Is there a light fermiophobic Higgs boson?

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The most general two Higgs doublet model potential without explicit CP violation depends on 10 real independent parameters. There are two different ways of restricting this potential to 7 independent parameters. This gives rise to two different potentials, $V_{(A)}$ and $V_{(B)}$. The phenomenology of the two models is different, because some trilinear and quartic Higgs couplings are different. As an illustration, we calculate the decay width of $h^0 \rightarrow \gamma\gamma$, where precisely due to the different trilinear couplings the loop of the charged Higgs boson gives different contributions. We also discuss the possibility for the existence of a light fermiophobic Higgs boson. [S0556-2821(99)04615-9]

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I. INTRODUCTION

Despite the great success of the standard $SU(2)\times U(1)$ electroweak model [standard model (SM)], one of its fundamental principles, the spontaneous symmetry breaking mechanism, still awaits experimental confirmation. This mechanism, in its minimal version, requires the introduction of a single doublet of scalar complex fields and gives rise to the existence of a neutral particle with mass m_H. The combined analysis [1] of all electroweak data as a function of m_H favors a value of m_H close to 100 GeV/c^2 and predicts with a 95% confidence level an upper bound of $m_H < 200$ GeV/c^2. Hence, one can still envisage the possibility of a Higgs boson discovery in the closing stages of the CERN e^+e^- collider LEP operation.

Nevertheless, even if this turned out to be true, one still would like to know if there is just one family of Higgs fields or, on the contrary, if nature has decided to replicate itself. In our view this is the main motivation to consider multi-Higgs-boson models. In this paper we continue the study of the two-Higgs-doublet model (2HDM). Following our previous work [2], we examine models without explicit CP violation and which are also naturally protected from developing a spontaneous CP breaking minimum. There are two different ways of achieving this. To illustrate the different phenomenology we calculate, in both models, the decay width for the process $h^0 \rightarrow \gamma\gamma$, which can be particularly relevant if h^0 is a fermiophobic Higgs boson.

II. POTENTIALS

The Higgs mechanism in its minimal version (one scalar doublet) introduces in the theory an arbitrary parameter — the Higgs boson mass m_H. In fact, the potential depends on two parameters, which are the coefficients of the quadratic and quartic terms. However, the perturbative version of the theory replaces them by the vacuum expectation value $v = 247$ GeV and by m_H. If we generalize the theory introducing a second doublet of complex fields, the number of free parameters in the potential V grows from 2 to 14. At the same time, the number of scalar particles grows from 1 to 4. In this general form the potential contains genuine new interaction vertices which are independent of the vacuum expectation values and of the mass matrix of the Higgs bosons. However, these new interactions can be avoided if one imposes the restriction that V be invariant under charge conjugation C. In fact, if Φ_i with $i=1,2$ denote two complex scalar doublets with hyper-charge 1, under C the fields transform themselves as $\Phi_i \rightarrow \exp(i\alpha_i)\Phi_i^*$ where the parameters α_i are arbitrary. Then, choosing $\alpha_1=\alpha_2=0$, and defining $x_1=\phi_1^\dagger\phi_1$, $x_2=\phi_2^\dagger\phi_2$, $x_3=\Re\{\phi_1^\dagger\phi_2\}$ and $x_4=\Im\{\phi_1^\dagger\phi_2\}$ it is easy to see that the most general 2HDM potential without explicit C violation[1] is

$$V=-\mu_1^2x_1-\mu_2^2x_2-\mu_{12}^2x_3+\lambda_1x_1^2+\lambda_2x_2^2+\lambda_3x_3^2+\lambda_4x_4^2 +\lambda_5x_1x_2+\lambda_6x_1x_3+\lambda_7x_2x_3. \quad (1)$$

In general, the minimum of this potential is of the form

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[1]At this level C conservation is equivalent to CP conservation since all fields are scalars.

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix} \tag{2a}$$

$$\langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2 e^{i\theta}\end{pmatrix}; \tag{2b}$$

in other words, it breaks CP spontaneously. To use this potential in perturbative electroweak calculations the physical parameters that should replace the λ's and μ's are the following:

(i) the position of the minimum, v_1, v_2 and θ, or alternatively, $v^2 = v_1^2 + v_2^2$, $\tan\beta = v_2/v_1$ and θ;

(ii) the masses of the charged boson, m_+, and of the three neutral bosons, m_1, m_2 and m_3;

(iii) and the three Cabibbo-like angles α_1, α_2 and α_3 that represent the orthogonal transformation that diagonalizes the 3×3 mass matrix[2] of the neutral sector.

