Lightest Higgs boson production at photon colliders in the two Higgs doublet model type III

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The branching ratios of the lightest *CP*-even Higgs boson h^0 are calculated in the framework of the general two higgs doublet model. Different scenarios are presented taking into account constraints on the flavor changing neutral currents factors obtained in previous works. Plausible scenarios where appear flavor changing processes at tree level like $b\bar{s}$ and $t\bar{c}$ are analyzed for relevant parameters. The loop-induced Higgs couplings to photon pairs can be tested with a photon collider. The number of events of h^0 as a resonance in photon colliders are calculated taking into account its corresponding background signal at TESLA, CLIC, and NLC.

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I. INTRODUCTION

Although the electroweak standard model (SM) [1] has been experimentally tested with excellent results, the scalar sector of the model, responsible for the electroweak symmetry breaking remains without any experimental test; thus the big mismatch of the SM is the absence of the Higgs boson. A wide variety of models have been introduced to address the puzzles of the electroweak symmetry breaking and the hierarchy mass problem. For instance supersymmetry [2], large extra-dimensions [3], strong dynamics leading to a composite Higgs boson [4] and little Higgs models [5]. There are many other problems that are not addressed by the SM and suggest new physics beyond the SM; one of them is the mixing between families, which is related to neutrino oscillations and flavor changing neutral current (FCNC) processes [6].

One simple extension of the SM is the so-called two Higgs doublet model (2HDM) which adds a new Higgs boson doublet with the same quantum numbers as the first one, and in this way allows a new rich variety of phenomenology. In one attempt to solve the hierarchy problem for the quarks in the third family, one kind of these 2HDMs gives masses to the up sector with one Higgs doublet and to the down sector with the other one. This model is the so-called 2HDM type II, and precisely it is the one that appears in the framework of the minimal supersymmetric standard model (MSSM) [2]. The FCNC processes can be avoided at tree level in the 2HDM by imposing discrete symmetries [7]. These symmetries lead us to 2HDM type I or II. However, our study is going to focus on the 2HDM type III without any discrete symmetry, a general version of the 2HDM, in which the FCNC processes appear at tree level in the Yukawa couplings.

Using the experimental data from the LEP collider, the lower bound $m_h \geq 114$ GeV has been found through direct search of the Higgs boson [8]. On the other hand, radiative corrections of the electroweak parameters lead to a light Higgs boson in the SM scenario with a mass below 220 GeV [9]. Otherwise, TeV scale is being tested by the Fermilab Tevatron and will soon be explored at the CERN Large Hadron Collider (LHC). If the Higgs boson is SM-like its discovery is guaranteed at the LHC; its mass will be measured with high precision and in some channels, the signals will be strong enough to allow the knowledge of certain combinations of Higgs partial widths up to 10–30% level [10]. Further, there is a project called the international linear collider (ILC) which could study the dynamics of the new physics with high precision [11]; it could measure the production cross section of a light Higgs boson in Higgsstrahlung or WW fusion as well as the important branching fractions with a few percent level.

Although is a challenge the discovery of the Higgs boson, an important issue is to decide what kind of model it is coming from, which can be elucidated through its coupling with the standard particles. In the SM, the higgs boson-fermion-antifermion couplings are always proportional to the particle masses. Other models have deviations [12] or they are changed like 2HDM by a mixing angle. A Higgs boson with a mass in the range predicted by precision tests of the SM will be discover at LHC. However, it could be the ILC project in all its modes that tests whether this particle is indeed the SM Higgs boson or whether it is eventually one of the Higgs states in extended models like the 2HDM or MSSM. The range of physics to be done at e^+e^- colliders can be significantly extended by operating the machine with one or both of the e^- beams converted to real high energy photons by Compton backscattering of laser light from incoming e^- bunches. The photon collider option could contribute to the picture by precise measurements of the Higgs coupling to $\gamma\gamma$, it would be an important probe of the quantum loops which would be sensitive to new particles with masses beyond direct search. Experimental studies about the expected precision measurement for the rates $\gamma\gamma \to H \to X$ have been done for various photon colliders designs (TESLA, NLC, CLIC, JLC). The results show that $\gamma\gamma \to H \to \bar{b}b$ could be measured at about 2% level for a light Higgs boson, and the channels WW^* at 5% and ZZ^* at 11% [13].

In this work we focus on the lightest CP-even Higgs boson h^0 in the 2HDM-III, its partial decay widths, at tree level and at one-loop level, taking into account the contribution of new physics due to FCNC from the Yukawa couplings. We calculate the number of events of the h^0 boson as a resonance in a photon collider with its associated background signal.

II. THE TWO HIGGS DOUBLET MODEL TYPE III

The 2HDM includes a second Higgs doublet, and both doublets acquire vacuum expectation value (VEV) different from zero, they are

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \phi_i^0 \end{pmatrix}, \qquad \langle\Phi_i\rangle = \begin{pmatrix} 0 \\ v_i/\sqrt{2} \end{pmatrix}, \qquad i = 1, 2. \quad (1)$$

The scalar spectrum has mass eigenstates which contain two CP-even neutral Higgs bosons (h^0, H^0) coming from the mixing of $\Re(\phi_i^0)$ with mixing angle α; two charged Higgs bosons ($H^\pm$) which are a mix of the would-be Goldstone bosons $G_W^\pm$ through the mixing angle $\tan\beta = v_2/v_1$; and one CP-odd Higgs (A^0) which mix the neutral would-be Goldstone boson G_Z^0. We will consider a general 2HDM-III where the Higgs doublets can couple with the up and down quark sector at the same time because there is not any discrete symmetry. Further in this model, FCNCs appear at tree level and we consider a CP invariant model in order to reduce the number of parameters in the scalar potential. Then the Yukawa Lagrangian for the quarks in this model can be written as follows [14–16]

$$-\mathcal{L}_Y^{(III)} = \eta_{ij}^{U,0}\bar{Q}_{iL}^0\tilde{\Phi}_1 U_{jR}^0 + \eta_{ij}^{D,0}\bar{Q}_{iL}^0\Phi_1 D_{jR}^0 + \xi_{ij}^{U,0}\bar{Q}_{iL}^0\tilde{\Phi}_2 U_{jR}^0 + \xi_{ij}^{D,0}\bar{Q}_{iL}^0\Phi_2 D_{jR}^0 + \text{h.c.}, \quad (2)$$

where Φ_i are the Higgs doublets, η_{ij}^0 and ξ_{ij}^0 are nondiagonal 3×3 matrices and the suffix "0" means that these fermion states are not mass eigenstates. From Eq. (2) is clear that the mass terms for the up-type or down-type sectors depend on two Yukawa coupling matrices. The rotation of the quarks and leptons allow us to diagonalize one of the matrices but in general not both simultaneously, then one Yukawa coupling remains nondiagonal, leading to the FCNC at tree level.

