Probing flavor parameters in the scalar sector and new bounds for the fermion sector

R. Gaitán, J.H. Montes de Oca, and J.A. Ordúz-Ducuara

Departamento de Física, FES Cuautitlán, Universidad Nacional Autónoma de México
Estado de México, 54770, México
∗E-mail: rgaitan@unam.mx

In this paper we study the Flavor-Changing mediated by Higgs boson within Two-Higgs Doublet Model-III context. We explore the parameter space and, considering recent results, find new limits for the model parameters. We also obtain the total Higgs decay width and the branching ratios for different channels taking limits for the $t \rightarrow cV$ and $b \rightarrow s\gamma$ processes. Considering different constraints, we estimate the branching ratio for the $h \rightarrow t^*c$ in the model as well as the bounds for the $b \rightarrow s\gamma$, $h \rightarrow \mu\tau$ and $h \rightarrow \gamma Z$. Considering the quark top decays to $W\bar{b}$, we obtained $\text{Br}(h \rightarrow Wc\bar{b}) \sim 10^{-3}$.

1. Introduction

The Standard Model (SM) describes the universe at scale $O(10^2 \text{ GeV})$. Different experiments have examined the SM observables which have good agreement with the theoretical predictions. Currently LHC explores the nature at energy scale of order TeV's and the SM works very well to analyze the structure of the matter. However there are different questions about the unknown phenomena: the matter-antimatter asymmetry, the CP violation and flavor-changing neutral currents (FCNC) mediated by gauge and scalar bosons. In this paper we shall explore the last one where the neutral scalar boson can change the fermion flavor; we focus on the $h \rightarrow VV'$ processes where the $h$ is the lightest scalar and $V, V' = Z, \gamma, g$.

We shall discuss the Flavor-Changing Neutral Scalar Interactions (FCNSI) inside the Two-Higgs Doublet Model type III (THDM-III) context considering different scenarios for the parameters of the model. Previous studies have considered different versions for this THDM-III [1–5], we shall focus on the Flavor-Changing (FC) mediated by scalars and then study Higgs decay processes. The FC context mediated by scalar bosons where the rare top decays have been studied, in particular in the THDM, the literature have reported the following branching ratios (Br) [6–8]: $\text{Br}(t \rightarrow uh) = 5.5 \times 10^{-6}$, $\text{Br}(t \rightarrow ch) = 1.5 \times 10^{-3}$, $\text{Br}(t \rightarrow u\gamma) \sim 10^{-6}$, $\text{Br}(t \rightarrow c\gamma) \sim 10^{-6}$, $\text{Br}(t \rightarrow uZ) \sim 10^{-7}$, $\text{Br}(t \rightarrow cZ) \sim 10^{-7}$.

There are different theoretical and experimental motivations to explore FC. Theoretically, for instance, to constrain the parameter space, and then obtain bounds over the parameters of the model. If we introduce new fermions, is possible to obtain the FC, at tree-level, when the new fermions and the SM fermions are mixed [9–11]. On the other side, if we introduce a new gauge group, and consider that the SM fermion charges related to extra gauge group are...
non-universal family, it could generate the FC as was shown in refs. [12–16]. The motivation to explore the FC is to test the SM and its behavior faced on New Physics scenarios.

From an experimental point of view, the uncertainties in the results motivate the flavor physics. Recently, ATLAS and CMS have published results for FC processes: $l_i \rightarrow l_j \gamma$ and $l_i \rightarrow l_j h$ [6, 17–20]. Besides, other collaborations have reported limits for the FC in the lepton sector: $\text{Br}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) = 2.1 \times 10^{-8}$ [19], $\text{Br}(\tau^- \rightarrow \mu^- \pi^+ \pi^-) = 10^{-7}$ (Belle), $10^{-6}$ (BaBar), $10^{-5}$ (CLEO) [21]. From LHCb results on $B^+ \rightarrow K^+ \mu^+ \mu^- (e^+ e^-)$ process have motivated the studies on the non-universal family couplings [22, 23], the orthogonality of the CKM matrix [19, 24] and the universality violation [25].

