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The decay $H \to \gamma\gamma$ in Multi-Higgs doublet models

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ABSTRACT: We study the dominant decays of the lightest Higgs boson in models with 2 and 3 Higgs doublets, for the case when its couplings to fermions are absent at tree-level. It is found that the branching ratio for the decay $H \to \gamma\gamma$ is above the one into fermion pairs, which is evaluated also at the 1-loop level.

The search for the Higgs boson of the standard model (SM) [1], is the most important test of the symmetry breaking and mass generation of the theory. Current limits on the SM Higgs mass coming from direct searches for the Higgs boson, specifically from the study of the reaction $e^+e^- \to Z \to (Z^* \to ff)h$ at LEPI. The combined limit of the four experiments on the Higgs mass is $m_h > 65.4$ GeV [2]. At LEPII with the total energy $\sqrt{s} = 130 - 200$ GeV, the dominant Higgs production process is $e^+e^- \to hZ$, where the final state particles in the analysed Higgs boson channels are $e^+e^- \to (Z \to qq, bb, \nu\nu, \tau\tau, e^+e^-, \mu\mu)(h \to bb, \tau\tau)$. Combined limit of the four experiments with $\sqrt{s} = 195.6$ GeV gives $m_h \geq 102.6$ GeV at 95% C.L.. LEPII running with the total energy 200 GeV will be able to discover standard Higgs boson with a mass up to 107 GeV [2]. On the other hand, indirect bound on the Higgs mass can be obtained from precision electroweak measurements. Although the sensitivity to the Higgs boson mass through radiative corrections is only logarithmic, the increasing precision in the measurement of electroweak observables allows to derive constraints on m_h, around of $m_h = 71^{+75}_{-42} \pm 5$ GeV [3]. Other constraints coming from tree level unitarity in $W_L - W_L$ scattering, $m_h \leq 1$ TeV [4], validity of perturbation theory, $m_h \leq 930$ GeV [3], and the analisys done of vacuum stability, $m_h \geq 120$ GeV [5]. On the other hand, the search techniques for intermediate and heavy Higgs boson are known, and their implementation requires the next gen-

eration of hadron colliders LHC [6]. One of the most important reactions for the search for the Higgs boson at LHC is $pp \to (h \to \gamma\gamma)$ which is the most promising one for the search in the region $100 \leq m_h \leq 140$ GeV [2]. In this paper we shall study the Higgs sector for two particular models, which contain 2 and 3 Higgs doublets respectively, for the case when some Higgs boson couples only to gauge bosons but not to fermions, at tree-level. In this case the decay into $\gamma\gamma$ is expected to dominate for the lower part of the intermediate mass region, however the decays into fermion pairs can be generated also at the 1-loop level, and one needs to include their contribution into the total width, in order to know the precise values of branching ratios, which to our knowledge has not been done in the literature [8]. We shall discuss first the Lagrangian for the model with two doublets, then the dominant branching ratios for the intermediate mass range are evaluated, and we also discuss the limits on the Higgs mass that can be obtained from the LEP data. Later on, it will be explained how to obtain the corresponding results for the 3-Higgs doublet model. The extension of the SM with two Higgs doublets has been studied in great detail before [10]. In terms of components the two doublets are written as: $\Phi_1 = (\phi_1^+, \phi_1^0)^T$, $\Phi_2 = (\phi_2^+, \phi_2^0)^T$. It happens that the Yukawa coupling of the Higgses with the fermions can be choosen in two ways, usually denoted as models I and II. In model I, one doublet is used to generate masses for both the U- and D-type quarks, whereas in model II

one doublet generates the masses of the U-type quarks and the second one generates the masses of the D-type quarks. We shall consider here only model I. After diagonalizing the general Higgs potential, one gets the scalar mass eigenstates, which include one charged pair ($H^{\pm}$), two CP-even scalars (h^0, H^0, with $m_H > m_h$), and one CP-odd scalar (A^0). Thus, the free parameters are the scalar masses, the mixing angle α and the ratio of vev's $\tan\beta = v_2/v_1$. The mass eigenstates can be written in terms of the components of the Higgs doublets; for the CP-even scalars for example, one has:

$$H^0 = 2^{1/2}[(Re\phi_1^0 - v_1)\cos\alpha + (Re\phi_2^0 - v_2)\sin\alpha] \tag{1}$$

$$h^0 = 2^{1/2}[-(Re\phi_1^0 - v_1)\sin\alpha + (Re\phi_2^0 - v_2)\cos\alpha] \tag{2}$$