In a previous paper [2] we have examined the different types of extrema for potential V. In particular it was shown in [2] that there are two ways of naturally imposing that a minimum with CP violation never occurs. This, in turn, leads to two different 7-parameter potentials. The first one, denoted $V_{(A)}$, is the potential discussed in the review article of Sher [3] and corresponds to setting $\mu_{12}^2 = \lambda_6 = \lambda_7 = 0$ in Eq. (1). The second 7-parameter potential, which we shall call $V_{(B)}$, is essentially the version analyzed in the *Higgs Hunters Guide* [4] and it corresponds to the conditions $\lambda_6 = \lambda_7 = 0$ and $\lambda_3 = \lambda_4$. As we have already pointed out [2] but would like to stress again, these potentials have different phenomenology. This is illustrated in Sec. III when we consider the fermiophobic limit of both models.

Since $V_{(A)}$ and $V_{(B)}$ do not have spontaneous CP violation, the number of so-called "physical parameters" is immediately reduced to 7. In fact, $\theta = 0$ and only one rotation angle, α, is needed to diagonalize the 2×2 mass matrix of the CP-even neutral scalars. This is clearly seen if we transform the initial doublets Φ_i into two new ones H_i given by

$$\begin{pmatrix}H_1\\ H_2\end{pmatrix} = \frac{1}{\sqrt{v_1^2+v_2^2}}\begin{pmatrix}v_1 & v_2\\ -v_2 & v_1\end{pmatrix}\begin{pmatrix}\Phi_1\\ \Phi_2\end{pmatrix}. \tag{3}$$

In this Higgs basis, only H_1 acquires a vacuum expectation value. Then, the $T_3 = +\frac{1}{2}$ component and the imaginary part of the $T_3 = -\frac{1}{2}$ component of H_1 are the $W^\pm$ and Z would-be Goldstone bosons, respectively. The C-odd neutral boson, A^0, is the imaginary part of the $T_3 = -\frac{1}{2}$ component of H_2. On the other hand, the light and heavy CP-even neutral Higgs bosons, h^0 and H^0, are linear combinations of the real parts of the $T_3 = -\frac{1}{2}$ component of H_1 and H_2.

Notice that $V_{(A)}$ is invariant under the Z_2 transformation $\Phi_1 \to \Phi_1$ and $\Phi_2 \to -\Phi_2$, whereas in $V_{(B)}$ only the μ_{12}^2 term breaks the $U(1)$ symmetry, $\Phi_2 \to e^{i\alpha}\Phi_2$. Because this breaking occurs in a quadratic term, it does not spoil the renormalizability of the model. Hence, in both cases the terms that were set explicitly to zero will not be needed to absorb infinities that occur at higher orders. The complete renormalization program of the model based on $V_{(A)}$ was carried out in [5]. The results for $V_{(B)}$ are similar but the cubic and quartic scalar vertices have to be changed appropriately.

For the sake of completeness we will close this section with a summary of the results that will be used later. As we have already said they are not new and can be obtained either from [3] or [4]. We agree with both.

For $V_{(A)}$ the minimum conditions are

$$0 = T_1 = v_1(-\mu_1^2 + \lambda_1 {v_1}^2 + \lambda_+ {v_2}^2) \tag{4a}$$

$$0 = T_2 = v_2(-\mu_2^2 + \lambda_2 {v_2}^2 + \lambda_+ {v_1}^2) \tag{4b}$$

with $\lambda_+ = \frac{1}{2}(\lambda_3 + \lambda_5)$. They lead to the following solutions: either (i)

$$v_1^2 = \frac{\lambda_2\mu_1^2 - \lambda_+\mu_2^2}{\lambda_1\lambda_2 - \lambda_+^2} \tag{5a}$$

$$v_2^2 = \frac{\lambda_1\mu_2^2 - \lambda_+\mu_1^2}{\lambda_1\lambda_2 - \lambda_+^2} \tag{5b}$$

or (ii)

$$v_1^2 = 0 \tag{6a}$$

$$v_2^2 = \frac{\mu_2^2}{\lambda_2}. \tag{6b}$$

The masses of the Higgs bosons and the angle α are given by the following relations:

$$m_{H^+}^2 = -\lambda_3(v_1^2 + v_2^2) \tag{7a}$$

$$m_{A^0}^2 = \frac{1}{2}(\lambda_4 - \lambda_3)(v_1^2 + v_2^2) \tag{7b}$$

$$m_{H^0,h^0}^2 = \lambda_1 v_1^2 + \lambda_2 v_2^2 \pm \sqrt{(\lambda_1 v_1^2 - \lambda_2 v_2^2)^2 + v_1^2 v_2^2(\lambda_3+\lambda_5)^2} \tag{7c}$$

$$\tan 2\alpha = \frac{v_2 v_1(\lambda_3+\lambda_5)}{\lambda_1 v_1^2 - \lambda_2 v_2^2}. \tag{8}$$