In 2HDM-III there is a global symmetry which can make a rotation of the Higgs doublets and fix one VEV equal to zero [14,17,18]. In such a way, $v_1 = v$ and $v_2 = 0$, and the mixing parameter $\tan\beta = v_2/v_1$ can be eliminated from the Lagrangian. Expanding the Yukawa Lagrangian in this parameterization, it is found that

$$\begin{aligned}
-\mathcal{L}_Y^{(III)} = {} & h^0\bar{U}\left(-\frac{s_\alpha}{v}M_U^{\text{diag}} + \frac{c_\alpha}{\sqrt{2}}\xi^U\right)U + h^0\bar{D}\left(-\frac{s_\alpha}{v}M_D^{\text{diag}} + \frac{c_\alpha}{\sqrt{2}}\xi^D\right)D + H^0\bar{U}\left(\frac{c_\alpha}{v}M_U^{\text{diag}} + \frac{s_\alpha}{\sqrt{2}}\xi^U\right)U \\
& + H^0\bar{D}\left(\frac{c_\alpha}{v}M_D^{\text{diag}} + \frac{s_\alpha}{\sqrt{2}}\xi^D\right)D - \frac{i}{\sqrt{2}}A^0\bar{U}\gamma_5\xi^U U + \frac{i}{\sqrt{2}}A^0\bar{D}\gamma_5\xi^D D - \frac{i}{v}G_Z^0\bar{U}\gamma_5 M_U^{\text{diag}}U + \frac{i}{v}G_Z^0\bar{D}\gamma_5 M_D^{\text{diag}}D \\
& + G_W^+\bar{U}\left\{\frac{\sqrt{2}c_\beta}{v}(-M_U^{\text{diag}}\mathcal{K}P_L + \mathcal{K}M_D^{\text{diag}}P_R)\right\}D + H^+\bar{U}\{\mathcal{K}\xi^D P_R - \xi^U\mathcal{K}P_L\}D + \text{h.c.}, \quad (3)
\end{aligned}$$

where $\mathcal{K}$ is the Cabbibo-Kobayashi-Maskawa matrix and $s_\alpha = \sin\alpha$, $c_\alpha = \cos\alpha$. This Eq. (3) shows how the FCNC processes are generated in this kind of model. In this case, there are two matrices 3×3 which lead to 12 new parameters if we suppose that these matrices are real and symmetric.

In the SM the couplings $\phi f\bar{f}$ are proportional to m_f. Since ξ_{ij} are couplings like $\phi f_i\bar{f}_j$ and, if one wishes to avoid fine tuning, then the structure of the mass spectrum and the mixing hierarchy suggest a natural parameterization for FCNC vertices, it would be the one proportional to the masses of the particles. In the present work we take into account the Cheng-Sher-Yuan (CSY) parameterization which is the geometric mean of the Yukawa couplings of the quark fields [15],

$$\xi_{ij} \equiv \frac{\sqrt{m_i m_j}}{v}\lambda_{ij}. \quad (4)$$

This is an ansatz for the Yukawa texture matrices looking for a phenomenological similarity with SM couplings. Under these assumptions, the relative couplings between the SM ones and those in 2HDM type III are proportional to

$$R_f^{h^0} = -\sin\alpha + \frac{1}{\sqrt{2}}\cos\alpha\lambda_{ff}, \quad (5)$$

where the parameters λ_{ff} are those that generate a hierarchy between the up-type and down-type couplings.

Bounds and restrictions on the λ_{ij} for the quark sector and ξ_{ij} for the leptonic sector can be found in literature [14,17,19–21]. Many scenarios for the λ_{ij} parameters have been analyzed under different phenomenological considerations. In the case of the leptonic sector, some constraints have been imposed on the λ_{ij} using different lepton flavor violating processes and the $(g-2)_\mu$ factor. Analysis of

TABLE I. Some constraints on the flavor changing neutral parameters obtained in the literature[14,17,19,21]. They are taken into account in Sec. IV.

Constraint	Process	Restriction
$\xi_{\mu\tau}^2 \in [7.62 \times 10^{-4}; 4.44 \times 10^{-2}]$	$(g-2)_\mu$	$m_{A^0} \to \infty$
$\xi_{\tau\tau} \in [-1.8 \times 10^{-2}; 2.2 \times 10^{-2}]$	$\tau^- \to \mu^- \gamma$	$m_{A^0} \to \infty$
$\xi_{\mu\mu} \in [-0.12; 0.12]$	$\tau^- \to \mu^+ \mu^- \mu^-$	$m_{A^0} \to \infty$
$\xi_{\mu e} \in [-0.39; 0.39]$	$\tau^- \to e^- e^- \mu^+$	$m_{A^0} \to \infty$
$\lambda_{bb} \in [-100; 100]$	Perturbations	$v_2 = 0$
$\lambda_{tt} \in [-\sqrt{8}; \sqrt{8}]$	Perturbations	$v_2 = 0$
$\lvert\lambda_{tc}\rvert \lesssim 2.3/\cos\alpha$	Precision test	$m_h \lesssim 170$ GeV

possible detection of the Higgs boson at Tevatron and LHC using lepton flavor violating decays have already been presented [22]. Although the quark sector has been less restricted three different scenarios are discussed in Ref. [14] using the available phenomenology. The first scenario discussed, it assume the whole set of $\lambda_{ij} \sim \lambda$ common to all the flavor changing couplings but it was discarded by low energy experiments. The second one is useful to guide to the third one which has more physical relevance. The third scenario is established when the new parameters which are mixing the first and the second generation are negligible and λ_{bb}, λ_{bs} are bigger than one while λ_{tt}, λ_{tc} are smaller than 1. In Table I we display a summary of the bounds that we use in the present work. The leptonic element $\xi_{\mu\tau}$ has a bound coming from $(g-2)$ muon factor and it is interesting because the interval does not contain the zero like the others do. The bounds on λ_{bb} and λ_{tt} are obtained using the criterion of validness of perturbation theory looking at the vertex $\bar{t}bH^+$ [20]. On the other hand, bounds for the parameter λ_{tc} have actually been calculated taking into account the contribution of $h^0 t\bar{c}$ vertex at one-loop level to the electroweak precision observables [21].

III. h^0 DECAYS IN THE 2HDM-III

We assume that h^0 is the lightest Higgs boson in the model and their decays into another Higgs bosons as final states are forbidden. The decay channels to heavy quarks and leptons are $h^0 \to t\bar{t}, b\bar{b}, \tau^+\tau^-, \mu^+\mu^-$; and the relevant FCNC decays at tree level in the 2HDM type III are $h^0 \to t\bar{c}, b\bar{s}, \mu^+\tau^-$ which, in the CSY parameterization could be as large as the standard ones. The decay width of a scalar particle into two different fermions is [22]

$$\Gamma(\phi \to f_i \bar{f}_j) = \frac{N_C}{8\pi} m_\phi |A(\phi f_i \bar{f}_j)|^2 \left(1 - \left(\frac{m_i + m_j}{m_\phi}\right)^2\right) \times \sqrt{1 + \left(\frac{m_i^2 - m_j^2}{m_\phi^2}\right)^2 - \left(\frac{m_i^2 + m_j^2}{m_\phi^2}\right)^2}, \quad (6)$$

with $N_C = 1(3)$ for leptons (quarks) and $A(\phi f_i f_j)$ stands for the Feynman's rule for the $\phi f_i f_j$ vertex.