The interaction of fermions with Higgs bosons in model I are given by the Yukawa Lagrangian,

$$
\begin{aligned}
L = & -\frac{g}{2m_W \sin\beta}[\bar{D}M_D D + \bar{U}M_U U] \times \\
& (H^0 \sin\alpha + h^0 \cos\alpha) \\
& + \frac{ig\cot\beta}{2m_W}[-\bar{D}M_D\gamma_5 D + \bar{U}M_U\gamma_5 U]A^0 \\
& + \frac{g\cot\beta}{2^{3/2}m_W}(H^+\bar{U}[M_U K P_L - K M_D P_R]D \\
& + h.c.)
\end{aligned}
\tag{3}
$$

where $P_{R,L} = (1 \pm \gamma_5)/2$, $M_{U,D}$ are the diagonal mass matrices of the U- and D-type quarks, K is the Kobayashi-Maskawa mixing matrix. It happens for this type of models that the important coupling $h^0 VV$ ($V = Z, W$) is proportional to $\sin(\beta - \alpha)$. Moreover, if the mixing angle takes the value $\alpha = \pi/2$, then there is no mixing among H^0 and h^0, and one has that h^0 interact only with the gauge bosons, with the coupling proportional to $\sin(\beta - \pi/2) = -\cos\beta$.

The dominant decays of h^0 in the mass range $m_h > 2m_Z$ are into WW, ZZ; whereas for the intermediate mass range (80 GeV $< m_h < 2m_Z$) the allowed decays are into $\gamma\gamma$, $Z\gamma$, WW^*, ZZ^* , which will compete also with the decays into fermion pairs, generated at the 1-loop level.

The decay width into photon pairs can be written as:

$$\Gamma(h^0 \to \gamma\gamma) = \cos^2\beta \Gamma_{sm}^W(h^0 \to \gamma\gamma), \tag{4}$$

where Γ_{sm}^W denotes the W-loop contribution to the decay width of the SM Higgs boson; the decay width for $h^0 \to Z+\gamma$ has also the same form, and it will be below the one for $h^0 \to \gamma\gamma$, as in the SM case, thus we shall not discuss it further here. Similarly, we find that the decays into WW^* and ZZ^* can be written in the same form, namely [6]

$$\Gamma(h^0 \to VV^*) = \cos^2\beta \; \Gamma(\phi_{sm}^0 \to VV^*) \tag{5}$$

Finally, the expression for the decay width into fermion pairs ($h^0 \to f\bar{f}$), that results after one evaluates the 1-loop amplitude is written as follows:

$$\Gamma(h^0 \to f\bar{f}) = \frac{G_F\alpha^2\pi m_h}{2\sqrt{2}\sin^4\theta_W}m_f^2\cos^2\beta F \tag{6}$$

where m_i is the mass of the fermion that enters in the loop, and $F = F(m_h, m_i, m_W)$ is a function that arises from the loop integration, which is written as follows,

$$F = [|F_1|^2 + |F_2|^2]|K_i f|^2, \tag{7}$$

where,

$$
\begin{aligned}
F_1 = & \; 4m_W^2 C_{12} + m_h^2(C_0 - C_{12} + C_{23} - C_{11}) \\
& + m_i^2(C_{12} - C_0), \\
F_2 = & \; 4m_W^2(C_0 - C_{11} + 2C_{12}) - m_h^2(-C_0 + C_{11} \\
& + C_{12} + C_{23}) + m_i^2(2C_{11} - C_0),
\end{aligned}
\tag{8}
$$

where $C_{ij} = C_{ij}(m_h, m_i, m_W)$ can be written in terms of the scalar integral C_0, as discussed in [11]. From this expression one notices that the width is again proportional to m_f, which will suppress the width, thus only the heaviest fermions will contribute significantly. This result can be understood easily if one follows the chirality in the graphs, which need a mass insertion to be different from zero. In the following analysis we include only the contribution from the top quark to the loop, which is the dominant one. The resulting branching ratios are presented in fig. 1, where one can see that the decay into a photon pair dominates for mass values of the Higgs up to about m_Z.

On the other hand, if one considers a model which allows Higgs-fermion couplings, and one assumes that there are no Flavour Changing Neutral Currents (FCNC) mediated by the neutral
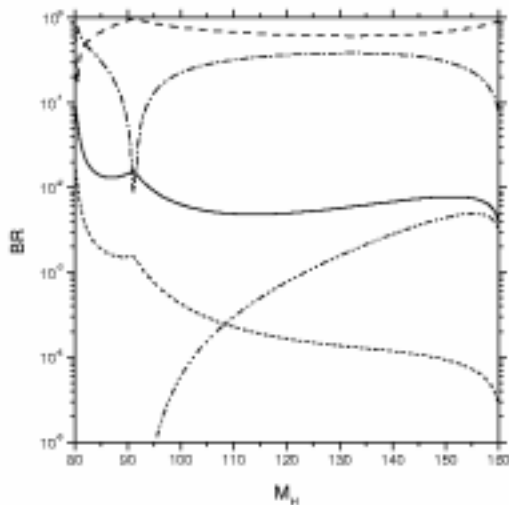
Figure 1: Branching ratios for the decay of the Higgs boson; $h \to \gamma\gamma$: solid , $h \to b\bar{b}$: dashed, $h \to WW^*$: long-dashed, $h \to ZZ^*$: dot-dashed, $h \to Z\gamma$: dot-dot-dashed.