Our paper is organized as follows: In section 2, we discuss the model and methods to consider the FC mediated by scalar bosons. We show the ways to obtain the FC at loop level in the $h \rightarrow VV'$ process mediated by fermions. We implemented SARAH [26] for THDM type III, the amplitudes are obtained by FeynArts [27] and the Passarino-Veltman functions are evaluated by LoopTools [28]. In section 3 we present the results considering our parametrization for the $\text{Br}$, as well as decay width. We introduce bounds coming from meson processes which are taken from ref. [29]. Section 4 contains a discussion of our results and the conclusions.

2. Model and Methods

We shall consider the THDM-III where the most general potential

$V(\Phi_1 \Phi_2) = m^2_{11} \Phi_1\dagger \Phi_1 + m^2_{22} \Phi_2\dagger \Phi_2 - [m^2_{12} \Phi_1\dagger \Phi_2 + \text{h.c.}]$

$+ \frac{1}{2} \lambda_1 (\Phi_1\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2\dagger \Phi_2)^2$

$+ \lambda_3 (\Phi_1\dagger \Phi_1)(\Phi_2\dagger \Phi_2) + \lambda_4 (\Phi_1\dagger \Phi_2)(\Phi_2\dagger \Phi_1)$

$+ \left\{ \frac{1}{2} \lambda_5 (\Phi_1\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1\dagger \Phi_1)$

$+ \lambda_7 (\Phi_2\dagger \Phi_2)] \Phi_1\dagger \Phi_2 + \text{h.c.} \right\}$.

where $m^2_{ii}, \lambda_i$ are reals, and $\Phi_{1,2}$ denote the complex doublet scalar fields. The scalar masses spectrum can be found in detail in ref. [32]. The perturbativity condition for the the validity of a tree approximation in the interactions of the SM-like Higgs boson is imposed by requiring that the couplings $|\lambda_i| \leq 4\pi$.

The interaction and physical states for the scalars are related through the mixing parameters $\alpha$ and $\beta^2$. We assume the alignment limit [33], which states a relation between $\alpha$ and $\beta$, such as $\beta - \alpha = \pi/2 - \delta$ for $\delta << 1$, corresponding to the decoupling limit [31]. In particular, we take $\delta = 1 \times 10^{-2}$, which means the coupling of the lightest Higgs to fermions and gauge bosons is SM-like.

In a general way, the Yukawa sector for the THDM-III is given by

$\mathcal{L}^{THDM-III}_{Y_{LS}} = Y_1^u \tilde{Q}_L \tilde{u}_R^0 + Y_2^u \tilde{Q}_L \tilde{u}_R^0$

$+ Y_1^d \tilde{Q}_L \Phi_1 d_R^0 + Y_2^d \tilde{Q}_L \Phi_2 d_R^0 + \text{h.c.}$

(1)

\(^1\)The potential in different parametrizations can be found in [2, 30]
\(^2\)the $\tan \beta$ is more convenient to use for the analysis. We denote $\tan \beta = t_\beta$. 

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with \( Q_L^0 = \begin{pmatrix} u_L & d_L \end{pmatrix}^T \), \( \Phi_{1,2} = \begin{pmatrix} \phi_{1,2}^+ & \phi_{1,2}^0 \end{pmatrix}^\dagger \), and \( \Phi_f = i\sigma_2\Phi^*_f \). \( Y_i \) are the Yukawa matrices, \( \phi^0_i \) is the neutral Higgs eigenstate, and \( \phi^\pm_i \) contains the charged pseudo-goldstone boson.

Analogously, the Yukawa interaction can be written for leptons.

