Higgs decay mediated by top-quark with flavor-changing neutral scalar interactions

J. A. Orduz-Ducuara
División de Matemáticas e Ingeniería,
FES-Acatlán, UNAM
C.P. 53150,
Estado de México, México.
E-mail: jaorduz@ciencias.unam.mx

Abstract. We explore the flavor-changing parameters mediated by a Higgs boson within the THDM-III context. In particular, the $h \rightarrow t^*c$ processes, and check the high suppression for the FC in the THDM-III context for the low $t_\beta$ parameters. Our exploration in the $\chi^u_{ij} - \chi^d_{ij}$-parameter space shows the allowed regions for different $t_\beta$ values. We explored different modes for Higgs decays, considered the experimental constraints to get scattering plots for the FC parameters and some relevant decay modes. We expect future results to figure out the FC and its implications in the scalar sector.

Higgs, Flavor-Changing Neutral Scalar Interactions, Multi-Higgs

1. Introduction
Different experiments have examined the Standard Model observables which have good agreement with the theoretical results. 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 we have some questions to solve: the matter-antimatter asymmetry, the CP violation and flavor-changing neutral currents (FCNC) mediated by gauge and scalar bosons. In this document, we shall discuss the last one where the neutral scalar boson can change the fermion flavor.

We shall discuss the Flavor-Changing Neutral Scalar Interactions (FCNS) in 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]. In fact, the total Higgs decay is given by [2]:

$$\Gamma_{total} \approx \Gamma(h \rightarrow b\bar{b}) + \Gamma(h \rightarrow c\bar{c}) + \Gamma(h \rightarrow WW^*) + \Gamma(h \rightarrow ZZ^*) + \Gamma(h \rightarrow c\bar{b}W^-);$$

however the purpose of this paper is focused on flavor-changing mediated by Higgs bosons, in particular, we explore the $hc\nu-\text{vertex}$, which is interesting for the last term in eq. (1).

Several reports have shown the following theoretical and experimental limit values for the branching ratios (Br) [3]: $\text{Br}(t \rightarrow uh) = 5.5 \times 10^{-6}$, $\text{Br}(t \rightarrow ch) = 1.5 \times 10^{-3}$, $\text{Br}(t \rightarrow u\gamma) \sim 10^{-6}$, $\text{Br}(t \rightarrow c\gamma) \sim 10^{-6}$, $\text{Br}(t \rightarrow uZ) \sim 10^{-7}$, $\text{Br}(t \rightarrow cZ) \sim 10^{-7}$.

Our calculation introduces the Passarino-Veltman functions implemented on Looptools, FeynCalc, FeynArts and SARAH [4–6].
This letter is organized as follows: section 2 shows the models and methods in the THDM-III context, section 3 we expose a results for the $h \to t^*c$ process and section 4 contains the conclusions.

2. Models and Methods
We shall consider the THDM-III where the most general potential is [7]

$$V(\Phi_1 \Phi_2) = m_{11}^2 \Phi_1 \Phi_1 + m_{22}^2 \Phi_2 \Phi_2 - [m_{12}^2 \Phi_1 \Phi_2 + \text{h.c.}] + \frac{1}{2} \lambda_1 (\Phi_1 \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2 \Phi_2)^2 + \lambda_3 (\Phi_1 \Phi_1) (\Phi_2 \Phi_2) + \lambda_4 (\Phi_1 \Phi_2) (\Phi_2 \Phi_1) + \left\{ \frac{1}{2} \lambda_5 (\Phi_1 \Phi_2)^2 + \left[ \lambda_6 (\Phi_1 \Phi_1) + \lambda_7 (\Phi_2 \Phi_2) \right] \Phi_1 \Phi_2 + \text{h.c.} \right\}.$$ 

In a general way, the Yukawa sector for the THDM-III is given by [8]

$$\mathcal{L}_{\text{Yukawa-THDM-III}}^{f} = \frac{g}{2} \left( \frac{m_i}{m_W} \right) d_i \left[ \cos \alpha \frac{1}{\cos \beta} \delta_{ij} + \sqrt{\frac{2 \sin (\alpha - \beta)}{g \cos \beta}} \left( \frac{m_W}{m_i} \right) \left( \tilde{Y}^d_{ij} \right) \right] d_j H^0 + \frac{g}{2} \left( \frac{m_i}{m_W} \right) \bar{d}_i \left[ - \sin \alpha \frac{1}{\cos \beta} \delta_{ij} + \sqrt{\frac{2 \cos (\alpha - \beta)}{g \cos \beta}} \left( \frac{m_W}{m_i} \right) \left( \tilde{Y}^d_{ij} \right) \right] \gamma^5 d_j A^0 + \frac{g}{2} \left( \frac{m_i}{m_W} \right) \left[ \sin \frac{1}{\sin \beta} \delta_{ij} + \sqrt{\frac{2 \sin (\alpha - \beta)}{g \sin \beta}} \left( \frac{m_W}{m_i} \right) \left( \tilde{Y}^u_{ij} \right) \right] u_j H^0 + \frac{g}{2} \left( \frac{m_u}{m_W} \right) \bar{u}_i \left[ - \cos \frac{1}{\sin \beta} \delta_{ij} + \sqrt{\frac{2 \cos (\alpha - \beta)}{g \sin \beta}} \left( \frac{m_W}{m_i} \right) \left( \tilde{Y}^u_{ij} \right) \right] u_j H^0 + \frac{ig}{2} \left( \frac{m_u}{m_W} \right) \bar{u}_i \left[ - \cot \delta_{ij} + \sqrt{\frac{2}{g \sin \beta}} \left( \frac{m_W}{m_i} \right) \left( \tilde{Y}^u_{ij} \right) \right] \gamma^5 u_j A^0. \tag{2}$$

Where the (2) is the Lagrangian density for the fermion-fermion-ϕ; and $\phi = A^0, H^0, h^0$ which are the pseudoscalar, heavy Higgs and standard model Higgs, and the superscript (zero) labels the mass eigenstates.