For $h^0 \to W^+W^-, Z^0Z^0$ it is necessary to consider on-shell and off-shell processes according to the Higgs mass. The widths for the on-shell processes are

$$\Gamma(h^0 \to W^+W^-) = \frac{g^2}{64\pi} \frac{m_{h^0}^3}{m_W^2} \sin^2\alpha \left(1 - 4\frac{m_W^2}{m_{h^0}^2}\right)^{1/2} \times \left(1 - 4\frac{m_W^2}{m_{h^0}^2} + 12\frac{m_W^4}{m_{h^0}^4}\right), \quad (7)$$

$$\Gamma(h^0 \to ZZ) = \frac{g^2}{128\pi} \frac{m_{h^0}^3}{m_W^2} \sin^2\alpha \left(1 - 4\frac{m_Z^2}{m_{h^0}^2}\right)^{1/2} \times \left(1 - 4\frac{m_Z^2}{m_{h^0}^2} + 12\frac{m_Z^4}{m_{h^0}^4}\right). \quad (8)$$

For off-shell processes one of the gauge boson in the final state is a virtual one which can decay into two fermions. The decay widths in the context of the SM Higgs boson can be found in Ref. [23]. And the decay widths for the 2HDM are similar but they have an extra $\sin^2\alpha$ factor, which comes from the couplings in the 2HDM.

At one-loop level the considered decays are $h^0 \to \gamma\gamma, gg, \gamma Z$. The first one, the decay width of h^0 into photons is given by

$$\Gamma(h^0 \to \gamma\gamma) = \frac{\alpha^2 g^2}{1024\pi^3} \frac{m_{h^0}^3}{m_W^2} \left| \sum_{i=0,1/2,1} N_{Ci} e_i^2 F_i R_i^{h^0} \right|^2, \quad (9)$$

where F_i are functions depending on the particle running into the loop and $i = 0, 1/2, 1$ correspond to scalar, fermion, and gauge boson, respectively. They are defined in Ref. [23]. Then, the sum is over top and bottom quarks, $W^\pm$ gauge boson and $H^\pm$ the scalar charged Higgs boson. $R_i^{h^0}$ are relative couplings given by the 2HDM-III. Now, the Feynmman's rule for the vertex $h^0H^+H^-$ assuming an invariant CP potential is [22]

$$h^0H^+H^- \sim \frac{g \sin\alpha}{m_W}\left(\frac{1}{2} m_{h^0}^2 - m_{H^+}^2\right), \quad (10)$$

but we also consider the Feynmman's rule asumming a relationship like SUSY between the Higgs boson masses and the electroweak scale, it is [22,23]

$$h^0H^+H^- \sim -2gm_W \sin\alpha\left(\frac{1}{4\cos^2\theta_W} - 1\right). \quad (11)$$

Both cases are examined comparing with the SM in Fig. 1.

The process $h^0 \to gg$ is quite similar to the last one, but it can only have quarks into the loop. Using again the two heaviest quarks the decay width is

$$\Gamma(h^0 \to gg) = \frac{\alpha_s^2 g^2 m_{h^0}^3}{128\pi^3 m_W^2}\left|\sum_i \tau_i[1 + (1 - \tau_i)f(\tau_i)]R_i^{h^0}\right|^2, \quad (12)$$

with $\tau_i \equiv 4m_i^2/m_{h^0}$ and $f(\tau_i)$ also defined in Ref. [23].

Finally we take the process $h^0 \to \gamma Z$. This loop could be more difficult than the others and it depends on fermionic, scalar and bosonic sectors. The decay width is written as

$$\Gamma(h^0 \to \gamma Z) = \frac{\alpha^2 g^2}{512\pi^3}\frac{m_{h^0}^3}{m_W^2}|A_F + A_W|^2\left(1 - \frac{m_Z^2}{m_{h^0}^2}\right)^3, \quad (13)$$

where the amplitudes A_F and A_W are defined in Refs. [23,24]. All these loop processes are sensitive to variations of parameters which are model dependent.

A. Different scenarios for 2HDM-III

Figure 1 shows the ratios $\Gamma(h^0 \to \gamma\gamma)^{\rm 2HDM}/\Gamma(h^0 \to \gamma\gamma)^{\rm SM}$, $\Gamma^*(h^0 \to \gamma\gamma)^{\rm 2HDM}/\Gamma(h^0 \to \gamma\gamma)^{\rm SM}$, $\Gamma(h^0 \to gg)^{\rm 2HDM}/\Gamma(h^0 \to gg)^{\rm SM}$ and $\Gamma(h^0 \to \gamma Z)^{\rm 2HDM}/\Gamma(h^0 \to \gamma Z)^{\rm SM}$ versus the Higgs boson mass, m_{h^0}, under different choices of the model parameters as it is indicated in the figure caption. The rate $\Gamma^*(h^0 \to \gamma\gamma)^{\rm 2HDM}$ is the partial width taking into account the $h^0H^+H^-$ coupling given by Eq. (11). The cases d in Figs. 1(a) and 1(b)are identical because $\alpha = 0$. In Fig. 1(b) we can see that there are not any asymptotic values of the parameters which approach to the SM values. Equation (12) leads to a case which asymptotically converge to the values expected in the SM framework. On the other hand, it avoids a growing coupling that can be a mismatch in the perturbation limit as should have happened using Eq. (11). The cases labeled a correspond to the asymptotic limits of the 2HDM-III to the SM values, and therefore for these cases the ratios are equal to one, except for the Fig. 1(b) as we already mentioned. The other cases show possible deviations from the SM. The decay widths are suppressed in the low Higgs boson mass range due to the factor $\sin\alpha$ in the $R_i^{h^0}$ couplings coming from the 2HDM.