For the neutral scalar fields the Yukawa Lagrangian in the mass eigenstates is given by

\[
\mathcal{L}_n^{THDM-III} = \frac{g}{2} \left( \frac{m_i}{m_W} \right) D_i \left[ \cos \alpha \delta_{ij} + \frac{\sqrt{2} \sin(\alpha - \beta)}{g \cos \beta} \left( \frac{m_W}{m_i} \right) (\tilde{Y}_2^d)_{ij} \right] d_j H^0
\]

\[
+ \frac{g}{2} \left( \frac{m_i}{m_W} \right) d_i \left[ -\sin \alpha \delta_{ij} + \frac{\sqrt{2} \cos(\alpha - \beta)}{g \cos \beta} \left( \frac{m_W}{m_i} \right) (\tilde{Y}_2^d)_{ij} \right] d_j h^0
\]

\[
+ \frac{ig}{2} \left( \frac{m_i}{m_W} \right) \tilde{u}_i \left[ \sin \alpha \delta_{ij} + \frac{\sqrt{2} \sin(\alpha - \beta)}{g \sin \beta} \left( \frac{m_W}{m_i} \right) (\tilde{Y}_2^u)_{ij} \right] u_j H^0
\]

\[
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\]

\[
+ \frac{ig}{2} \left( \frac{m_u}{m_W} \right) \tilde{u}_i \left[ -\cot \beta \delta_{ij} + \frac{\sqrt{2}}{g \sin \beta} \left( \frac{m_W}{m_i} \right) (\tilde{Y}_2^u)_{ij} \right] u_j A^0.
\]

The complete Yukawa Lagrangian can be revised, for instance, in ref. [1].

### 2.1. FC by scalar sector

Next we shall describe a way to parametrize the FCNSI [3, 34]. In general each of the Yukawa matrices are non-diagonal; however their linear combination, which is the mass matrix, is diagonal. The FC is given when the diagonalization of the fermion mass matrices does not imply the diagonalization of the Yukawa couplings.

In this sector the interaction between fermions and scalar is given by the Yukawa couplings \( (Y_f) \). In the SM the couplings is given by

\[
g_{hf}^{SM} = Y_f^{SM} = \sqrt{2} \frac{m_f}{v}
\]

where \( m_f \) is fermion mass and \( v \) is the vacuum expectation value (VEV).

For the THDM-III, after the spontaneous symmetry breaking the mass matrix is

\[
M_f = \frac{1}{\sqrt{2}} \left( v_1 Y_1^f + v_2 Y_2^f \right)
\]

where \( v_1 \) and \( v_2 \) are VEV’s associated to the \( \phi^0_1 \) and \( \phi^0_2 \), respectively, and are related by \( t_\beta = \frac{v_2}{v_1} \). \( Y^{u,d}_f \) is the Yukawa couplings that could be complex. In a general form, the eq. (3) is non-diagonal; it can be diagonalized through biunitary transformation \( U_{L,R} \):

\[
(U^{f\dagger}_L)^\dagger M_f (U^f_R) = \tilde{M}_f
\]

Note that the widetilde over the quantities means the physics basis.

In order to reduce the free parameters, one can rewrite the eq.(3) as

\[
\tilde{Y}^f_1 = \sqrt{2} \frac{M_f}{v \cos \beta} - \tilde{Y}^f_2 t_\beta,
\]

and substitutes in eq. (1).

Then it is possible to have mixing between the fermion flavor at tree level. On going, we suppress the tilde and index in the the Yukawa matrix.
2.2. FCNSI at loop-level
The FC processes at loop-level have some restrictions. At this level, the effects must be much smaller than the effects at tree level. The FCNSI is an interesting topic for the high precision studies on the scalar sector because it could give a signal of new physics.

\[ \phi(p_3) \rightarrow V_\mu(p_2)^2 \rightarrow V'_\mu(p_1)^1 \rightarrow f_i \rightarrow x_2 \rightarrow x_3 \rightarrow f_j \]

**Fig. 1** The Feynman diagrams for the $h \rightarrow VV'$. $x_1$ and $x_2$ vertices gets highly suppressed if the $V = \gamma$ while the $x_3$ vertex contains the FC.

