Rare top decay $t \to c\gamma$ with flavor changing neutral scalar interactions in two Higgs doublet model

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Models beyond the Standard Model with extra scalars have been highly motivated by the recent discovery of a Higgs boson. The Two Higgs Doublet Model Type III considers the most general case for the scalar potential, allowing mixing between neutral CP-even and CP-odd scalar fields. This work presents the results of the study on the $t \to c\gamma$ decay at one loop level if neutral flavor changing is generated by top-charm-Higgs coupling given by the Yukawa matrix. For instance, a value for the branching ratio $\text{Br}(t \to c\gamma) \sim 10^{-6}$ for $\tan\beta = 2.5$ and general neutral Higgs mixing parameters, $1.16 \leq \alpha_1 \leq 1.5$, $-0.48 \leq \alpha_2 \leq -0.1$. The number of events for the $t \to c\gamma$ decay with an integrated luminosity of $300 \, \text{fb}^{-1}$ is estimated as $10 \lesssim N_{\text{Eff}} \lesssim 100$ for the parameters of the model constrained by experimental data.

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I. INTRODUCTION

The observation of the scalar-like Higgs boson with a mass of 126 GeV at the Large Hadron Collider (LHC) [1, 2] has motivated the study of extended models with multiple scalar multiplets. The mass hierarchy between the up-type and down-type quarks suggests the consideration of models with two complex $SU(2)_L$ doublet scalar fields, referred to as Two Higgs Doublet Models (THDM). There are two versions of THDM, labeled as type I and type II, with invariance under a $Z_2$ discrete symmetry which ensures CP conservation in the scalar sector [3]. In the first case, all quarks acquire mass through one doublet [4, 5] whereas in type II [6] one doublet gives mass to the up-type quarks while the other doublet gives mass to the down-type quarks.

In the so called type III both doublets simultaneously give masses to all quark types, which will hence be referred as Model III [7]. In any type of THDM five physical Higgs particles are predicted, three of them are neutral with CP-even or CP-odd states and a charged pair. An important feature in Model III is the mixing between the CP-even and CP-odd states for neutral scalar fields given by the mixing parameters $\alpha_1, \alpha_2$ and $\alpha_3$ [8–10]. Current measurements in LHC imply that the 126 GeV scalar particle is in good agreement with the Higgs boson being CP even [11, 12].

Model III without $Z_2$ discrete symmetry is a general version that generates Flavor Changing Neutral Scalar Interactions (FCNSI) in Higgs-fermion Yukawa couplings and CP violation in the Higgs potential [13–17]. One motivation to look for new sources of CP violation beyond the SM is the matter-antimatter problem [22, 23] as well as the fermion electric dipole moments [18–21]. In particular we are interested in the $t \to c\gamma$ rare decay. The LHC excludes the ranges of $\text{Br}(t \to c\gamma) > 5.9 \times 10^{-3}$, meanwhile in future results it is expected to set an upper bound of order $10^{-5}$ [33].

In [34] is estimated a value for $\text{Br}(t \to c\gamma) \sim 10^{-8}$ with charged Higgs mass $m_{H^\pm} \sim 200 \, \text{GeV}$ as well as small values of the $\beta$ mixing parameter, $\tan\beta = 0.1$. A detailed study in the framework of Model III with FCNC shows more feasible values for branching ratio in the range $10^{-12} < \text{Br}(t \to c\gamma) < 10^{-7}$ with the masses of the scalars...
between 200 GeV and 800 GeV [7, 35–38]. For the different THDM types, the Br \( t \to c\gamma \) is enhanced for specific regions of scalar masses and mixing parameters [30, 39, 40].

The rare top decay has been analyzed in extended models other than THDM, for instance [41–45]. In a previous work [46, 47], it was shown that Br \( t \to c\gamma \) is sensitive to \( \tan \beta \) in the framework of Model III, obtaining Br \( t \to c\gamma \) \( \sim 1 \times 10^{-6} \) for \( 8 \leq \tan \beta \leq 15 \). The rare top-quark decays at one loop with FCNC coming from additional fermions and gauge bosons has been studied in several extensions of the SM such as MSSM, Left-Right symmetry Models, top color assisted technicolor, little Higgs and two Higgs doublets with four generations of quarks [7, 32, 34–38, 48]. FCNC and CPV between quarks and scalars can also contribute to interactions with rare top decay [49, 50].