On the other hand, for $V_{(B)}$ the minimum conditions are

$$0 = T_1 - \frac{\mu_{12}^2}{2} v_2 \tag{9a}$$

$$0 = T_2 - \frac{\mu_{12}^2}{2} v_1 \tag{9b}$$

with the T_i given by the previous equations (4). The solution of this set of equations is

[2]The mass matrix corresponding to the neutral components ($T_3 = -\frac{1}{2}$) of the doublets is a 4×4 matrix, but one eigenvalue is zero because it corresponds to the Z would-be Goldstone boson.

$$v_1^2=\frac{\lambda_1-\lambda_2\pm\sqrt{(\lambda_1-\lambda_2)^2-4(\lambda_1-\lambda_+)(\lambda_2-\lambda_+)[(\lambda_+v^2-\mu_1^2)(\lambda_2v^2-\mu_2^2)-\frac{1}{4}\mu_{12}^4]}}{2(\lambda_1-\lambda_+)(\lambda_2-\lambda_+)} \tag{10a}$$

$$v_2^2=\frac{\lambda_2-\lambda_1\pm\sqrt{(\lambda_1-\lambda_2)^2-4(\lambda_2-\lambda_+)(\lambda_1-\lambda_+)[(\lambda_+v^2-\mu_2^2)(\lambda_1v^2-\mu_1^2)-\frac{1}{4}\mu_{12}^4]}}{2(\lambda_1-\lambda_+)(\lambda_2-\lambda_+)}. \tag{10b}$$

Notice that, in this case, the solution with vanishing vacuum expectation value in one of the doublets is not possible. Now the masses and the value of α are given by

$$m_{H^+}^2=-\lambda_3(v_1^2+v_2^2)+\mu_{12}^2\frac{v_1^2+v_2^2}{v_1v_2} \tag{11a}$$

$$m_{A^0}^2=\frac{1}{2}\mu_{12}^2\frac{v_1^2+v_2^2}{v_1v_2} \tag{11b}$$

$$m_{H^0,h^0}^2=\lambda_1v_1^2+\lambda_2v_2^2+\frac{1}{4}\mu_{12}^2\left(\frac{v_2}{v_1}+\frac{v_1}{v_2}\right)\pm\sqrt{\left[\lambda_1v_1^2-\lambda_2v_2^2+\frac{1}{4}\mu_{12}^2\left(\frac{v_2}{v_1}-\frac{v_1}{v_2}\right)\right]^2+\left(v_1v_2(\lambda_3+\lambda_5)-\frac{1}{2}\mu_{12}^2\right)^2} \tag{11c}$$

$$\tan 2\alpha=\frac{2v_1v_2\lambda_+-\frac{1}{2}\mu_{12}^2}{\lambda_1v_1^2-\lambda_2v_2^2+\frac{1}{4}\mu_{12}^2\left(\frac{v_2}{v_1}-\frac{v_1}{v_2}\right)}. \tag{12}$$

III. FERMIOPHOBIC LIMIT

Despite the fact that $V_{(A)}$ and $V_{(B)}$ are different, it is obvious that the gauge bosons and the fermions couplings to the scalars are the same for both models. In particular, the introduction of the Yukawa couplings without tree-level flavor changing neutral current is easily done extending the Z_2 symmetry to the fermions. This leads to two different ways of coupling the quarks and two different ways of introducing the leptons, giving a total of four different models, usually denoted as models I, II, III and IV (cf. e.g. [5]).

In here, we use model I, where only Φ_2 couples to the fermions. Then, the coupling of the lightest Higgs scalar, h^0, to a fermion pair (quark or lepton) is proportional to $\cos\alpha$. As α approaches $\pi/2$ this coupling tends to zero and in the limit it vanishes, giving rise to a fermiophobic Higgs boson.

Examining Eqs. (8) and (12) we see that the fermiophobic limit ($\alpha=\pi/2$) can be obtained in potential A in two ways: either $\lambda_+=0$ or $v_1=0$. In potential B there is only one possibility $2v_1v_2\lambda_+=\frac{1}{2}\mu_{12}^2$. In this latter case, Eqs. (11) and (12) give immediately:

$$m_{A^0}^2=2\,\lambda_+(v_1^2+v_2^2) \tag{13a}$$

$$m_{H^0}^2=2\,\lambda_2v_2^2+2\,\lambda_+v_1^2=m_{A^0}^2+2(\lambda_2-\lambda_+)v^2\sin^2\beta \tag{13b}$$

$$m_{h^0}^2=2\,\lambda_1v_1^2+2\,\lambda_+v_2^2=m_{A^0}^2-2(\lambda_+-\lambda_1)v^2\cos^2\beta. \tag{13c}$$

In the former case ($V_{(A)}$), $\lambda_+=0$ gives

$$m_{H^0}^2=2\,\lambda_2v_2^2 \tag{14a}$$

$$m_{h^0}^2=2\,\lambda_1v_1^2 \tag{14b}$$

while $v_1=0$ gives a massless h^0. In this analysis we have assumed that $v_1<v_2$. The reversed situation leads to similar conclusions since one is then interchanging the role of the two doublets.

