$

where l is the lepton field and λ_{ij}^S (λ_{ij}^P) is the scalar (pseudoscalar) coupling. Notice that we consider the appropriate operators with the lowest possible dimension in order to obtain the LFV decays¹.

The $H^0 \rightarrow l_1^- l_2^+$ decay (see Fig.1) exists at least in one loop with the help of the scalar unparticle propagator, which is obtained by using the scale invariance [8, 10]:

$$\int d^4x \, e^{ipx} < 0 | T \Big(O_U(x) \, O_U(0) \Big) 0 > = i \frac{A_{d_u}}{2 \, \pi} \, \int_0^\infty ds \, \frac{s^{d_u - 2}}{p^2 - s + i\epsilon} = i \, \frac{A_{d_u}}{2 \sin (d_u \pi)} \, (-p^2 - i\epsilon)^{d_u - 2}, \tag{3}$$

with the factor A_{d_u}

$$A_{d_u} = \frac{16 \,\pi^{5/2}}{(2 \,\pi)^{2 \, d_u}} \,\frac{\Gamma(d_u + \frac{1}{2})}{\Gamma(d_u - 1) \,\Gamma(2 \, d_u)} \,. \tag{4}$$

The function $\frac{1}{(-p^2-i\epsilon)^{2-d_u}}$ in eq. (3) becomes

$$\frac{1}{(-p^2 - i\epsilon)^{2-d_u}} \to \frac{e^{-i\,d_u\,\pi}}{(p^2)^{2-d_u}}\,,\tag{5}$$

for $p^2 > 0$ and a non-trivial phase appears as a result of non-integral scaling dimension.

Now, we present the matrix element square of the LFV H^0 decay (see Fig. 1 for the possible self energy and vertex diagrams):

$$|M|^{2} = 2\left(m_{H^{0}}^{2} - (m_{l_{1}^{-}} + m_{l_{2}^{+}})^{2}\right)|A|^{2} + 2\left(m_{H^{0}}^{2} - (m_{l_{1}^{-}} - m_{l_{2}^{+}})^{2}\right)|A'|^{2}, \tag{6}$$

where

$$A = \int_{0}^{1} dx f_{self}^{S} + \int_{0}^{1} dx \int_{0}^{1-x} dy f_{vert}^{S},$$

$$A' = \int_{0}^{1} dx f_{self}'^{S} + \int_{0}^{1} dx \int_{0}^{1-x} dy f_{vert}'^{S},$$
(7)

and the explicit expressions of $f_{self}^S, f_{self}^{\prime S}, f_{vert}^S, f_{vert}^{\prime S}$ read

¹The operators with the lowest possible dimension are chosen since they have the most powerful effect in the low energy effective theory (see for example [24]).

$$\begin{split} f^{S}_{self} &= \frac{-i c_{1} (1-x)^{1-d_{u}}}{16 \pi^{2} \left(m_{l_{2}^{+}} - m_{l_{1}^{-}}\right) (1-d_{u})} \sum_{i=1}^{3} \left\{ \left(\lambda_{il_{1}}^{S} \lambda_{il_{2}}^{S} + \lambda_{il_{1}}^{P} \lambda_{il_{2}}^{P}\right) m_{l_{1}^{-}} m_{l_{2}^{+}} (1-x) \right. \\ & \times \left. \left(L_{self}^{d_{u}-1} - L_{self}^{\prime d_{u}-1}\right) - \left(\lambda_{il_{1}}^{P} \lambda_{il_{2}}^{P} - \lambda_{il_{1}}^{S} \lambda_{il_{2}}^{S}\right) m_{i} \left(m_{l_{2}^{+}} L_{self}^{d_{u}-1} - m_{l_{1}^{-}} L_{self}^{\prime d_{u}-1}\right) \right\}, \end{split}$$

$$\begin{split} f_{self}^{\prime S} &= \frac{i c_1 (1-x)^{1-d_u}}{16 \pi^2 \left(m_{l_2^+} + m_{l_1^-}\right) (1-d_u)} \sum_{i=1}^3 \left\{ \left(\lambda_{il_1}^P \lambda_{il_2}^S + \lambda_{il_1}^S \lambda_{il_2}^P\right) m_{l_1^-} m_{l_2^+} (1-x) \right. \\ &\times \left(L_{self}^{d_u-1} - L_{self}^{\prime d_u-1}\right) - \left(\lambda_{il_1}^P \lambda_{il_2}^S - \lambda_{il_1}^S \lambda_{il_2}^P\right) m_i \left(m_{l_2^+} L_{self}^{d_u-1} + m_{l_1^-} L_{self}^{\prime d_u-1}\right) \right\}, \end{split}$$