The content of this paper is as follows. The next section introduces the model and the interactions between quarks and neutral Higgs bosons. In section III we calculate Br \( t \to c\gamma \) in the framework of the Model III with FCNSI including CP violation in the scalar sector, in section IV we present the restrictions to the parameters involved in the rare top decay. We present the results of our analysis in section V. Finally, the conclusion is stated in section VI.

### II. Flavour Changing Neutral Scalar Interactions

Given \( \Phi_1 \) and \( \Phi_2 \) two complex \( SU(2)_L \) doublet scalar fields with hypercharge-one, the most general gauge invariant and renormalizable Higgs scalar potential is [51]

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

(1)

where \( m_{11}^2, m_{22}^2 \) and \( \lambda_1, \lambda_2, \lambda_3, \lambda_4 \) are real parameters and \( m_{12}^2, \lambda_5, \lambda_6, \lambda_7 \) can be complex parameters. The most general \( U(1)_{EM} \)-conserving vacuum expectation values (VEV) are

\[
\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix},
\]

(2)

\[
\langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 e^{i\xi} \end{pmatrix},
\]

(3)

where \( v_1 \) and \( v_2 \) are real and non-negative, \( 0 \leq |\xi| \leq \pi \), and \( v^2 = v_1^2 + v_2^2 = \frac{4M_h^2}{\xi^2} = (246 \text{ GeV})^2 \). Without loss of generality, the phase in the Eq. (2) was eliminated through the \( U(1)_Y \) global invariance, leaving the \( \xi \) phase in the VEV of Eq. (3). This \( \xi \) phase is a source of spontaneous CP violation which can be absorbed by redefining the free parameters [52].

The neutral components of the scalar Higgs doublets in the interaction basis are \( \frac{1}{\sqrt{2}} (v_a + \eta_a + i\chi_a) \), where \( a = 1, 2 \). As a result of the explicit CP symmetry breaking, a mixing matrix \( R \) relates the mass eigenstates \( h_i \) with the \( \eta_i \) as follows

\[
h_i = \sum_{j=1}^{3} R_{ij} \eta_j,
\]

(4)

where the state orthogonal to the Goldstone boson associated to \( Z \) boson is \( \eta_3 = -\chi_1 \sin \beta + \chi_2 \cos \beta \) and \( R \) is parametrized as [53]:

\[
R = \begin{pmatrix}
c_1 c_2 & s_1 c_2 & s_2 \\
-c_1 s_2 s_3 + s_1 c_3 & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\
-c_1 s_2 c_3 + s_1 c_3 & -c_1 s_1 + s_1 s_2 c_3 & c_2 c_3
\end{pmatrix},
\]

(5)

with \( c_i = \cos \alpha_i, s_i = \sin \alpha_i \) for \( -\frac{\pi}{2} \leq \alpha_{1,2} \leq \frac{\pi}{2} \) and \( 0 \leq \alpha_3 \leq \frac{\pi}{2} \). The neutral Higgs bosons \( h_i \) satisfy the mass relation \( m_{h_1} \leq m_{h_2} \leq m_{h_3} \) [54, 57]. In the CP conserving case \( \eta_1 \) and \( \eta_2 \) are CP-even and mixed in a \( 2 \times 2 \) matrix while \( \eta_3 \) is CP-odd without mixing with \( \eta_1 \) and \( \eta_2 \). However, due to the CP-symmetry breaking in the general case, the neutral
Higgs bosons $h_{1,2,3}$ do not have well defined CP states. The most general structure for the Yukawa couplings among fermions and scalar is

$$\mathcal{L}_{Yukawa} = \sum_{i,j=1}^{3} \sum_{a=1}^{2} \left( \bar{q}_{L}^{i} Y_{aij}^{u} u_{R}^{i} \Phi_{a}^{*} \right) + \sum_{i,j=1}^{3} \sum_{a=1}^{2} \left( \bar{q}_{L}^{i} Y_{aij}^{d} d_{R}^{i} \Phi_{a}^{*} \right) + \sum_{i,j=1}^{3} \sum_{a=1}^{2} \left( \bar{q}_{L}^{i} Y_{aij}^{l} l_{R}^{i} \Phi_{a}^{*} \right) + h.c.,$$