The triple couplings involving two gauge bosons and a scalar particle, like, for instance, $Z_\mu Z^\mu h^0$, are always proportional to the angle $\delta=\alpha-\beta$. In particular, the couplings for h^0 are proportional to $\sin\delta$ whereas the corresponding H^0 couplings are proportional to $\cos\delta$. This general result can be understood if one recalls the argument about the role played by neutral scalars in restoring the unitarity in the scattering of longitudinal W's, i.e. in $W_L^+W_L^-\to W_L^+W_L^-$. The restoration of unitarity requires that the sum of the squares of the $W^+W^-h^0$ and $W^+W^-H^0$ couplings add up to a constant proportional to the $SU(2)$ gauge coupling, g.

Current searches of the SM Higgs boson at LEP put the mass limit at 89 GeV/c^2 [6]. Since the production mechanism is the reaction $e^+e^-\to Z^*\to Zh^0$, this limit can be sub-

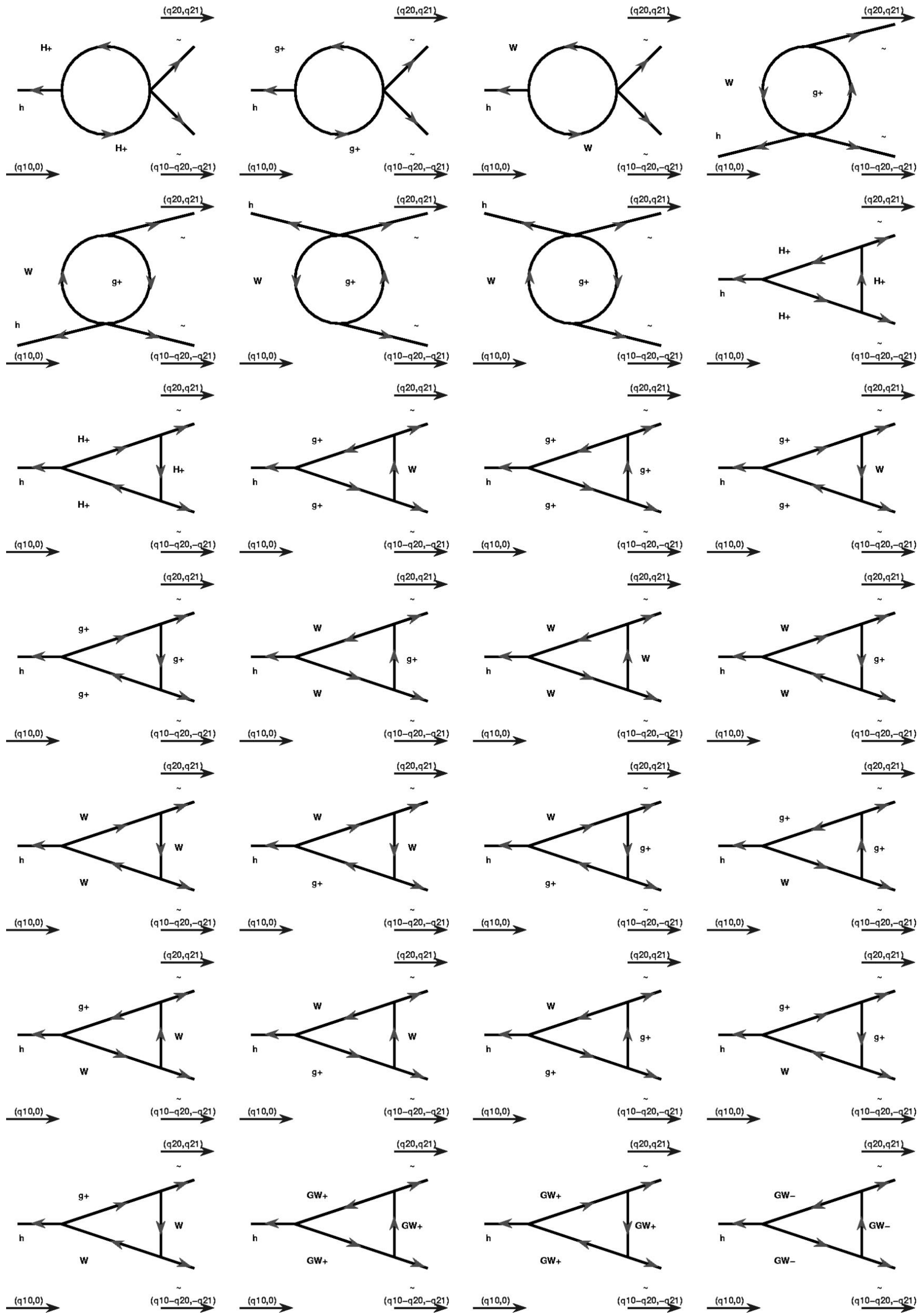

FIG. 1. The contributing graphs to $h^0 \rightarrow \gamma\gamma$ in the fermiophobic limit.

stantially lower in the 2HDM if $\sin\delta$ is small. In our numerical application to the two γ decay of a light fermiophobic h^0 we will explore the region $\sin^2\delta \leqslant 0.1$ [7].

Bounds on the Higgs masses have been derived by several authors [8]. Recently next-to-leading order calculations [9] in the SM give a prediction for the branching ratio $Br(B \rightarrow X_s\gamma)$ which is slightly larger than the experimental CLEO measurement [10]. In model II the charged Higgs loops al-

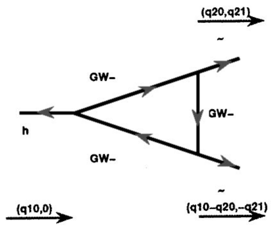

FIG. 1 (*Continued*).

ways increase the SM value. Hence, this process provides good lower bounds on $m_{H^\pm}$ as a function of $\tan\beta$ [9]. On the contrary, in model I the contribution from the charged Higgs boson reduces the theoretical prediction and so brings it to a value closer to the experimental result. This reduction is larger for small $\tan\beta$, since in model I the H^+ coupling to quarks is proportional to $\tan^{-1}\beta$. However, a small $\tan\beta$ gives a large top Yukawa coupling which leads to large new contributions to R_b, the B_0-$\overline{B}_0$ mixing. A recent analysis by Ciuchini *et al.* [9] derives the bounds $\tan\beta > 1.8$, 1.4 and 1.0 for $m_{H^\pm}=85$, 200 and 425 GeV/c^2, respectively.