We analyze the $h \rightarrow VV'$ process shown in fig. 1, which is at higher level of precision where the remarked vertices ($x_i$) imply loop correction. $x_{1,2}$-vertices: neutral vector boson and two fermions with FCNC. $x_3$-vertex: scalar boson and two fermions with FCNC mediated by the scalar bosons, this vertex contains FCNSI at tree-level.

\[ f_i, f_j, V \]

**Fig. 2** The $f_i f_j V$ at one-loop level mediated by the scalar boson.

In general, the couplings are given by $g_{ijh} = Y_{ij}^h P_L + Y_{ij}^P P_R$, which represents the Higgs and pair of fermions vertex, $P_{R,L}$ are projectors and $i, j$ are the generation of fermions. Constraints for the parameters come from experimental data, e.g.: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}[18]$. Other constraints on the FC Yukawa couplings ($Y_{ij}$) are shown in ref. [35].

3. Phenomenological results
In this section we show phenomenological results. First part shows, a exploration on the parameter space which contains the phenomenological results for the parameter space: $\chi_{ij}^u - \chi_{ij}^d$. In second part, we show the total decay width for the Higgs and the Br’s for processes $h \rightarrow bb, \bar{l}l, gg, \gamma\gamma$ and $Z\gamma$; and also the allowed regions for different values of $t_\beta$. Moreover we take the recent results $t \rightarrow cZ, cg; b \rightarrow s\gamma$ and $h \rightarrow \gamma Z$ and explore the parameter space with the THDM-III context [29].
3.1. Constraints for the flavor parameters mediated by scalar boson

In order to explore the Yukawa couplings we use the Cheng-Sher parametrization [36]³

\[ Y^f_{ij} = \sqrt{2} \frac{\sqrt{m_i m_j}}{v} \chi^f_{ij} \]  

(4)

where \( m_i \) and \( m_j \) are the fermion masses, and \( \chi^f_{ij} \) are free dimensionless parameters which shall probe the flavor-changing mediated by scalar bosons. This kind of parametrization is interesting to probe the parameter space, and explore the flavor parameters in the 2HDM-III. An completed review on THDM can be found in [32]; our paper uses the current constraints and explores the some observables versus the flavor parameters.

For our research, we consider the \( \chi \)-parameters dependent on type quark because there is not reason to assume that all those are equal as was mentioned in ref.[8]. Besides we will label them as \( \chi^u_{ij} \) and \( \chi^d_{ij} \). For this work we will include the contribution coming from the heavy fermions.

We consider the experimental bound for the \( \text{Br}(h \to \gamma\gamma) \) and explore the parameters of the THDM-III. Fig. 3 shows the allowed regions for the parameter space taking different values for the \( t_\beta \) parameter.

![Figure 3: Parameter space for the \( \Gamma_t \) (total decay width) for the Higgs boson, we consider \( m_h = 125 \text{ GeV}, \text{Br}(h \to \gamma\gamma) = 2.27 \times 10^{-3}, m_H = 300 \text{ GeV} \) and \( m_{H^\pm} = 350 \text{ GeV} \).](image)

We assume the universality for parameters \( \chi^u_{ij}, \chi^d_{ij} \), which means the same order for all \( \chi^u_{ij}, \chi^d_{ij} \). The hierarchy for Yukawa couplings arise from the fermion masses, as shows the Cheng-Sher

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³This relation has been used in different papers [1, 34, 37]. Different analysis on the Yukawa couplings have explored the FC some results can be found in ref. [38, 39].
ansatz in eq. 4. The up-quark Yukawa couplings associated with $-40 \leq \chi_{ij}^{u,d} \leq 40$ are:

\[
|Y_{11}^u| \leq 5.2 \times 10^{-4}, \\
|Y_{21}^u| \leq 0.012, \\
|Y_{22}^u| \leq 0.27, \\
|Y_{31}^u| \leq 0.14, \\
|Y_{32}^u| \leq 3.3, \\
|Y_{33}^u| \leq 39.6, \\
\]