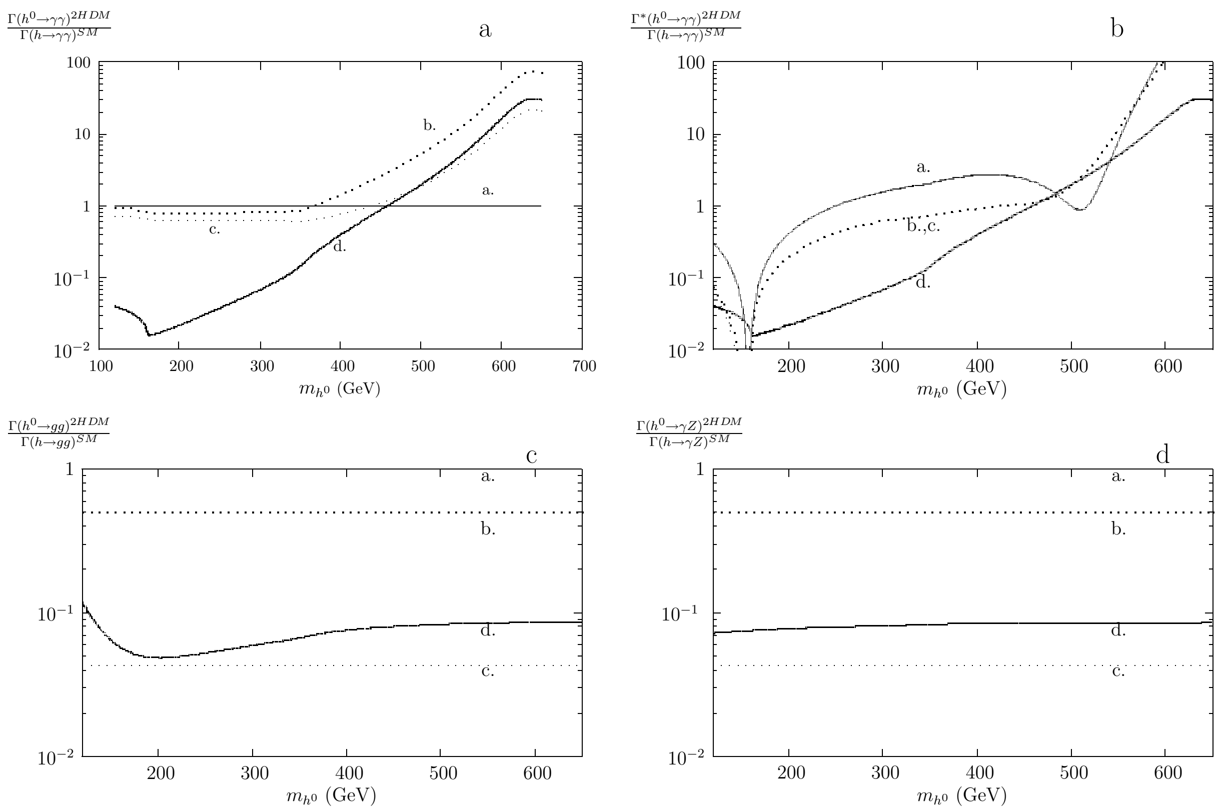

FIG. 1. Sensitivity of $\frac{\Gamma(h^0\to\gamma\gamma)^{\rm 2HDM}}{\Gamma(h^0\to\gamma\gamma)^{\rm SM}}$, $\frac{\Gamma^*(h^0\to\gamma\gamma)^{\rm 2HDM}}{\Gamma(h^0\to\gamma\gamma)^{\rm SM}}$, $\frac{\Gamma(h^0\to gg)^{\rm 2HDM}}{\Gamma(h^0\to gg)^{\rm SM}}$, and $\frac{\Gamma(h^0\to\gamma Z)^{\rm 2HDM}}{\Gamma(h^0\to\gamma Z)^{\rm SM}}$ using different values of 2HDM-III parameters. (a) $\alpha = \pi/2$, $m_{H^\pm} = 1$ TeV; (b) $\alpha = \pi/4$, $m_{H^\pm} = 500$ GeV, $\lambda_{tt} = 1$, $\lambda_{bb} = 10$; (c) $\alpha = \pi/4$, $m_{H^\pm} = 500$ GeV, $\lambda_{tt} = 1$, $\lambda_{bb} = 1$; (d) $\alpha = 0$, $m_{H^\pm} = 500$ GeV, $\lambda_{tt} = 1$, $\lambda_{bb} = 1$. The two figures for $\frac{\Gamma(h^0\to\gamma\gamma)^{\rm 2HDM}}{\Gamma(h\to\gamma\gamma)^{\rm SM}}$ correspond to the $h^0H^+H^-$ coupling given by Eqs. (11) and (12) respectively.

Figure 2 shows the branching ratios for h^0, when FCNC processes are introduced in the possible Higgs h^0 decays in the framework of the 2HDM-III. The CSY parameterization is used and a particular case is taken into account when all λ_{ij} in the quark sector are equal to one, but for the leptonic sector we take the values shown in Table I. Thus, Fig. 2 lists all the branching ratios for h^0 in the 2HDM-III with 1 TeV for the charged Higgs mass and $\alpha = (\pi/2, \pi/4, 0)$. For the scalar contribution to $\Gamma(h \to \gamma\gamma)$ we only take into account the coupling given by Eq. (12) and this choice is also made in the next figures. The case $\alpha = \pi/2$ and a heavy charged Higgs boson reproduces the SM branching ratios, and it gives us the chance to check consistency, we compare results using computational packages as HDECAY [25]; for small values of m_{h^0} the dominant decays are $b\bar{b}$ and V^*V [23]. For the case $\alpha = 0$ the decay modes WW and ZZ disappear and therefore the modes tt and tc are dominant modes in the region of heavy Higgs boson mass. For a light Higgs boson the dominant decay mode is bb, and the branching fraction for $h \to \gamma\gamma$ is 1 order of magnitude lower than the SM prediction, it is because the W contribution is not present in the loop and only quarks contribute. The comparison between plots in Fig. 2 let us know what happens with FCNC scenarios with respect to the SM predictions. The $\tau^+\tau^-$ branching fraction is 1 order of magnitude bigger than the SM mode and for a heavy Higgs boson it is higher than the gg one, contrary to the SM. On the other hand, $\gamma\gamma$ and gg modes are at the same order. The FCNC $h^0 \to b\bar{s}$ is the same order of $h^0 \to b\bar{b}$ for $m_{h^0} < 180$ GeV; but in the kinematic limits for $h^0 \to t\bar{c}$ decay the $B(h^0 \to b\bar{b})^{2HDM}$ is 1 order of magnitude lower than the SM. We also note that the case d in Fig. 1 corresponds to the scenario shown in Fig. 2(c). As we already note, the behavior of the ratio plotted in Fig. 1(b) is quite similar to the case d, therefore the possible scenarios using the coupling (11) are comparable to the scenario 2C.

Figure 3 shows the branching fractions taking into account a more realistic scenario according to the phenomenological constraints for λ_{ij} from Table I. In this case, the channels $b\bar{b}$ and $b\bar{s}$ are the leading decays in the light Higgs mass limit. This is because in the range of intermediate Higgs boson mass, b decays still dominate, but at a heavier Higgs boson mass, the vector bosons reach some importance and b decays loose supremacy, opening a window for the $t\bar{t}$ channel. The leptonic τ decays are of the same order than gg, and always bigger than the other loop decays. It is remarkable that the FCNC channel $\mu^+\tau^-$ is more important than $t\bar{c}$, almost in 1 order of magnitude. The larger values for the vertex factors in the leptonic sector allow these processes to be relevant in the sector of about 1 decay through these channels each $10^4 - 10^5$ Higgs events. Finally we can say that the μ^+e^- is indiscernible because of the small size of the coupling.