One can rewrite the Yukawa couplings as $Y^f_{ij} = \sqrt{2} \frac{M_f}{v \cos \beta} - \tilde{Y}^f_{ij} t_\beta$; because we explore a simple model where the flavor-changing is due to the $\chi^f_{ij}$-parameters, and it is simple if we reduce the number of those parameters, which are associated to the Yukawa couplings; namely $Y^f_{ij} = \sqrt{2} \frac{m_i m_j}{v} \chi^f_{ij}$, where the $m_i$ and $m_j$ are the fermion masses and $\chi^f_{ij}$ are the dimensionless parameters that will probe the flavor-changing mediated by scalar bosons.

We explore the THDM-III because it is possible to have mixing between the fermion flavors at tree level. For the purpose of this paper, we introduce $B \to X_s \gamma$ processes considering $\Gamma(B \to X_s \gamma) \approx \Gamma(b \to s \gamma)$, since the non-perturbative effects are small [9]. We consider the constraints coming from $t \to cV, b \to s \gamma, h \to l_l^+ l_l^-, h \to \gamma Z$, to show the correlation between branching ratios $b \to s \gamma$ and $h \to \gamma Z$, and found excluded regions (e. g. figs. 3-4).

3. Results
Figs. 3 and 4 show a correlation between parameters of the model, considering different constraints coming from $t$ and $b$-quark and $h$ decays [10].
Figure 1. The fig. a) shows the Feynman diagrams for $h \to VV'$ considered to constrain our parameter analysis. The figs. c)-d) are the Feynman diagram for the $q_i q_j V$ process at one-loop level with a scalar as a flavor-changing mediator.

Figure 2. The Feynman diagram for the $h \to t^* c$.

The process that is represented in fig. 2 was proposed by ref. [2] to explore the flavor-changing modes.

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 find that if $t_\beta \lesssim 10^{-3}$ then $-200 \lesssim \chi_{ij}^u \lesssim 200$, while $t_\beta \lesssim 10^{-4}$ then $-200 \lesssim \chi_{ij}^d \lesssim 200$. Those figs. (3 and 4) show that $\chi_{ij}^d - t_\beta$ is more suppressed than the $\chi_{ij}^u - t_\beta$ for the lowest $t_\beta$ values.

In figs 5-6, the dark regions represent the highly allowed region. We generated randomly the parameter set, as follow, $-200 \leq \chi_{ij}^{u,d} \leq 200, 0 \leq t_\beta \leq 100, 350 \text{ GeV} \leq m_{H,H^\pm} \leq 1000 \text{ GeV}$, as well considering the experimental bounds for the $t, b$ and $h$ branching ratios at tree and one-loop level.

If we consider the $W^-$ decays to $\nu_l l$ then we obtain $\text{Br}(h \to ll\bar{q}q)$ of order $10^{-4}$, therefore our results are interesting if we compare to the experimental results ($\text{Br}(h \to ll\bar{q}q)\sim 10^{-2} - 10^{-3}$) as is shown in ref. [11] for $m_h = 125 \text{ GeV}$. We found $\text{Br}(h \to t^* c) \sim 10^{-3}$ for the $1 \lesssim t_\beta \lesssim 20$ (fig. 7), which is a very interesting channel to explore in the LHC or the next generation of colliders.

Fig. 7 shows an interesting channel ($\text{Br}(h \to t^* c)$) to probe new physics and we expect the
4. Conclusions

We have explored the $h \rightarrow t^* c$ processes, and checked the high suppression considering FC mediated by Higgs boson.

Our exploration in the $\chi^u_{ij} - \chi^d_{ij}$ parameter space showed the allowed regions for different $t_\beta$ values (see figs. 3-4). Besides we explore the different modes for Higgs decays to (see figs. 5-6). 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 figs. 5-6, 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.

Acknowledgments

I acknowledge support from CONACYT-SNI (Mexico).
Figure 7. The Br for the process $h \rightarrow t^*c$ that we have predicted.

References

[1] Arroyo M, Diaz-Cruz J L, Diaz E and Orduz-Ducuara J A 2016 Chin. Phys. C40 123103 (Preprint 1306.2343)
[2] Diaz-Cruz L, Diaz-Furlong A, Gaitán-Lozano R and Montes de Oca J 2012 (Preprint 1203.6893)
[3] collaboration T A (ATLAS) 2013 ATLAS-CONF-2013-081
[4] Hahn T and Perez-Victoria M 1999 Comput. Phys. Commun. 118 153–165 (Preprint hep-ph/9807565)
[5] Hahn T 2001 Comput. Phys. Commun. 140 418–431 (Preprint hep-ph/0012260)
[6] Staub F 2015 Adv. High Energy Phys. 2015 840780 (Preprint 1503.04200)
[7] Gunion J F and Haber H E 2003 Phys. Rev. D67 075019 (Preprint hep-ph/0207010)
[8] Diaz-Cruz J L, Noriega-Papaqui R and Rosado A 2005 Phys. Rev. D71 015014 (Preprint hep-ph/0410391)
[9] El-Khadra A X and Luke M 2002 Ann. Rev. Nucl. Part. Sci. 52 201–251 (Preprint hep-ph/0208114)
[10] Gaitán R, Montes de Oca J and Orduz-Ducuara J 2017 Progress of Theoretical and Experimental Physics 2017 073B02
[11] Dittmaier S et al. (LHC Higgs Cross Section Working Group) 2011 (Preprint 1101.0593)