(6)

where $Y_{aij}^{u,d,l}$ are the $3 \times 3$ Yukawa matrices. $q_{L}$ and $l_{L}$ denote the left handed fermion doublets under $SU(2)_{L}$, while $u_{R}$, $d_{R}$, $l_{R}$ correspond to the right handed singlets. The zero superscript in fermion fields stands for the interaction basis. After getting a correct spontaneous symmetry breaking by the VEV using Eq. (2) and Eq. (3), the mass matrices become

$$M_{u,d,l}^{a} \equiv \frac{1}{\sqrt{2}} v_{a} Y_{a},$$

(7)

where $Y_{a}^{f} = V_{L}^{f} Y_{a}^{0} (V_{R}^{f})^{\dagger}$, for $f = u, d, l$. The $V_{L,R}^{f}$ matrices are used to diagonalize the fermion mass matrices and relate the physical and interaction states. Note that in Model III the diagonalization of mass matrices does not imply the diagonalization of the Yukawa matrices, as it happens in the THDM type I or II. An important consequence of non-diagonal Yukawa matrices in physical states is the presence of FCNCSI between neutral Higgs bosons and fermions.

The focus is on the up-type quark Yukawa interactions that contain the Feynman rules for the rare top decay. Replacing from Eq. (4) and Eq. (7) in the Yukawa Lagrangian of Eq. (6), the interactions between neutral Higgs bosons and fermions can be written as interactions of the THDM with CP conserving (type I or II) plus additional contributions, which arise from any of the $Y_{u,d,l}$ Yukawa matrices. The relation among the mass matrix $M^{F}$ and the Yukawa matrices $Y_{u,d,l}$, for $F = u, d, l$, is used to write the Yukawa Lagrangian, Eq. (6), as a function only of one Yukawa matrix, $Y_{1}^{F}$ or $Y_{2}^{F}$. We choose to write the interactions as a function of the Yukawa matrix $Y_{2}$, that is $Y_{1}^{F} = \frac{\sqrt{2}}{v_{d}} M^{F} - \frac{v_{u}}{v_{d}} Y_{2}^{F}$ is replaced in Eq. (6). From now on, in order to simplify the notation, the subscript 2 in the Yukawa couplings will be omitted. The interactions between quarks and Higgs bosons in the mass eigenstates are explicitly written as

$$\mathcal{L} = \frac{1}{\sqrt{2}} \cos \beta \sum_{i,j,k} \bar{u}_{i} M_{ij}^{u} (A_{k} P_{L} + A_{k}^{*} P_{R}) u_{j} h_{k} + \frac{1}{\sqrt{2}} \cos \beta \sum_{i,j,k} \bar{d}_{i} M_{ij}^{d} (A_{k}^{*} P_{L} + A_{k} P_{R}) d_{j} h_{k}$$

$$+ \frac{1}{\sqrt{2}} \cos \beta \sum_{i,j,k} \bar{u}_{i} Y_{ij}^{u} (B_{k} P_{L} + B_{k}^{*} P_{R}) u_{j} h_{k} + \frac{1}{\sqrt{2}} \cos \beta \sum_{i,j,k} \bar{d}_{i} Y_{ij}^{d} (B_{k}^{*} P_{L} + B_{k} P_{R}) d_{j} h_{k}$$

$$+ \left[ \frac{\sqrt{2}}{v} \cos \beta \sum_{ij} \bar{u}_{i} \left( (KY^{d})_{ij} P_{R} - (Y^{u} K)_{ij} P_{L} \right) d_{j} H^{+} \right]$$

$$+ \frac{\sqrt{2}}{v} \tan \beta \sum_{ij} \bar{u}_{i} \left( -(KM^{d})_{ij} P_{R} + (M^{u} K)_{ij} P_{L} \right) d_{j} H^{+}$$

$$+ \frac{\sqrt{2}}{v} \bar{d}_{i} \sum_{ij} \left( (M^{d} K)_{ij} P_{R} - (M^{u} K)_{ij} P_{L} \right) d_{j} G_{W}^{+} + h.c.,$$

(8)

where we define

$$A_{k} = R_{k1} - iR_{k3} \sin \beta,$$

$$B_{k} = R_{k2} \cos \beta - R_{k1} \sin \beta + iR_{k3}. $$

(9)

The fermion spinors are denoted as $(u_{1}, u_{2}, u_{3}) = (u, c, t)$, where the indexes $i, j = 1, 2, 3$ denote the family generations in Eq. (8), while $k = 1, 2, 3$ is used for the neutral Higgs bosons and $P_{R,L} = \frac{1}{2}(1 \pm \gamma_{5})$. Note that a CP conserving case is obtained only if two neutral Higgs bosons are mixed with well-defined CP states, for instance $\alpha_{2} = \alpha_{3} = 0$ is the usual limit.