Figure 4 is a similar scenario to Fig. 3, but the hierarchy between $\lambda_{tt(tc)}$ and $\lambda_{bb(bs)}$ is changed by 1 order of magni-

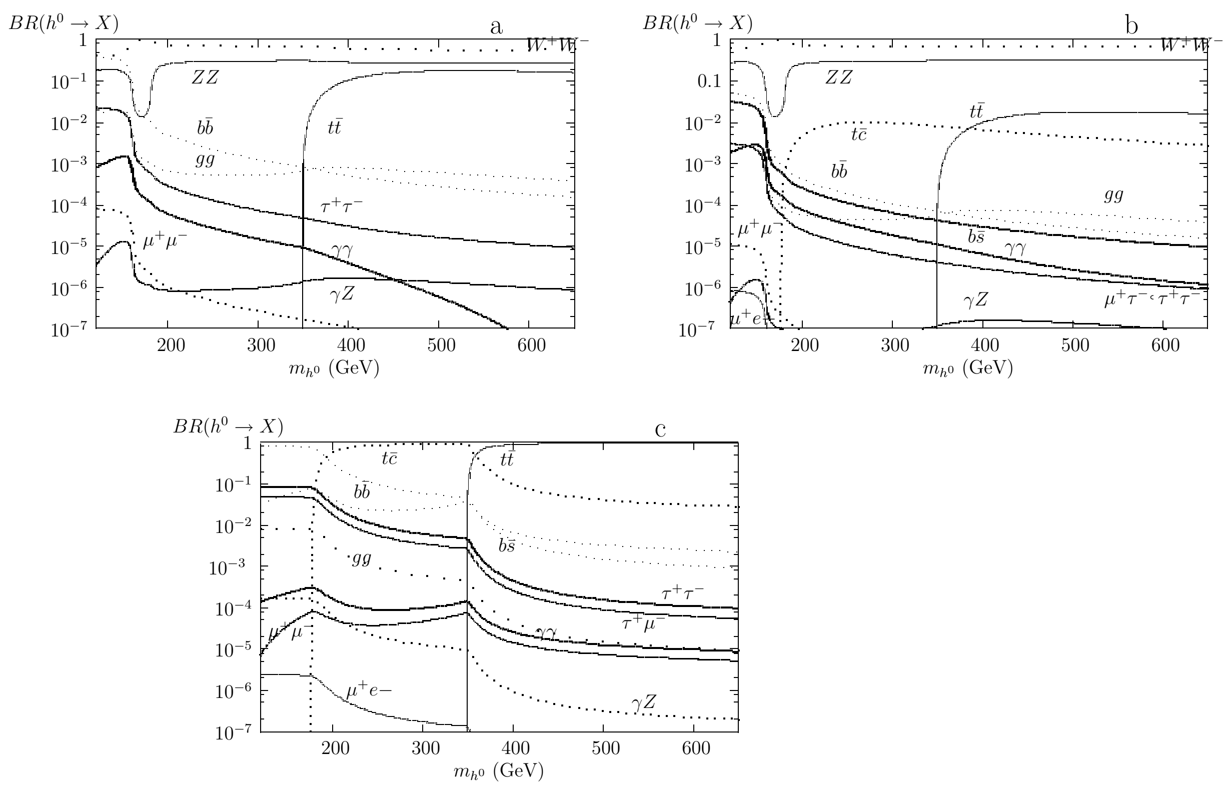

FIG. 2. h^0 branching ratios in the 2HDM-III with $\lambda_{ij} = 1$. (a), (b), and (c) correspond to $\alpha = \pi/2, \pi/4, 0$, respectively.

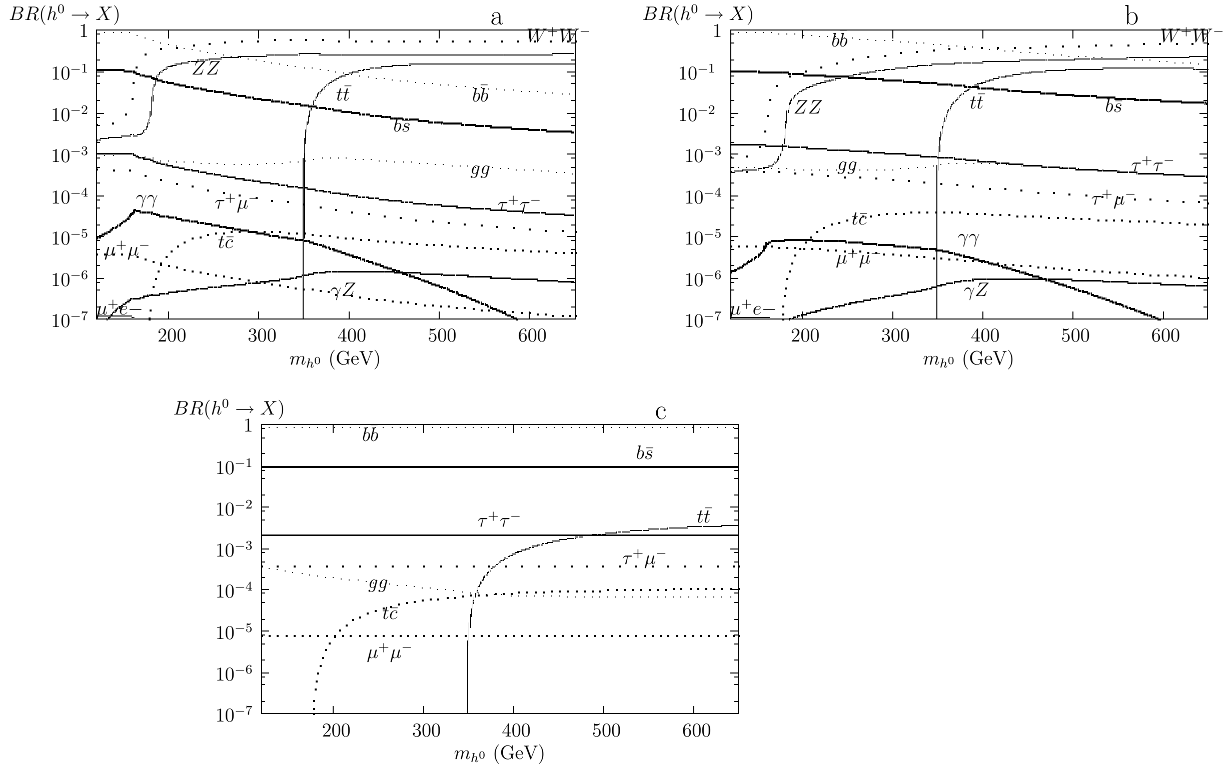

FIG. 3. Branching ratios in the 2HDM-III for $\lambda_{tc} = \lambda_{tt} = 0.1$, $\lambda_{bs} = \lambda_{bb} = 50$, $\lambda_{\mu\mu} = \lambda_{\tau\tau} = \lambda_{\mu\tau} = \lambda_{e\mu} = 10$. Figures (a), (b), and (c) are $\alpha = 3\pi/8, \pi/4, 0$, respectively.