$$\begin{split} f_{vert}^{S} &= \frac{i c_{1} m_{i} \left(1-x-y\right)^{1-d_{u}}}{16 \pi^{2}} \sum_{i=1}^{3} \frac{1}{L_{vert}^{2-d_{u}}} \left\{ \left(\lambda_{il_{1}}^{P} \lambda_{il_{2}}^{P} - \lambda_{il_{1}}^{S} \lambda_{il_{2}}^{S}\right) \left\{ \left(1-x-y\right) \right. \\ &\times \left. \left(m_{l_{1}^{-}}^{2} x + m_{l_{2}^{+}}^{2} y - m_{l_{2}^{+}} m_{l_{1}^{-}}\right) + x y m_{H^{0}}^{2} - \frac{2 L_{vert}}{1-d_{u}} - m_{i}^{2} \right\} \\ &- \left. \left(\lambda_{il_{1}}^{P} \lambda_{il_{2}}^{P} + \lambda_{il_{1}}^{S} \lambda_{il_{2}}^{S}\right) m_{i} \left(m_{l_{1}^{-}} \left(2 x - 1\right) + m_{l_{2}^{+}} \left(2 y - 1\right)\right) \right\}, \end{split}$$

$$f_{vert}^{\prime S} = \frac{i c_1 m_i (1 - x - y)^{1 - d_u}}{16 \pi^2} \sum_{i=1}^3 \frac{1}{L_{vert}^{2 - d_u}} \left\{ (\lambda_{il_1}^S \lambda_{il_2}^P - \lambda_{il_1}^P \lambda_{il_2}^S) \left\{ (1 - x - y) \right\} \\ \times \left(m_{l_1^-}^2 x + m_{l_2^+}^2 y + m_{l_2^+} m_{l_1^-} \right) + x y m_{H^0}^2 - \frac{2 L_{vert}}{1 - d_u} - m_i^2 \right\} \\ + \left(\lambda_{il_1}^S \lambda_{il_2}^P + \lambda_{il_1}^P \lambda_{il_2}^S \right) m_i \left(m_{l_1^-} (2 x - 1) + m_{l_2^+} (1 - 2 y) \right) \right\},$$
(8)

with

$$L_{self} = x \left(m_{l_1^-}^2 (1-x) - m_i^2 \right),$$

$$L'_{self} = x \left(m_{l_2^+}^2 (1-x) - m_i^2 \right),$$

$$L_{vert} = \left(m_{l_1^-}^2 x + m_{l_2^+}^2 y \right) (1-x-y) - m_i^2 (x+y) + m_{H^0}^2 x y,$$
(9)

and

$$c_1 = \frac{g A_{d_u}}{4 m_W \sin(d_u \pi) \Lambda_u^{2(d_u - 1)}}.$$
 (10)

In eq. (8), the scalar and pseudoscalar couplings $\lambda_{il_{1(2)}}^{S,P}$ represent the effective interaction between the internal lepton i, $(i = e, \mu, \tau)$ and the outgoing $l_1^-(l_2^+)$ lepton (anti lepton). Finally, the BR for $H^0 \rightarrow l_1^- l_2^+$ decay can be obtained by using the matrix element square as

$$BR(H^0 \to l_1^- l_2^+) = \frac{1}{16 \pi m_{H^0}} \frac{|M|^2}{\Gamma_{H^0}}, \qquad (11)$$

with the Higgs total decay width Γ_{H^0} . In the numerical analysis, we consider the BR due to the production of sum of charged states, namely,

$$BR(H^0 \to l_1^{\pm} \, l_2^{\pm}) = \frac{\Gamma(H^0 \to (\bar{l}_1 \, l_2 + \bar{l}_2 \, l_1))}{\Gamma_{H^0}} \,. \tag{12}$$

Discussion

In this section, we analyze the BRs of the LFV $H^0 \rightarrow l_1^- l_2^+$ decays with the assumption that the flavor violation is induced by the scalar unparticle mediation. The U- lepton-lepton vertex drives the LF violation and the decays under consideration exist in the loop level, in the effective theory. In the scenario studied there are number of free parameters, namely, the scaling dimension of the scalar unparticle, the couplings, the energy scale Λ_u , the Higgs mass and its total decay width. These parameters should be restricted by using the current experimental limits and the mathematical considerations. Here we choose the scaling dimension in the range $1 < d_u < 2, d_u > 1$ not to face with the non-integrable singularity problem in the decay rate [8] and $d_u < 2$ to obtain convergent momentum integrals [13]. For the U- lepton-lepton couplings $\lambda_{ij}^{S(P)_2}$ we consider two different scenarios:

- the diagonal couplings λ_{ii} respects the lepton family the hierarchy, $\lambda_{\tau\tau} > \lambda_{\mu\mu} > \lambda_{ee}$, and the off-diagonal couplings, $\lambda_{ij}, i \neq j$ are family blind and universal. Furthermore, we take the off diagonal couplings as, $\lambda_{ij} = \kappa \lambda_{ee}$ with $\kappa < 1$. In our numerical calculations, we choose $\kappa = 0.5$.
- the diagonal $\lambda_{ii} = \lambda_0$ and off diagonal $\lambda_{ij} = \kappa \lambda_0$ couplings are family blind with $\kappa = 0.5$.