III. RARE TOP DECAY $t \rightarrow c\gamma$

The expression for the $t \rightarrow c\gamma$ decay amplitude is a magnetic transition written as

$$\mathcal{M} = \bar{u}(p') \left[ F_{1} \sigma_{\mu\nu} + F_{2} \sigma_{\mu\nu} \gamma_{5} \right] q'^{\nu} u(p) e^{\mu} (q),$$

(10)
where $p' = p - q$, $\epsilon^\mu(q)$ is the photon polarization; when the photon is on-shell, $q^2 = 0$, and $\epsilon^\mu(q) q_\mu = 0$. The invariant amplitudes $F_{1,2}$ are obtained in terms of the model parameters as shows Eq. (11). Eq. (10) corresponds to a five-dimension operator, and then the on-shell $t \to c \gamma$ amplitude must be represented by a set of loop diagrams. Fig. (1) shows the dominant contributions for the rare top decay $t \to c \gamma$ at one loop coming from neutral and charged Higgs bosons. The charged contributions, see Fig. 1(b) and Fig. 1(c), are suppressed by the bottom quark mass compared to the top quark mass in the neutral Higgs contribution. In order to study the effects of FCNSI we analyze only the dominant contribution, see Fig. 1(a). In order to obtain the partial width of the $t \to c \gamma$ decay in Model III we apply the method previously used in [32]. Integrating over the internal momentum, the partial width is

$$\Gamma(t \to c \gamma) = \frac{G_F m_t^3}{192 \pi^3 \cos^4 \beta} |Y_{ct}|^2 \sum_k |f_1(\hat{m}_k) A_k^* B_k + f_2(\hat{m}_k) A_k B_k^*|^2,$$

(11)

where $G_F^{-1} = \sqrt{2} v^2$, $v = 246$ GeV, $\alpha \approx 1/128$ at electroweak scale and the functions $f_{1,2}$ are defined as

$$f_1(\hat{m}_k) = \int_0^1 dx \int_0^{1-x} dy \frac{x(x+y-1)}{x^2 + xy - (2 - \hat{m}_k^2) x + 1},$$

(12)

$$f_2(\hat{m}_k) = \int_0^1 dx \int_0^{1-x} dy \frac{(x-1)}{x^2 + xy - (2 - \hat{m}_k^2) x + 1},$$

(13)

with $\hat{m}_i = \frac{m_{h_i}}{m_t}$ for $i = 1, 2, 3$. The branching ratio can be approximated as

$$\text{Br}(t \to c \gamma) \approx \frac{\Gamma(t \to c \gamma)}{\Gamma_{\text{top}}},$$

(14)

where $\Gamma_{\text{top}}$ at NLO is given by [33]

$$\Gamma_{\text{top}} = \frac{G_F m_t^3}{8 \pi \sqrt{2}} \left( 1 - \frac{M_W^2}{m_t^2} \right)^2 \left( 1 - 2 \frac{M_W^2}{m_t^2} \right) \left[ 1 - \frac{2\alpha_s}{3\pi} \left( \frac{2\pi^2}{3} - \frac{5}{2} \right) \right].$$

(15)
This result provides an important constraint on the $Y_{tc}$ coupling. Following references \[58,62\], the branching ratio of the $b \to s\gamma$ decay is a function of the Wilson coefficients and it can be written as:

$$\text{Br}(B \to X_s\gamma) \approx a + a_{77} \delta C_7^2 + a_{88} \delta C_8^2 + \text{Re}(a_7 \delta C_7) + \text{Re}(a_8 \delta C_8) + \text{Re}(a_{78} \delta C_7 \delta C_8^*),$$

with $a \approx 3.0 \times 10^{-4}$, $a_{77} \approx 4.7 \times 10^{-4}$, $a_{88} \approx 0.8 \times 10^{-4}$, $a_7 \approx (-7.2 + 0.6i) \times 10^{-4}$, $a_8 \approx (-2.0 - 0.6i) \times 10^{-4}$ and $a_{78} \approx (2.5 - 0.9i) \times 10^{-4}$. The main contributions due to Wilson coefficients, beyond the W-boson contribution, are given by charged Higgs and flavor changing (FC) Yukawa couplings.