Higgs bosons, then the couplings $h^0 ff$ are proportional to m_f, and then the production rates will be highly suppressed; whereas if one allows for the presence of FCNC, then the Higgs-fermions couplings are not neccessarily proportional to the fermion masses [12], and the cross-section can be large.

One can use the experimental results to constrain the mass of the Higgs boson for this kind of models. This can be done using the LEP bound $BR(Z \to \nu\nu\gamma\gamma) < 10^{-6}$ [7], which can be written for this model as,

$$BR(Z \to \nu\nu\gamma\gamma) = BR(Z \to \nu\nu + h^0)BR(h^0 \to \gamma\gamma),$$
$$(9)$$

which depends only on m_h and $\tan\beta$.

Fig. 2 shows the excluded region in the plane $\tan\beta - m_h$, obtained from the previous equation. It is important to point out that this is the first bound that is obtained for a model of this type, which eventhough is valid only for an specific value of α, it does not depends on the remmaining parameters of the general Higgs potential. For low values of $\tan\beta$ the limit on the Higgs mass is $m_h > 91$ GeV, which is similar to the one obtained for the SM Higgs.

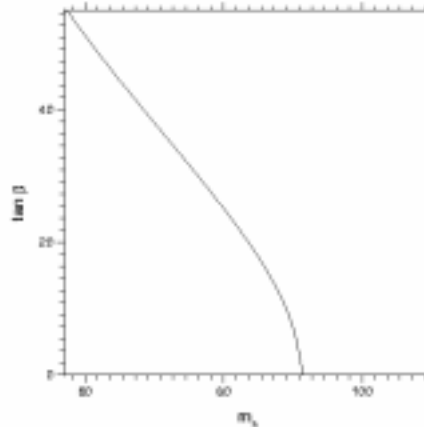Finally, we have also evaluated the branching ratios of Higgs bosons within the context of

Figure 2: Regions in the plane $\tan\beta - m_h$ excluded by the LEP results (shaded), for the models discussed in the text.

a model with 3-Higgs doublets, where 2 of them behave like the doublets of model II in the 2-doublet case. The third doublet couples only to vector bosons, and we find again that the dominant decay in the intermediate mass range, is into photon pairs.

The scalar potential for this model, which allows for the existence of one CP-even Higgs boson that does not couples at fermions, is the following,

$$V = V(\Phi_1, \Phi_2) + V(\Phi_3) \qquad (10)$$

where $V(\Phi_1, \Phi_2)$ is the two-Higgs doublet model [10], whereas Φ_3 contains the Higgs scalars that do not mix with the other Higgs bosons; each of the doublets can be written as $\Phi_i = [\phi_i^+, h_i + v_i + i\eta_i]$. Then, h_3 can be choosen as the light Higgs that only couples to gauge bosons, whose coupling is $g_{h_3 VV} = \sin\gamma g_{\phi^0_{sm} VV}$ (where $\tan\gamma = v_3/(v_1^2 + v_2^2 + v_3^2)^{1/2}$).

We have derived all the relevant Feynman rules of the model, needed to evaluate the decay widths at tree-level and 1-loop, and the final results is that all the branching ratios of h_3 can be obtained from the ones obtained previously for the two Higgs doublets model I, just by replacing $-\cos\beta \to \sin\gamma$. Thus, the previous limits on the Higgs mass apply also for this scalar. Models with N-doublets have been analyzed in the literature too [14], and it is possible to translate our limits for such models by taking the appropriate

limit.

In summary, we find that the scalar sectors studied in this paper have an interesting phenomenology in their own. And, it is possible to use the LEP results to put limits on the Higgs mass, which are comparable to the ones obtained for the SM Higgs for low values of $\tan \beta$, namely $m_h > 91$ GeV.

At e^+e^- machines with TeV CM-energies, it will be possible to produce the Higgs boson of these models by WW fusion, and also in association with Z. The production of a Higgs by photon-photon fusion, could be also important too, unfortunately we found that at LEP energies the event rate is far bellow detectability. On the other hand, the phenomenological consequences of these models at hadron colliders are also interesting. Because of the absence of Higgs-fermions couplings, it will not be possible to produce the Higgs in association with top pairs, and neither by gluon fusion (which will occur only at the 2-loop level), which have proved to be usefull for the SM case. Thus, the main production mechanism will be in association with W/Z, however since the decays into gauge bosons will dominate, its detection could be feasible. Clearly, a detailed study is needed in order to determine the detection feasibilities of these modes, which is beyond the scope of this work.

Acknowledgments

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