(5)

meanwhile for down-quark are:

\[
|Y_{11}^d| \leq 9.1 \times 10^{-4}, \\
|Y_{21}^d| \leq 0.0043, \\
|Y_{22}^d| \leq 0.02, \\
|Y_{31}^d| \leq 0.031, \\
|Y_{32}^d| \leq 0.14, \\
|Y_{33}^d| \leq 1.15. \\
\]

(6)

We note that the interactions between neutral scalars and quarks have proportional terms to $\cos(\alpha - \beta)$ or $\sin(\alpha - \beta)$. If the alignment limit is considered then $\cos(\alpha - \beta) \approx 0$ and $\sin(\alpha - \beta) \approx 1$. In particular, the Feynman rules for lightest neutral scalar and quarks contain the Yukawa couplings with factor $\cos(\alpha - \beta)$ and additional terms like $\frac{\cos(\alpha)}{\sin(\beta)}$ for up quarks or $\frac{\sin(\alpha)}{\cos(\beta)}$ for down quarks. This linear combinations appear in the amplitude for $h \rightarrow \gamma\gamma$ decay in the following form:

\[
|M|^2 \sim K_1 |Y_{ij}^u \cos(\alpha - \beta) - \frac{\cos(\alpha)}{\sin(\beta)}|^2 + K_2 |Y_{ij}^d \cos(\alpha - \beta) - \frac{\sin(\alpha)}{\cos(\beta)}|^2, \\
\]

(7)

where $K_1$ and $K_2$ contain the Passarino-Veltman integrals involved in the decay at one loop. In Fig.4 the linear behavior arise from the smallness in the alignment limit and the inverse behavior is attribute to the inversions in the mixing parameters for the quarks Yukawa interactions.

3.2. Branching ratios for the lightest neutral scalar

Within the THDM-III context is feasible the FC exploration and the structure of the Yukawa couplings. In this work, we consider universality between fermions of different generations. We have inspired in the Yukawa couplings structure coming from textures (see eq. (4)), which are dependent on the one parameter related to the quark type [1, 40].

As it is know the FCNSI are suppressed, e.g. the $\text{Br}(h \rightarrow \mu\tau) \lesssim 10^{-2}$ [18]. More limits have been explored from the top physics [7, 38]. Our results are shown in fig. 4 considering two scenarios for $\tan\beta = 1, 10$. We show fermion and boson decays, where we use the labeled style line with the final states to represent our results and the thicker style line are the experimental results. This figure shows excluded range for the different mode decays versus the $\chi_{ij}^d$. 

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We explore the Higgs decays to pair bosons at one-loop level. To explore those channels, we used the Cheng-Sher parametrization for the fermions and consider the FCNSI.

Fig. 4 shows modes of the $h$ decay versus the $\chi_{dd'}$, we found some enhancement regions for these channel with neutral boson in the final states. The Br’s for different processes inside the THDM-III context and their observed results [41, 42]. We show different scenarios for the parameters $\chi_{uij}^{u}, \chi_{ij}^{d}$ and $t_{\beta}$.

3.3. Constraints from the recent experimental results

We consider the recent experimental results coming from [43] for processes $t \to c V$ that could give evidence for the new physics. This kind of processes are studied in THDM-I,II and III context [8, 38] and their results are constrained, however those data can get enhancement as the same manner as there is an enhancement in the Yukawa coupling exploration.

We use the Feynman diagrams shown in fig. 5. In order to probe the beyond standard model physics and get strong constraints over the flavor parameters, we introduce $B \to X_s \gamma$ processes considering $\Gamma(B \to X_s \gamma) \simeq \Gamma(b \to s \gamma)$, since the non-perturbative effects are small [29]. The experimental limit for $Br(B \to X_s \gamma)$, reported by [19], is used to constraint the numerical analysis.

Processes shown in fig. 5 constrain Flavor parameters. These processes allow to perform precision studies on the top decay [44]. Besides it is possible to analyze the FC at loop-level considering a neutral scalar.