We note that Eq.(11) contains free parameters of the THDM, such as the masses of the neutral Higgs bosons, the mixing angles $\alpha_i$, $\beta$ and Yukawa couplings. In order to set allowed values for free parameters we first review the possible constraints that $b \to s\gamma$ decay can impose on the $Y_{tc}$ coupling. Following references \[58,62\], the branching ratio of the $b \to s\gamma$ decay is a function of the Wilson coefficients and it can be written as:

$$\text{Br}(B \to X_s\gamma) \approx \frac{1}{3\tan^2\beta} f_{7,8}^{(1)}(y_t) + f_{7,8}^{(2)}(y_t),$$

while the FC contribution is

$$C_{7,8}^{H,\text{FC}} = \frac{2M_W}{g_{m_i} K_{t_8} \cos \beta} (Y^u K)_{t_8} f_{7,8}^{(1)}(y_t) + \frac{2M_W}{g_{m_i} K_{t_8} \cos \beta} (K Y^d)_{t_8} f_{7,8}^{(2)}(y_t)$$

with $y_t = m_t^2/M_H^2$ and the explicit relations $f_{7,8}^{(1),(2)}(x)$ can be found in Ref. \[58,62\]. Using the hierarchy of the Kobayashi-Maskawa matrix ($K$) we have the following approximations $(Y^u K)_{t_8} \approx Y_{te} K_{t_8}$ and $(K Y^d)_{t_8} \approx K_{tb} Y_{bb}$. In order to have a bound to the $Y_{tc}$ FC Yukawa coefficient, it was considered that $(K Y^d)_{t_8}$ gives the most important contribution. The limits on the $B \to X_s\gamma$ decay come from BaBar, Belle and CLEO \[63,65,65,67\]. The current world average for $E > 1.6$ GeV, given by HFAG \[68\], is

$$\text{Br}(B \to X_s\gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}.$$  

This result provides an important constraint on the $(Y_{tc}, Y_{bb})$ space, Fig.(2), with $m_{H^\pm} = 500$ GeV and $0 < \tan \beta < 20$.

The second constraint considered is based in the branching ratio of the SM Higgs boson decay to bottom quark pairs, which has a reported value of $Br (H \to bb) = 5.77 \times 10^{-1} \pm 3.2\% \pm 3.3\%$ \[33\]. The width decay in the THDM for $h_1 \to bb$ is given by

$$\Gamma_{h_1 \to bb} = \frac{N_c m_{h_1}}{8\pi \sqrt{2}} \left(1 - 4 \frac{m_b^2}{m_{h_1}^2}\right)^{\frac{5}{2}} \left[C^2 \left(1 - 4 \frac{m_b^2}{m_{h_1}^2}\right) + D^2\right],$$

where $N_c = 3$. The limits on the FC Yukawa contribution are

$$C_{7,8}^{H,\text{FC}} \leq \pm 600 \text{ GeV}$$

and

$$\tan \beta < 20,$$

with $m_{h_1} \geq 600$ GeV and $\tan \beta = 1, 2.5, 5, 10$ and 15 .
FIG. 3: Allowed values for the Yukawa couplings $Y_{bb}$, scatter plot with compatible points with the experimental value of the $BR(H \rightarrow b\bar{b})$ and $\pi/2 \leq \alpha_{1,2} \leq \pi/2$.

FIG. 4: Allowed values for the Yukawa couplings, scatter plot with compatible points with the experimental values for $Br(H \rightarrow b\bar{b})$ and $Br(B \rightarrow X_s \gamma)$.

where

$$C^2 = \left[ \frac{m_b}{v \cos \beta} R_{11} + \frac{Y_{bb}}{\cos \beta} (R_{12} \cos \beta - R_{11} \sin \beta) \right]^2$$

(21)

and

$$D^2 = \left[ -\frac{m_b}{v \cot \beta} R_{13} + \frac{Y_{bb}}{\cos \beta} R_{13} \right]^2.$$ (22)

Note that the matrix elements $R_{11}, R_{12}$ and $R_{13}$ are independent of the mixing parameter $\alpha_3$. Figure 3 shows the behavior of $Y_{bb}$ as function of $\tan \beta$ for random values of $\alpha_{1,2}$. After that previous constrains are imposed, the allowed values for Yukawa couplings are $-0.02 \leq Y_{bb} \leq 0.06$ and $-0.12 \leq Y_{tc} \leq 0.02$ for $1 \leq \tan \beta \leq 15$, see Figure 4. The non-diagonal elements of the Yukawa matrix responsible of the FCNSI, shown in Eq.(8), must be suppressed [69].