The Higgs contribution to the ρ parameter is [11]

$$\Delta\rho=\frac{1}{16\pi^2 v^2}[\sin^2\delta\ F(m^2_{H^\pm},m^2_{A^0},m^2_{H^0}) + \cos^2\delta\ F(m^2_{H^\pm},m^2_{A^0},m^2_{h^0})] \tag{15}$$

where

$$F(a,b,c)=a+\frac{bc}{b-c}\ln\frac{b}{c}-\frac{ab}{a-b}\ln\frac{a}{b}-\frac{ac}{a-c}\ln\frac{a}{c}.$$

Since the current experimental value of $\rho=1.0012\pm0.0013\pm0.0018$ [12] exceeds the SM prediction by 3σ, one should at least try to avoid a positive $\Delta\rho$.[3] A simpler examination of the function $F(a,b,c)$ shows that this is impossible if $m_{H^\pm}$ is the largest mass. On the other hand, if $m_{A^0}>m_{H^\pm}$, one obtains a negative value for $\Delta\rho$ which grows with the splitting m_{A^0}-$m_{H^\pm}$. In line with our limit ($\sin^2\delta\leqslant0.1$), negative values of $\Delta\rho$ of the order of the experimental statistical error, i.e. $\Delta\rho\approx-10^{-3}$, can be obtained essentially in two ways: either with a large $m_{H^\pm}\approx300$ GeV/c^2 but with a modest m_{A^0}-$m_{H^\pm}$ splitting ($m_{A^0}\approx340$ GeV/c^2) or with a smaller $m_{H^\pm}\approx100$ GeV/c^2 but with $m_{A^0}\approx200$ GeV/c^2. The variation of $\Delta\rho$ with m_{h^0} is rather modest, less than 10% for the range 20 GeV/$c^2\leqslant m_{h^0}\leqslant100$ GeV/c^2. With seven parameters in the Higgs sector it is difficult and not very illuminating to discuss in detail all possibilities. So this discussion should be regarded as a simple justification for the fact that a fermiophobic Higgs boson scenario is not ruled out by the existing experiments. We would like to stress that there could exist a light h^0 almost decoupled from the fermions ($\alpha\approx\pi/2$) and at the same time with a small LEP production rate via the Z-bremsstrahlungs reaction $Z^*\to Zh^0(\sin^2\delta\approx10^{-1})$. If such a boson exists, it will decay mainly via the process $h^0\to\gamma\gamma$.