The Higgs mass and its total decay width are other parameters existing in the numerical calculations. The Higgs mass should lie in a certain range if the SM is an acceptable theory. From the theoretical point of view, not to face with the unitarity problem (the instability of the Higgs potential), one considers the upper (lower) bound as 1.0 TeV (0.1 TeV) [25]. On the other hand, electroweak measurements results in the prediction of the Higgs mass as $m_{H^0} = 129^{+74}_{-49}$ [1], which is in the range of theoretical limits. In our numerical calculation we choose the values $m_{H^0} = 110 (GeV)$, $m_{H^0} = 120 (GeV)$ and $m_{H^0} = 150 (GeV)$ to observe the Higgs mass

²We consider that the scalar λ_{ij}^S and pseudo scalar λ_{ij}^P couplings have the same magnitude, namely $\lambda_{ij}^S = \lambda_{ij}^P = \lambda_{ij}$.

dependence of the BRs of the LFV decays under consideration. The total Higgs decay width is estimated by using the possible decays for the considered Higgs mass. The light Higgs boson, $m_{H^0} \leq 130 \, GeV$, mainly decays into $b\bar{b}$ pair [26, 27]. However, its detection is difficult due to the QCD background and the $t\bar{t}H^0$ channel, where the Higgs boson decays to $b\bar{b}$, is the most promising one [28]. For a heavier Higgs boson $m_{H^0} \sim 180 \, GeV$, the suitable production exist via gluon fusion and the leading decay mode is $H^0 \to WW \to l^+ l'^- \nu_l \nu_{l'}$ [29, 30, 31].

Notice that for the energy scale Λ_u we take $\Lambda_u = 10 (TeV)$ and throughout our calculations we use the input values given in Table (1).

Parameter	Value
m_e	$0.0005 \; ({\rm GeV})$
m_{μ}	$0.106 \; (GeV)$
$m_{ au}$	$1.780 \; (GeV)$
$\Gamma(H^0) _{m_{H^0}=110GeV}$	$0.0026 \; (GeV)$
$\Gamma(H^0) _{m_{H^0}=120GeV}$	$0.0029 \; (GeV)$
$\Gamma(H^0) _{m_{H^0}=150GeV}$	$0.015 \; ({\rm GeV})$
G_F	$1.1663710^{-5} (GeV^{-2})$

Table 1: The values of the input parameters used in the numerical calculations.

In Fig.2, we present the BR $(H^0 \to \mu^{\pm} e^{\pm})$ with respect to the scale parameter d_u , for the couplings $\lambda_{ee} = 0.1 \lambda_{\mu\mu} = 0.01 \lambda_{\tau\tau}$. Here, the lower (upper) solid-dashed line represents the BR for $\lambda_{\tau\tau} = 10 (50)$ and $m_{H^0} = 110 - 150 (GeV)^3$. The BR is strongly sensitive to the scale d_u and, it reaches to the values of the order of 10^{-6} for strong couplings λ_{ij} , $d_u \sim 1.1$, especially, for the light Higgs boson case. Fig.3 is devoted to the the BR $(H^0 \to \mu^{\pm} e^{\pm})$ with respect to the flavor blind coupling λ_0 . Here, the lower (intermediate, upper) solid-dashed line represents the BR for $d_u = 1.3$ ($d_u = 1.2$, $d_u = 1.1$) and $m_{H^0} = 110 - 150 (GeV)$. This figure shows that the BR $(H^0 \to \mu^{\pm} e^{\pm})$ enhances considerably even for the large values of the scale parameter d_u , in the case that the couplings are flavor blind.

Fig.4, represents the BR $(H^0 \to \tau^{\pm} e^{\pm})$ with respect to the scale parameter d_u , for the couplings $\lambda_{ee} = 0.1 \lambda_{\mu\mu} = 0.01 \lambda_{\tau\tau}$. Here, the lower (intermediate, upper) solid-dashed line represents the BR for $\lambda_{\tau\tau} = 1.0 (10, 50)$ and $m_{H^0} = 110 - 150 (GeV)$. The BR reaches to the values of the order of 10^{-6} even for weak couplings λ_{ij} , $d_u \sim 1.1$. Fig.5 shows the BR $(H^0 \to \tau^{\pm} e^{\pm})$ with respect to the coupling λ_0 . Here, the lower (intermediate, upper) solid-dashed line represents the BR for $d_u = 1.3 (d_u = 1.2, d_u = 1.1)$ and $m_{H^0} = 110 - 150 (GeV)$.