V. RESULTS

Focusing on the rest of the parameters, note that the masses of the $h_i$ neutral Higgs bosons are set so that the mass of the lightest Higgs boson $h_1$ is equal to the mass value of the observed scalar reported by ATLAS and CMS,
FIG. 5: Allowed values for the mixing parameter $\alpha_1, \alpha_2$, scatter plot with points compatible with the experimental values for $Br(H \rightarrow b\bar{b})$, $Br(B \rightarrow X_s\gamma)$ and $Br(t \rightarrow c\gamma) < 5.9 \times 10^{-3}$, for fixed values of $\tan\beta = 1, 2.5, 5, 10$ and $Y_{tc} = 0.01$.

FIG. 6: Allowed values for the mixing parameters $\alpha_1, \alpha_2$, scatter plot with points compatible with the experimental values for $Br(H \rightarrow b\bar{b})$, $Br(B \rightarrow X_s\gamma)$ and $Br(t \rightarrow c\gamma) < 5.9 \times 10^{-3}$, for fixed values of $\tan\beta = 1, 2.5, 5, 10$ and $Y_{tc} = -0.4$.

$m_{h_1} \approx 126$ GeV [1,2]. Contributions to $\sigma_{\gamma\gamma}$ from $h_2$ and $h_3$ are negligible for masses $m_{h_2}, m_{h_3} > 600$ GeV.

Also, note that the contribution from $h_1$ is independent of the mixing parameter $\alpha_3$, see the first row in matrix Eq.(5). Therefore, the set of free parameters considered in the partial width Eq.(11) is reduced only to the mixing angles $\{\alpha_1, \alpha_2, \beta\}$. Figures [5] and [6] show the allowed values for mixing parameters $\alpha_1$ and $\alpha_2$ when the current limit for the $Br(t \rightarrow c\gamma) < 5.9 \times 10^{-3}$ is considered [33]. Based in Fig.4 the Yukawa coupling $Y_{tc}$ was fixed with the two representative values $Y_{tc} = -0.04$, $0.01$.

In order to analyze the $Br(t \rightarrow c\gamma)$ we consider the allowed regions for the mixing parameters $\alpha_1$ and $\alpha_2$ previously fixed in [71]. The following regions can be obtained for $\alpha_1$ and $\alpha_2$ from $0.5 \leq R_{\gamma\gamma} \leq 2$ with $m_{H^\pm} = 300$ GeV and $\tan\beta = 2.5$ [54,57] [72]:

\[ R_1 = \{-1.39 \leq \alpha_1 \leq -1.2 \quad \text{and} \quad -0.13 \leq \alpha_2 \leq 0\}, \]
FIG. 7: The Model III branching ratio for $t \rightarrow c\gamma$ as a function of $\alpha_1$-$\alpha_2$ in regions $R_1$ and $R_2$.

and

$$R_2 = \{1.16 \leq \alpha_1 \leq 1.5 \text{ and } -0.48 \leq \alpha_2 \leq -0.1\}.$$  \hfill (24)

The ratio $R_{\gamma\gamma}$ given by

$$R_{\gamma\gamma} = \frac{\sigma(gg \rightarrow h_1) Br(h_1 \rightarrow \gamma\gamma)}{\sigma(gg \rightarrow h_{SM}) Br(h_{SM} \rightarrow \gamma\gamma)},$$  \hfill (25)

allows us to compare the prediction of the THDM with the SM prediction for the Higgs boson diphoton decay. Fig. (7) shows $Br(t \rightarrow c\gamma)$ as function of $\alpha_1$ and $\alpha_2$ in the allowed regions $R_1$ and $R_2$ with $\tan \beta = 2.5$. The $Br(t \rightarrow c\gamma)$ can be enhanced up to $10^{-6}$ in the regions $R_{1,2}$. The limits obtained in Model III are less restrictive than those obtained in 2HDM type I and type II, which are of the order $10^{-8}$ \cite{27, 29}. In 2021, LHC is expected to reach an integrated luminosity of the order of 300 fb$^{-1}$ \cite{74}. Experiments in LHC Run 3 with this amount of data could find evidence of new physics beyond SM, in particular processes with FCNC. The expected number of events can be naively estimated with the following approximation