[3] A more recent SM fit gives $\rho=0.9996+0.0031(-0.0013)$[13].

IV. DECAY $h^0\to\gamma\gamma$

The decay $h^0\to\gamma\gamma$ is particularly suitable to illustrate the fact that $V_{(A)}$ and $V_{(B)}$ give rise to different phenomenologies. In fact, the decay occurs at the one-loop level and for a fermiophobic Higgs boson one has vector bosons and charged Higgs boson contributions. The latter are different for models A and B, because the $h^0H^+H^-$ vertex is different. It is interesting to point out how this difference arises. Since the term in λ_4 does not contribute to this vertex, both potentials give rise to the same effective $h^0H^+H^-$ coupling, $g_{h^0H^+H^-}$: namely,

$$\begin{aligned}[][h^0H^+H^-]=&2\,v_2\lambda_2\cos^2\beta\cos\alpha+v_2\lambda_3\sin\alpha\cos\beta\sin\beta\\ &-v_1\lambda_5\cos^2\beta\sin\alpha-2\,v_1\lambda_1\sin^2\beta\sin\alpha\\ &+v_2\lambda_5\sin^2\beta\cos\alpha-v_1\lambda_3\cos\alpha\cos\beta\sin\beta.\end{aligned} \tag{16}$$

However, as we have already said, what is relevant for perturbative calculations is the position of the minimum of V and the values of its derivatives at that point. This means that one has to express all coupling constants in terms of the particle masses. This is simply done by inverting Eqs. (7) and (11). The result is

$$[h^0H^+H^-]_{(A)}=\frac{g}{m_W}\left(m^2_{h^0}\frac{\cos(\alpha+\beta)}{\sin2\beta}-\left(m^2_{H^+}-\frac{1}{2}m^2_{h^0}\right)\sin(\alpha-\beta)\right) \tag{17}$$

and

$$[h^0H^+H^-]_{(B)}=\frac{g}{m_W}\left((m^2_{h^0}-m^2_{A^0})\frac{\cos(\alpha+\beta)}{\sin2\beta}-\left(m^2_{H^+}-\frac{1}{2}m^2_{h^0}\right)\sin(\alpha-\beta)\right) \tag{18}$$

which clearly shows the difference that we have pointed out.

In Fig. 1 we show all the diagrams that were included. A previous work by Diaz and Weiler [14] did not include the Higgs-boson diagrams. Our calculation, in the 't Hooft–Feynman gauge, was done with XLOOPS [15,16]. We have been using this program to calculate other amplitudes in the framework of the 2HDM [17]. Throughout this process we have made several checks of the computer results. In this particular case we have verified that the contribution of the vector boson loops agrees with a calculation done by Spira *et al.* [18] using the supersymmetric version of the 2HDM.

In Fig. 2 we show the product m_{h^0} times the decay width (Γ) for the process $h^0\to\gamma\gamma$ in model A as a function of δ

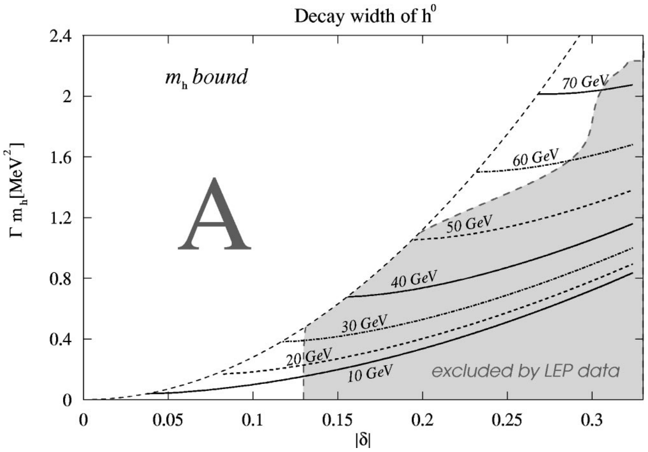

FIG. 2. Dependence on δ and m_{h^0} at $m_{H^+}=131$ GeV and $\alpha=\pi/2$ in potential A.