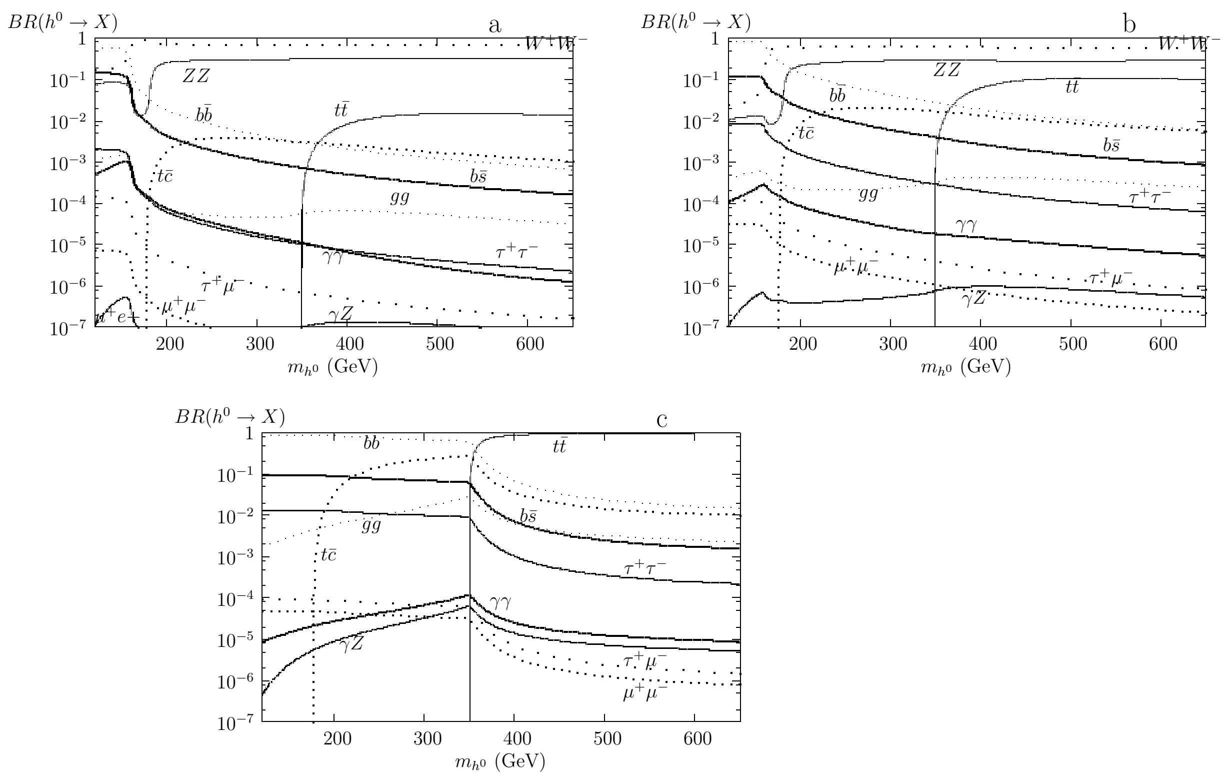

FIG. 4. Branching ratios in the 2HDM-III for $\lambda_{tc} = 1.5, \lambda_{tt} = 2.5$, $\lambda_{bs} = \lambda_{bb} = 10$, $\lambda_{\mu\mu} = \lambda_{\tau\tau} = 5$, $\lambda_{\mu\tau} = 1$. Figures (a), (b), and (c) correspond to $\alpha = 3\pi/8, \pi/4, 0$, respectively.

tude. The same assumption is made for the leptonic sector. In this case, the branching ratios for the h^0 into fermions without flavor changing are only 1 order of magnitude bigger than the similar ones with flavor changing.

In the 2HDM-III the ratio between two branching ratios can be written as

$$r_{ff/ff'} = \frac{B(h^0 \to f\bar{f})}{B(h^0 \to f\bar{f}')} \propto \left| \frac{-\sqrt{2}s_\alpha + c_\alpha \lambda_{ff}}{\lambda_{ff'} c_\alpha} \right|^2, \quad (14)$$

taking off kinematic factors. When $\lambda_{ff} \simeq \lambda_{ff'}$ but bigger than one the ratio $r_{ff/ff'} \simeq 1$, it means that the branching ratios are of the same order of magnitude for any value of α different of $\alpha = \pi/2$. This is the scenario presented in Fig. 4. However if $\lambda_{ff} \simeq \lambda_{ff'}$ but smaller than 1 the ratio $r_{ff/ff'}$ is proportional to $(\lambda_{ff} c_\alpha)^{-1}$ which implies that the branching ratio $B(h^0 \to f\bar{f})$ is going to be bigger than the branching ratio $B(h^0 \to f\bar{f}')$. This is precisely the situation shown in Fig. 3. Furthermore, in Fig. 3 when α goes from $3\pi/8$ to zero the ratio $r_{tt/tc}$ goes from $10^4 - 10^5$ to 10^2.

IV. h^0 PRODUCTION AND DETECTION AT PHOTON COLLIDER

A photon collider provides a scenario to look for new physics [26]. The colliders $\gamma\gamma$ and γe are based on Compton backscattering of laser light off the high energy electrons of linear collider. Nowadays, the e^+e^- colliders are related to ILC project [27]. Most of them are going to be able to work as a $\gamma\gamma$ collider such as TESLA [28], NLC [29], JLC [30], and CLIC [31]. These colliders have a huge importance, because typical cross sections of interesting processes in $\gamma\gamma$ collisions, as charged pair production, are higher than those in e^+e^- collisions by about 1 order of magnitude, so the number of events in $\gamma\gamma$ collisions would be larger than e^+e^- collisions. Besides, these photons could have a high degree of circular polarization, allowing more different J^{PC} states than e^+e^- collider.

The production of neutral scalars at photon colliders can be mediated by one-loop level processes, and it is interesting because the $\phi^0\gamma\gamma$ vertex is sensitive to small variations of particle couplings in the loop. In particular, different scenarios of 2HDM-III parameters can produce a huge change in the $h^0\gamma\gamma$ vertex. This sensitive vertex could allow the possibility of distinguish the scalar boson from different models [32]. In photon colliders the number of events of h^0 produced as a resonance of fermions in the final state, $\gamma\gamma \to h^0 \to f_i\bar{f}_j$, is given by [33]

$$N(\gamma\gamma \to h^0 \to f_i\bar{f}_j) = 8\pi F(y_{h^0})\mathcal{L}_{e^+e^-}(1 + \langle\lambda\lambda'\rangle_{y_{h^0}}) \times \frac{\Gamma(\gamma\gamma \to h^0)B(h^0 \to f_i\bar{f}_j)}{m_{h^0}^2 E_{e^+e^-}} \times \arctan\left[\frac{\Gamma_{res}}{\Gamma_{h^0}}\right], \quad (15)$$

where, $\lambda\lambda'$ is the product of the helicities of the two colliding photons, $F(y_{h^0})\mathcal{L}_{e^+e^-}$ is the differential luminosity for the $\gamma\gamma$ collider and the resolution width is defined by $\Gamma_{\rm res} \equiv \max\{\Gamma_{\rm exp}, \Gamma_{h^0}\}$ with $\Gamma_{\rm exp}$ being the experimental width allowed by the detector.