$$N \approx \sigma(p\bar{p} \rightarrow t\bar{t}) Br(\bar{t} \rightarrow \bar{b}W) Br(t \rightarrow c\gamma)L_{int}$$  \hfill (26)

where $\sigma(p\bar{p} \rightarrow t\bar{t}) \approx 176$ pb \cite{33}, $L_{int}$ is the integrated luminosity $\sim 300$ fb$^{-1}$, $Br(\bar{t} \rightarrow \bar{b}W) \approx 1$ and $Br(t \rightarrow c\gamma)$ is the obtained result in Model III, Eq. (14). Due to trigger and selection cuts only a fraction of the produced events are detected by the experiments. An efficiency of 2.4\% is achieved by CMS from simulation of $tc\gamma$ signal events taking into account all selection criteria \cite{73}. Therefore a more realistic estimation of the effective number of events has to be written as $N_{Eff} \approx 0.2 \times N$.

The limit that is expected to be reached in future experiments is $Br(t \rightarrow c\gamma) \sim 10^{-5}$ \cite{74}. If we consider this expected limit as $Br(t \rightarrow c\gamma) \sim (1 - 10)^{-5}$ with $N_{Eff} \geq 1$ and impose the restrictions discussed in the previous section, then the $N_{Eff}$ can be estimated for fixed values of $\tan \beta$. Fig. (8) shows $N_{Eff}$ as a function of $Y_{tc}$. The mixing parameters $\alpha_{1,2}$ are also bounded by same constraints and the allowed values of the $\alpha_{1,2}$ are shown in Fig. (9), Fig. (10) and Fig. (11) for fixed $\tan \beta$. The numerical values for $\tan \beta$ are fixed by the representative values $\tan \beta = 1.56, 2.5, 5, 10, 15$; however, the $N_{Eff}$ as function of $\tan \beta$ with the above restrictions is shown in Fig. (12). We find that there is more than one event, $N_{Eff} \geq 1$, from $\tan \beta \geq 1.56$.

VI. CONCLUSIONS

The expression for rare top decay $t \rightarrow c\gamma$ was calculated at one loop due to the FCNSI in an extended model with two scalar doublets. The SM predicted value for the $Br(t \rightarrow c\gamma)$ is extremely suppressed from LHC sensitivity, while
FIG. 8: Effective number of events for $t \to c\gamma$ as a function of $Y_{tc}$ for $\tan \beta = 1.56$, 2.5, 5, 10, 15 expected in LHC Run 3.

FIG. 9: Allowed regions for $\alpha_1$ and $\alpha_2$ when $Br(t \to c\gamma) \sim (1 - 10)^{-5}$ is assumed with $-0.385 \leq Y_{tc} \leq -0.307$ for $\tan \beta = 1.56$ and $-0.08 \leq Y_{tc} \leq -0.02$ for $\tan \beta = 15$.

FIG. 10: Allowed regions for $\alpha_1$ and $\alpha_2$ when $Br(t \to c\gamma) \sim (1 - 10)^{-5}$ is assumed with $-0.173 \leq Y_{tc} \leq -0.035$ for $\tan \beta = 5$. 
in the considered THDM type III with mixing in the neutral scalars the same branching ratio has been increased making it possible to test rare decays in future experiments. In this work we have studied a theoretical framework where \( Br(t \to c\gamma) \sim 10^{-5} \) can be viable for specific values of mixing parameters.

If the \( t \to c\gamma \) decay is observed in LHC, it will provide an important evidence of physics beyond SM. With the allowed regions for the \( \alpha_1, \alpha_2 \) and \( \tan \beta \simeq 2.5 \), Model III predicts \( Br(t \to c\gamma) \sim 10^{-6} \). Model III, with an integrated luminosity of 300 fb\(^{-1}\), predicts up to \( N_{Eff} \approx 100 \) events for \( t \to c\gamma \) decay with \( \alpha_1, \alpha_2 \) and \( \tan \beta \) given in previous section.

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