and for several values of m_{h^0} and a fixed value of m_{H^+}. This function shows a gentle rise with m_{h^0} which reflects the proportionality between $g_{h^0H^+H^-}$ and $m^2_{h^0}$. Looking at this coupling constant one could naively assume that there would be an enhancement for β approaching $\pi/2$, i.e. in our plot, when δ approaches zero. However, a close examination shows that such an enhancement does not exist. On the contrary, the coupling vanishes in this limit, since m_{h^0} goes to zero when $\beta\to\pi/2$. Alternatively, if one keeps m_{h^0} fixed, then the mass relation

$$m_{h^0}=\sqrt{2\lambda_1}v_1=\sqrt{2\lambda_1}v\cos\beta \tag{19}$$

imposes a lower bound for β. In Fig. 2 the dotted line gives this limit, evaluated assuming $\lambda_1=1/2$. The dashed area shows the exclusion region implied by the LEP experimental results. In the work of Ackerstaff *et al.* [19] an experimental bound on the SM $h\to\gamma\gamma$ branching ratio is derived. For a fermiophobic Higgs boson with $m_h<m_W$ the $\gamma\gamma$ branching ratio is 1. On the other hand, the production mechanism is suppressed by a factor $\sin^2\delta$. Hence, we have turned the OPAL experimental bounds into a bound on δ. Figure 3

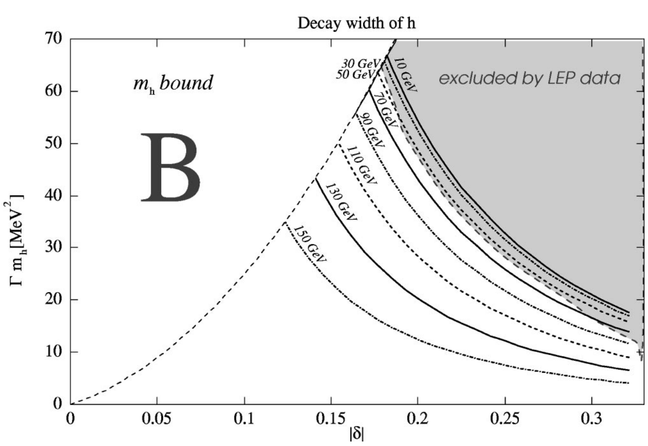

FIG. 3. Dependence on δ and m_{h^0} at $m_{H^+}=131$ GeV and $\alpha=\pi/2$ in potential B.

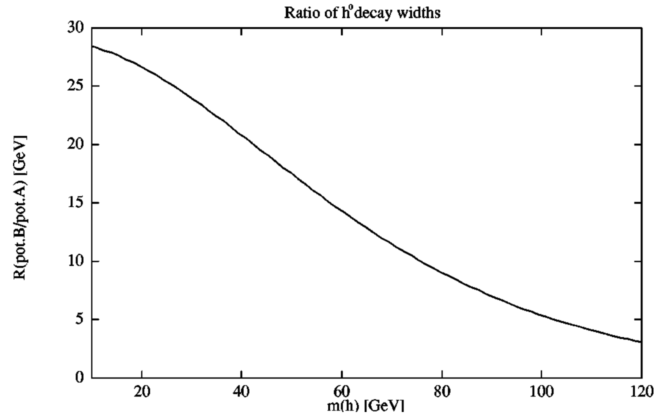

FIG. 4. Ratio of the decay widths from $V_{(B)}/V_{(A)}$ with $\delta=0.29$ and $m_{H^+}=200$ GeV and $m_{A^0}=250$ GeV.

gives the equivalent information for potential B.

In Fig. 4 we plot, as a function of m_{h^0}, the ratio R, of the widths calculated with potentials V_B and V_A, respectively. According to the fermiophobic limit, we set $\alpha=\pi/2$ and $\delta=0.29$. For the other relevant masses we have used $m_{H^+}=200$ GeV/c^2 and $m_{A^0}=250$ GeV/c^2. In the range of variation of m_{h^0}, i.e., 20 GeV/$c^2<m_{h^0}<120$ GeV/c^2, R decreases smoothly from 25 until 3. However, it is misleading to assume that potential A always gives smaller results. This is clearly shown in Fig. 5 where we plot the same function R evaluated with the same parameters except for m_{A^0} that was set up to 120 GeV/c^2. Again, R is a decreasing function of m_{h^0} that has a zero for m_{h^0} around 70 GeV/c^2 and increases afterwards. However, in this case, the values obtained with potential B are smaller than the corresponding ones for potential A.

This behavior can be qualitatively understood if one examines the coupling constants $[h^0H^+H^-]_{(A)}$ and $[h^0H^+H^-]_{(B)}$ given by Eqs. (17) and (18), respectively. In the range of m_{h^0} that we are considering, and for the same values of α, β and m_{H^+}, the coupling corresponding to potential A is always negative and decreases from about -85 GeV/c^2 until -230 GeV/c^2. On the contrary, the coupling constant corresponding to potential B is positive.