Fig.6 show the parameter space for the u- and d-type quark versus $t_{\beta}$. We used the constraints discussed previously; our analysis shows that it could be possible to have FC if we consider the quark type separately, since the parameter space is wider for the u-quark type. We found if $t_{\beta} \lesssim 10^{-3}$ then $-200 \lesssim \chi_{ij}^{u} \lesssim 200$, while if $t_{\beta} \lesssim 10^{-4}$ then $-200 \lesssim \chi_{ij}^{d} \lesssim 200$. 

Fig. 4  Br’s for different channels versus the flavor parameters for the d-type quark. We consider: a) (left-side) $t_{\beta} = 1$ and b) (right-side) $t_{\beta} = 10$, and for both cases $\chi_{ij}^{u} = 12$. 

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Fig. 5  Feynman diagrams for the fermion decays with $q_i$ u- and d-type, and $V = \gamma, Z, g$. We considered the contributions to the FC mediated by scalar bosons. Represented contributions are needed to avoid divergences.

We think is possible that the FC is generated by quark type in multi-Higgs models. The $\chi_{ij}^u - t_\beta-$parameter space is wider (fig. 6) respect to $\chi_{ij}^d - t_\beta-$parameter space (fig.6). And if we consider $\chi_{ij}^u = \chi_{ij}^d$ around zero, then $t_\beta-$parameter is more than $10^{-2}$. Higgs par-

Fig. 6  Scattering plot for the flavor parameters (a) $\chi_{ij}^u$ and (b) $\chi_{ij}^d$ versus $t_\beta$. Correlation between parameters of the model.

ticle is explored with leptons in the final states as $\tau\mu$; experimental reports have shown $\text{Br}(h \to \tau\mu) < 1.51 \times 10^{-2}$. [18, 43, 45].
We explore the lepton processes and tested the relation with the d-type quarks as is shown in fig. 7. This plot shows the correlation between \( h \to \tau \mu \) and \( b \to s\gamma \) processes. The linear and strong correlation between the \( Br(b \to s\gamma) \) and \( Br(h \to \tau \mu) \) is found in the regions \( \sim 10^{-5} - 10^{-3} \) for \( Br(b \to s\gamma) \) and \( \sim 10^{-9} - 10^{-6} \) for \( Br(h \to \tau \mu) \). Fig. 7 shows the region of the allowed values for the \( Br(b \to s\gamma) - Br(b \to \gamma Z) \) correlation. We found a exclusion region around \( Br(b \to \gamma Z) \sim 8 \times 10^{-6} \). The numerical results show stability for \( Br(h \to Z\gamma) \) near to the value \( 8 \times 10^{-5} \) meanwhile the \( Br(b \to s\gamma) \) decreases rapidly for the same random values. The behavior of the \( Br(h \to Z\gamma) \) is controlled by the dominant Feynman diagram with top quark as the internal line, which will give a proportional contribution to the Yukawa coupling without FC, \( Y_{3i}^d \).

\[ \text{Fig. 7} \quad \text{a) Scattering plot for the branching ratios of the processes } b \to s\gamma \text{ versus } h \to \tau \mu \]
\[ \text{b) Scattering plot for the branching ratios of the processes } b \to s\gamma \text{ versus } h \to \gamma Z. \]

In fig. 7, we consider the constraints coming from \( t \to cV, b \to s\gamma, h \to l^+_i l^-_j, h \to \gamma Z \), to show the correlation between branching ratios \( b \to s\gamma \) and \( h \to \gamma Z \) and we found excluded regions. The dark regions are the highly allowed as it is shown in figure. We generated randomly the parameter set, as follow, \(-200 \leq \chi_{u,d,l}^{u,d,l} \leq 200, 0 \leq t_\beta \leq 100, 350 \text{ GeV} \leq m_{H,H^\pm} \leq 1000 \text{ GeV}, \) as well considering the experimental bounds for the \( t, b \) and \( h \) branching ratios at tree and one-loop level. Our calculation introduces the Passarino-Veltman functions implemented on Looptools as was mentioned above.