³The BR $(H^0 \to \mu^{\pm} e^{\pm})$ for $m_{H^0} = 120 (GeV)$ is slightly smaller than the one for $m_{H^0} = 110 (GeV)$ and the difference enhances with the increasing values of the parameter d_u .

We observe that the BR $(H^0 \to \tau^{\pm} e^{\pm})$ reaches to the values of the order of 10^{-4} even for weak coupling $\lambda_0 \sim 1.0$ in the case that the couplings are flavor blind.

Finally, we analyze the BR $(H^0 \to \tau^{\pm} \mu^{\pm})$ in Figs.6 and 7. Fig.6 is devoted to the BR $(H^0 \to \tau^{\pm} \mu^{\pm})$ with respect to the scale parameter d_u , for the couplings $\lambda_{ee} = 0.1 \lambda_{\mu\mu} = 0.01 \lambda_{\tau\tau}$. Here, the lower (intermediate, upper) solid-dashed line represents the BR for $\lambda_{\tau\tau} = 1.0 (10, 50)$ and $m_{H^0} = 110 - 150 (GeV)$. The BR reaches to the values of the order of 10^{-6} even for weak couplings λ_{ij} and $d_u \sim 1.1$, similar to the $(H^0 \to \tau^{\pm} \mu^{\pm})$ decay. Fig.7 shows the BR $(H^0 \to \tau^{\pm} \mu^{\pm})$ with respect to the coupling λ_0 . Here, the lower (intermediate, upper) solid-dashed line represents the BR for $d_u = 1.3$ $(d_u = 1.2, d_u = 1.1)$ and $m_{H^0} = 110 - 150 (GeV)$. It is observed that the BR $(H^0 \to \tau^{\pm} \mu^{\pm})$ can get the values of the order of 10^{-4} for the weak coupling $\lambda_0 \sim 1.0$.

As a summary, the LFV decays of the Higgs boson H^0 are strongly sensitive to the unparticle scaling dimension and, for its small values $d_u < 1.1$, the BRs enhance considerably, especially for heavy lepton output. In the case that the *U*-lepton-lepton couplings are flavor blind, the BRs of the decays studied reach to the values of the order of 10^{-4} even for weak couplings. The possible production of the Higgs boson H^0 in LHC would stimulate one to study its LFV decays and the near future experimental results would be instructive to test the new physics which drives the flavor violation, here is the unparticle physics.

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Figure 1: One loop diagrams contribute to $H^0 \rightarrow l_1^- l_2^+$ decay with scalar unparticle mediator. Solid line represents the lepton field: *i* represents the internal lepton, l_1^- (l_2^+) outgoing lepton (anti lepton), dashed line the Higgs field, double dashed line the unparticle field.



Figure 2: The scale parameter d_u dependence of the BR $(H^0 \to \mu^{\pm} e^{\pm})$ for $\Lambda_u = 10 TeV$, the couplings $\lambda_{ee} = 0.1 \lambda_{\mu\mu} = 0.01 \lambda_{\tau\tau}$. Here, the lower (upper) solid-dashed line represents the BR for $\lambda_{\tau\tau} = 10 (50)$ and $m_{H^0} = 110 - 150 (GeV)$.



Figure 3: λ_0 dependence of the BR $(H^0 \to \mu^{\pm} e^{\pm})$ for $\Lambda_u = 10 \, TeV$. Here, the lower (intermediate, upper) solid-dashed line represents the BR for $d_u = 1.3$ $(d_u = 1.2, d_u = 1.1)$ and $m_{H^0} = 110 - 150 \, (GeV)$.



Figure 4: The scale parameter d_u dependence of the BR $(H^0 \to \tau^{\pm} e^{\pm})$ for $\Lambda_u = 10 TeV$, the couplings $\lambda_{ee} = 0.1 \lambda_{\mu\mu} = 0.01 \lambda_{\tau\tau}$. Here, the lower (intermediate, upper) solid-dashed line represents the BR for $\lambda_{\tau\tau} = 1.0 (10, 50)$ and $m_{H^0} = 110 - 150 (GeV)$.



Figure 5: λ_0 dependence of the BR $(H^0 \to \tau^{\pm} e^{\pm})$ for $\Lambda_u = 10 \, TeV$. Here, the lower (intermediate, upper) solid-dashed line represents the BR for $d_u = 1.3$ $(d_u = 1.2, d_u = 1.1)$ and $m_{H^0} = 110 - 150 \, (GeV)$.



Figure 6: The same as Fig.4 but for $H^0 \to \tau^{\pm} \mu^{\pm}$ decay.



Figure 7: The same as Fig.5 but for $H^0 \to \tau^{\pm} \mu^{\pm}$ decay.