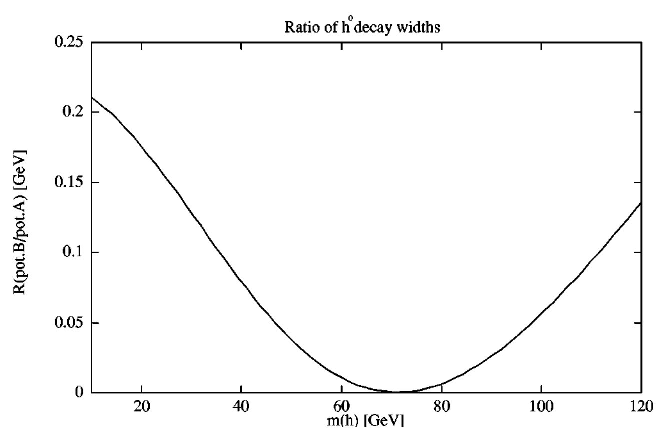

FIG. 5. Ratio of the decay widths from $V_{(B)}/V_{(A)}$ with $\delta=0.29$ and $m_{H^+}=200$ GeV and $m_{A^0}=120$ GeV.

TABLE I. Comparison between the widths for the WW^* and $\gamma\gamma$ channels.

	$\delta=0.1$		$\delta=0.3$	
m_h	$h\to WW^*$	$h\to\gamma\gamma$(A)	$h\to WW^*$	$h\to\gamma\gamma$(A)
90	2.6×10^{-6}	0.4×10^{-3}	2.3×10^{-5}	0.6×10^{-3}
120	2.2×10^{-3}	2.7×10^{-3}	1.9×10^{-2}	2.2×10^{-3}
150	5.7×10^{-2}	1.5×10^{-2}	5.0×10^{-1}	8.0×10^{-3}

For large values of m_{A^0} (around 250 GeV/c^2), it decreases from 930 GeV/c^2 until 780 GeV/c^2 for 20 GeV/$c^2 < m_{h^0} < 120$ GeV/c^2. These values of the coupling constant, when compared with the corresponding ones for potential *A*, explain the qualitative behavior of the ratio *R* given in Fig. 4. The explanation of Fig. 5 is more subtle, but again, it depends on the coupling constant of potential *B*. In fact, when $m_{A^0}=120$ GeV/c^2 the coupling corresponding to potential *B* starts at 100 GeV/c^2 and decreases smoothly until -60 GeV/c^2, having a zero around $m_{h^0}=95$ GeV/c^2. This behavior has two consequences. When the coupling is positive, its order of magnitude is the correct one to almost cancel the *W*-loop contributions to the width. Hence, *R* is small because potential *B* gives a small width. This cancellation is exact for m_{h^0} around 70 GeV/c^2 and after that, because the coupling changes sign, the charged Higgs contribution adds up to the normal *W*-loop result. Hence *R* increases.

Despite the fact that the $[hWW]$ coupling is suppresed by $\sin\delta$, one should keep in mind that when m_h is larger than m_W, the decay channel $h\to WW^*\to Wq\bar{q}$ starts to compete with the $\gamma\gamma$ channel. We have evaluated the WW^* decay width and in Table I we show some results in comparison with the width for the $\gamma\gamma$ channel evaluated for potential *A* and $m_{H^+}=100$ GeV. The table is representative of a situation that can be summarized qualitatively as follows: (i) for small $\delta(\delta=0.1)$ the WW^* width is comparable with the $\gamma\gamma$ width for $m_h=120$ GeV/c^2; (ii) for large $\delta(\delta=0.3)$ even at $m_h=120$ GeV/c^2 the WW^* decay width is already larger than the $\gamma\gamma$ width by a factor of 10.

V. CONCLUSION

We have examined the 2HDM where the potential does not explicitly break *CP* violation and furthermore it is naturally protected from the appearance of minima with *CP* violation [2]. There are two ways of accomplishing this, leading to two different potentials V_A and V_B. V_A is invariant under the discrete group Z_2 and V_B is invariant under $U(1)$ except for the presence of a soft breaking term. These two symmetries ensure that the parameters that, at the tree-level, were set to zero are not required to renormalize the models.

The potential V_A and V_B have different cubic and quartic scalar vertices. Then, it is obvious that they give different Higgs-boson–Higgs-boson interactions. However, even before one is able to test such interactions, one could still sense these two different phenomenologies via Higgs-loop contributions.

To illustrate this point we have considered a fermiophobic neutral Higgs boson, decaying mainly into two photons. The widths for the decays calculated with both potentials can differ by orders of magnitude for reasonable values of the parameters. Clearly, with four masses and two angles as free parameters, it is not worthwhile to perform a complete analysis. Nevertheless, we believe that the results presented here are sufficient for illustrative purposes. The experimental searches in this area should be made with an open mind for surprises.

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