Fig. 8 shows the Feynman diagram for our proposal process to be explore considering the FC and test the standard model.

The process that is represented in fig. 8 was proposed by ref. [46] to explore the flavor-changing modes.

If we consider the \( W^- \) decays to \( \nu_l l \) then we obtain \( Br \) of order \( 10^{-4} \), therefore our results are interesting if we compare to the experimental results (\( Br \sim 2.45 \times 10^{-3} \)) as is shown in ref. [47] for \( m_h = 125 \text{ GeV} \); for this channel, our results is plotted fig. 9 versus \( t_\beta \). We found \( Br(h \to t^* c) \sim 10^{-2} \) for the \( 1 \lesssim t_\beta \lesssim 20 \), which is a very interesting channel to explore in the LHC or the next generation of colliders.
Fig. 8  The Feynman diagram for the $h \rightarrow t^*c$.

Fig. 9  The Br for the process $h \rightarrow t^*c$ that we have predicted.

Fig. 9 shows an interesting channel to probe new physics and we expect the next experimental results to test the THDM-III as the simplest SM extension. Analysis in other context have been made in ref. [48], differences in the results are associated to the different models. In ref.[49] we found a scenario one order of magnitude above, however our results consider freedom in the parameters. Then it is possible to have $Br(h \rightarrow W\bar{b}) \sim 10^{-3}$, but it fixes the other parameters as is shown in table 1. We note that the numerical analysis shows the $Br(h \rightarrow t^*c)$ converges to the value $\sim 5 \times 10^{-3}$ when $\beta$ is large, $\tan \beta > 20$. Figure 9 is plotted for $\tan \beta$ in $[0, 20]$, however, for instance a random point $\tan \beta = 34.3609$ from the numerical analysis is written in table 1 to show the convergence.

Table 1  Representative values for the set of parameters associated to the fig.9.

| $Br(h \rightarrow t^*c)$ | $t_\beta$   | $\chi^u_{ij}$ | $\chi^d_{ij}$ | $m_{H^\pm}$ [GeV] | $m_{H}$ [GeV] |
|-------------------------|-------------|----------------|----------------|---------------------|---------------|
| 0.00477                 | 34.3609     | -0.41433       | 0.98872        | 498.982             | 981.502       |
| 0.00468                 | 10.4314     | 1.55977        | 0.95850        | 399.117             | 982.514       |
| 0.00559                 | 2.33911     | 0.08961        | 1.11261        | 510.238             | 541.895       |

Table 1 shows the allowed values for the parameters considering FC couplings, THDM-III, alignment ($\beta - \alpha = \pi/2 - \delta$) and the process represented in the fig.8.
4. Conclusions

We have explored the $h \rightarrow \gamma\gamma$ processes, and checked the high suppression for the FC in the THDM-III context \cite{50, 51}. Our exploration in the $\chi_{ijk}^h - \chi_{ijk}^d - \chi_{ijk}^s$ parameter space showed the allowed regions for different $t_\beta$ values (see fig. 3).

Besides we explore the different modes for Higgs decays (see fig. 4). After we considered the experimental constraints to get scattering plots for the FC parameters and some relevant decay modes. We expected the next results to figure out the FC and its implications in the scalar sector. Our results showed $\text{Br}(h \rightarrow \mu\tau) \lesssim 10^{-5}$ and $\text{Br}(h \rightarrow \gamma Z) \sim 10^{-6}$ as long as $\text{Br}(b \rightarrow s\gamma) \lesssim 10^{-4}$ as is shown in fig. 7, those engaging values for exploring in LHC. Besides we predicted $\text{Br}(h \rightarrow t^*c) \sim 10^{-3}$ for $1 \lesssim t_\beta \lesssim 20$, this a feasible channel to explore our model in the LHC. For the on-shell top quark we obtain the $\text{Br}(h \rightarrow Wc\bar{b}) \sim 4 \times 10^{-3}$ for $5 \lesssim t_\beta \lesssim 20$ and alignment constraint.

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