The background signal is given by the process $\gamma\gamma \to f\bar{f}$, and the number of events are [33]

$$N(\gamma\gamma \to f\bar{f}) = \frac{\Gamma_{\rm res}}{E_{e^+e^-}} F(y_{h^0})\mathcal{L}_{e^+e^-}\sigma_{\gamma\gamma\to f\bar{f}}(m_{h^0}^2, z_0), \quad (16)$$

where

$$\sigma_{\gamma\gamma\to f\bar{f}}(s, z_0) = \frac{4\pi\alpha^2 e_f^4 N_C}{s}\left\{-\beta z_0\left[1 + \frac{(1-\beta^2)^2}{1-\beta^2 z_0^2}\right] + \frac{3-\beta^4}{2}\ln\frac{1+\beta z_0}{1-\beta z_0} + \lambda\lambda'\beta z_0\left[1 + \frac{2(1-\beta^2)}{1-\beta^2 z_0^2} - \frac{1}{\beta z_0}\ln\frac{1+\beta z_0}{1-\beta z_0}\right]\right\}, \quad (17)$$

with $\beta \equiv (1 - 4m_f^2/s)^{1/2}$ and $z_0 = \cos\theta_0$ the maximum sweep detector angle. It is interesting to note that the cross section is evaluated in the h^0 resonance and worthwhile that the background is proportional to e_f^4.

In Fig. 5 using the same parameters as Fig. 4, we can see the number of events for the different channels of Higgs decays according to the 2HDM-III signal (s) and their corresponding background signal (b).

TESLA (TeV electron superconducting linear accelerator) will work with a solid angle resolution about $z_0 = 0.85$, an average polarization $\langle\lambda\lambda'\rangle_{h^0} = 0.8$, luminosity $dL_{\gamma\gamma}(z_0 \geq 0.8) = 1.15 \times 10^{34}$ cm^{-2} s^{-1} in a year, center-of-mass (CM) energy $E_{e^+e^-} = 500$ GeV and an experimental resolution of about 5 GeV [28].

Figure 5(a) shows the possible behavior of h^0 at TESLA collider. The $b\bar{b}$ channel would be in fact the best channel for h^0 decays in the low Higgs boson mass region. It is because always the production through h^0 decays is above the own background signal, which is different from the SM case where only in a small region of the Higgs boson mass between 120 and 170 GeV, the signal is bigger than the background signal [33]. On the other hand, the background signal for heavy lepton pair production is bigger than those decays into quarks. This result was expected, because photons couple through the electromagnetic charge, and leptons have integer charge, therefore their background does not have any suppression factor, as already happened with quarks. The h^0 signal from leptonic decays would be

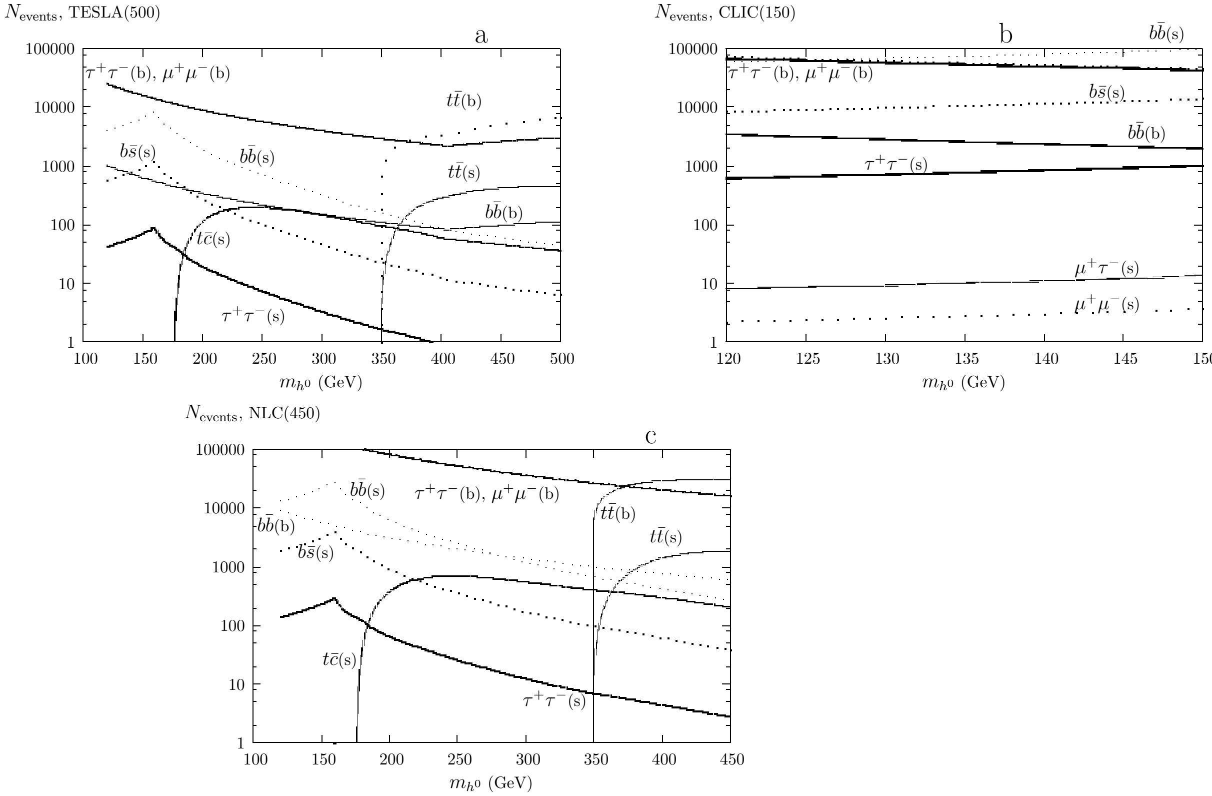

FIG. 5. Number of h^0 events in the 2HDM-III and the corresponding background signal at (a) TESLA(500), (b) CLIC(150) and (c) NLC(450).

undetectable, because we have one Higgs boson which decays in leptons each 10^4 charged pair $\tau^+\tau^-$ produced. And, the background signal for $t\bar{t}$ wouldbe always at least 1 order of magnitude bigger, however the detection of this 10% of its signal could be strongly dependent on the top decays.

Let us examine what could happen with FCNC processes in the quark sector, $t\bar{c}$ and $b\bar{s}$. We start with the $t\bar{c}$ process. The charm quark could be detected through its jet, but the top quark decays into bW^+, because it has no time to hadronize. The bottom quark wouldbe tagged and W boson could suffer leptonic decays $l^+\bar{\nu}$ or could generate a quark pair. The channel with W leptonic decays would be easily reconstructed by lost energy and information from the electromagnetic calorimeter, so the most promising signal would be jet + b − tagged + l + E. For the hadronic decay of the W boson, a background possibility is $b + b + 2$ jets. This option would have difficulties for h^0 detection because the $t\bar{c}$ signal is smaller than $b\bar{b}$ background signal. For the $b\bar{s}$ channel, we would have a jet and a b − tagged. In general, these FCNC channels will have no background, and we would have some statistics for h^0 detection. A deeper analysis including the noise by NLO-QCD corrections can be found in Ref. [34]. It is important to remark that the analysis for FCNC processes in the quark sector would be quite similar for the other photon colliders.

CLICHE (compact linear collider Higgs experiment) [31], developed on CLIC 1 at low energy, it will work with $\langle\lambda\lambda'\rangle_{h^0} = 0.94$, geometrical position of the detector at $z_0 = 0.85$, the luminosity $L_{\gamma\gamma}(z_0 \geq 0.8) = 4.7 \times 10^{34}$ cm^{-2}s^{-1}, CM energy $E_{e^+e^-} = 150$ GeV and experimental resolution of 3.3 GeV.

Figure 5(b) shows the possible behavior of h^0 at CLIC photon collider. It would be working at a lower energy than TESLA and therefore some QED and QCD phenomena that can appear in the laser vanish, increasing the number of events. CLIC could only create a light h^0 as far as 150 GeV, through the $b\bar{b}$ channel, which is the most promising channel for light scalar detection. CLIC could produce 10^6 events of h^0 in a year, by using $\gamma\gamma \to h^0 \to b\bar{b}$ signal, while the background could be 5% of the signal, this being a great scenario to measure the light h^0 properties. It is obvious that there are no kinematic conditions for top quark production. Now, the FCNC process $b\bar{s}$ could be bigger than $b\bar{b}$ background signal, then as we have already mentioned, this channel might be easily reconstructed, and thus we could have a huge window for FCNC detection at CLIC. For leptonic decays, again the background affect enormously the h^0 signal. The $\tau^+\tau^-$ h^0 signal would be 0.01% of the background, which could make the h^0 Higgs boson undetectable through leptonic decays. Something similar could happen with the $\mu^+\tau^-$ process.

Finally we analyze the h^0 production and detection at NLC (next linear collider) [29]. This collider will work with a polarization average $\langle \lambda\lambda' \rangle_{h^0} = 0.79$, $L_{\gamma\gamma}(z \geq 0.8) = 3.4 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ for a CM energy $E_{e^+e^-} = 450$ GeV and experimental width of the detector near 13.1 GeV.

Figure 5(c) shows the number of h^0 expected in NLC through fermionic decays and its noise signal. If m_{h^0} is below ~275 GeV then the Higgs boson should be detected and its couplings could be determinated in NLC through the $b\bar{b}$ decay, due to its signal is larger than the background signal. Same as TESLA, the background of $t\bar{t}$ channel is bigger than its h^0 signal, this obstruct the detection in the pair top production. The leptonic FCNC processes do not reach to appear in the figure, and the charged lepton pair production with h^0 in the resonance looses importance because of the $\tau^+\tau^-$ and $\mu^+\mu^-$ background signal. Again, the interesting FCNC channel would be given by the quark sector. The $b\bar{s}$ shows a production of 5000 h^0 events near the top resonance, getting too close to $b\bar{b}$ background signal. In this region, FCNC processes could be easily detected, but in the rest of the spectrum the detection would be strongly determinated by the b-tagging within the vertex detector.

V. CONCLUSION

The addition of a second Higgs doublet, as an extension of the SM, leads to different new physics scenarios. One of them is the 2HDM-III where discrete symmetries are not imposed and it generates a general Yukawa Lagrangian with FCNC at tree level. This fact makes the 2HDM-III a very complex model and there are no simple relationships between the scalar masses spectrum because the couplings of the scalar potential cannot always be written as a function of the scalar field masses as already happened in 2HDM-II. In the Yukawa sector there are 12 new parameters which generate FCNC or modify h^0 couplings in the SM.

We first study the decay widths of the lightest CP-even Higgs boson h^0 at tree level and at one-loop level. New physics effects can be tested in the loops for different values of the FCNC parameters, and hence different 2HDM-III scenarios can be proposed. The $h^0 \to \gamma\gamma$ process is sensitive to the couplings of the particles that are into the loop, and it leads to distinguish different models. In particular, it is remarkable the sensitivity of the $h^0 \to \gamma\gamma$ decay width to the $h^0H^+H^-$ coupling, which is illustrated in Fig. 1. The case for $\alpha = \pi/2$ and a heavy charged Higgs boson reproduces the SM predictions for the branchings ratios, except for $\Gamma^*(h^0 \to \gamma\gamma)^{\mathrm{2HDM}}$ in Fig. 1. In the other cases the one-loop widths are lower than in the SM. For the high Higgs boson mass range the 2HDM has parameter scenarios where $\Gamma(h^0 \to \gamma\gamma)$ is bigger than the SM predicted width.

In Fig. 2 we consider one scenario where all λ_{ij} in the quark sector are equal to one [14]. In this case the new FCNC at tree level are of the same order of the SM ones. However, the new physics is decoupled and the SM's branching ratios are reproduced when $\alpha = \pi/2$ and a heavy charged Higgs boson is used.

In the other figures we take into account more realistic scenarios for the λ_{ij}, using constraints on them which come from the 2HDM contributions to different phenomenology processes. The branching ratios of the one-loop decays are one or 2 orders of magnitude below the SM predictions due to the new channels $h^0 \to b\bar{s}$ and $h^0 \to t\bar{c}$ which are of the same order of $h^0 \to b\bar{b}$ and $h^0 \to t\bar{t}$, respectively. A very particular scenario is that when $\alpha = 0$. In this scenario WWh^0 and ZZh^0 couplings are equal to zero, and $h^0 \to b\bar{b}$ and $h^0 \to t\bar{t}$ are the most important channels for light and heavy Higgs boson, respectively. But the FCNCs at tree level $b\bar{s}$ and $t\bar{c}$ decay modes are close to them. Now, for $h^0 \to \gamma\gamma$ and $h^0 \to gg$ widths, the contributions into the loops are only coming from fermions because the gauge contribution to $h^0 \to \gamma\gamma$ decay vanishes taking $\alpha = 0$.

On the other hand, for the 2HDM-III we write down the expression (15), which says that for big values of $\lambda_{ff} \simeq \lambda_{ff'}$, the decays involving flavor change are of the same order that those without flavor change. Otherwise for small values of λ_{ij}, the flavor changing channels are too small. All this means that the detection of fermionic flavor changes at tree level is not enough to test the 2HDM-III. However if the branching ratios or the number of events of h^0 produced satisfy a relationship like Eq. (15), that could be the first indication that 2HDM-III is important to reveal the presence of new physics.

Finally, we have set up one SM-like scenario by introducing FCNC processes and we have analyzed the h^0 detection and production at photon colliders at TESLA, CLIC, and NLC. We have used fermionic decays and the cross sections have been evaluated in the h^0 resonance. We have calculated the background signals for h^0 decays, using the helicity formalism in order to do a naive analysis of the possible noise within the detector. The background signals are proportional to e_f^4, and then lepton channels have bigger noise than quark channels. The signal for the h^0 decays into a pair of quarks are 1 order of magnitude higher than the similar decays with flavor changing, however the second one does not have any background signal. This is an interesting scenario to produce and detect Higgs bosons and a possibility to test new physics beyond the SM.

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