Radiative decays of Higgs bosons in minimal extensions of the standard model*

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Recibido el 19 de marzo de 1993; aceptado el 4 de mayo de 1993

ABSTRACT. The radiative decay modes $H \to \gamma\gamma, \gamma Z$ have been found to be viable at SSC/LHC for detection of an intermediate mass range Higgs boson expected in the standard model (SM). A precise measurement of the decay widths of these modes may be used to distinguish among theories beyond the SM. We present results obtained for the respective decay widths in minimal extensions of the SM: left-right symmetric models with a minimal Higgs potential, the minimal supersymmetric standard model, and $\mathrm{SU}(2) \times \mathrm{U}(1)$ invariant Lagrangians in which any new physics appears as nonrenormalizable, effective interactions. We conclude that only in the last case the SM decay widths for these radiative modes may be enhanced.

RESUMEN. Se encuentra que los modos de decaimiento radiativos $H \to \gamma\gamma, \gamma Z$ serán accesibles en los aceleradores SSC/LHC para detectar el bosón de Higgs predicho por el modelo estándar (ME) con una masa dada en el intervalo intermedio. Una medición precisa de las anchuras respectivas de decaimiento pueden ser usadas para distinguir entre varias teorías que van más allá del ME. Presentamos resultados para dichos decaimientos en las siguientes extensiones mínimas del ME: modelos con simetría izquierda-derecha (ambidiestra) y un potencial de Higgs mínimo, el modelo supersimétrico mínimo y lagrangianos invariantes ante $\mathrm{SU}(2) \times \mathrm{U}(1)$ en el cual los nuevos efectos físicos aparecen como interacciones no-renormalizables y efectivas. Concluimos que sólo en el último caso se obtiene un incremento de $\Gamma(H \to \gamma\gamma)$ con respecto al resultado obtenido en el ME.

PACS: 14.80.Gt; 12.15.Cc

1. HIGGS HUNTING

All known experimental data for high energy processes are consistent with the standard model (SM) of the electroweak interactions provided the masses of the t-quark and the

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*Work supported by CONACyT (México), COLCIENCIAS (Colombia) and TWAS (Trieste).
**Also at Facultad de Ciencias Físico Matemáticas, Universidad Autónoma de Puebla.

Higgs boson H lie in the range 103 GeV $< m_t <$ 180 GeV and $m_H >$ 60 GeV at 91% c.l. [1]. Nevertheless, various theoretical arguments suggest that the SM can only be regarded as an effective low-energy theory, valid up to some energy scale Λ at which it would be replaced by some more fundamental theory. Certainly, Λ should be greater than the SM symmetry-breaking scale $\langle\Phi\rangle_0 = \nu = 2M_W \sin\theta_W/e \sim 240$ GeV. An essential point in this scheme will be to elucidate if Λ is greater or lower than ~ 1 TeV, which corresponds to the scale where the SM Higgs sector transits from a weakly to a strongly interacting regime, and the new physics involved in each case will be described by a decoupling or non-decoupling effective Lagrangian [2].

When considering alternatives to the SM, it is natural to concentrate in models which are theoretically motivated, their phenomenologies are reasonably constrained and calculationally well-defined. In the present paper we consider three atractive possibilities satisfying these criteria: left-right symmetric (LR) models with a minimal Higgs potential [3], the minimal supersymmetric standard model (MSSM) [4], and a SU(2) $\times$ U(1) invariant effective Lagrangian with new non-renormalizable (anomalous) interactions [2]. In particular, we are interested in studying the radiative decay modes of the neutral Higgs bosons predicted in these models. It has been pointed out [5] that the radiative decay modes $H \to \gamma\gamma, \gamma Z$ may be used in the hunt for an intermediate mass Higgs boson ($0.5m_Z < m_H < 2m_Z$) in the SM and the MSSM. If the $\gamma\gamma$ branching ratio is about 10^{-3}, the event rate at the SSC may be adequate in a few years of running time with the planned luminosity $L = 10\ \text{fb}^{-1}$ through the inclusive reactions $pp \to W(Z)HX$ [6] and $pp \to t\bar{t}HX$ [7]. It is therefore tempting to compare the expected decay widths for these radiative decay modes in the above extensions of the SM. An enhancement/suppression effect as compared with the SM prediction may then be used to discriminate among these extensions.

The $\gamma\gamma$ (γZ) decay modes constitute one-loop radiative processes induced by any charged particle that couples to H. The W_L-loop diagrams shown in Fig. 1 give the main numerical contribution in the SM for a branching ratio of about 10^{-3} [8]. We expect a strong sensitivity of the $\gamma\gamma$ (γZ) decay modes to new physics, in particular to new heavy charged particles which couple to H or to non-standard deviations of the $WW\gamma(Z)$ and WWH vertices.

We shall review various calculations for the $H \to \gamma\gamma$ (γZ) decay widths in the framework of LR models [3], MSSM [4] and an effective SU(2) $\times$ U(1) Lagrangian [2, 9, 10]. We find that in LR models the $\gamma\gamma$ (γZ) branching ratios are essentially the same as in the SM, in the MSSM there may be a suppression effect, while the anomalous couplings may enhance these branching ratios [11–14].

2. Standard model results

In the SM, the W_L-loop shown in Fig. 1 gives the main numerical contribution. The respective decay widths for the $\gamma\gamma$, γZ modes are given by [8, 14]

$$\Gamma_0(H \to \gamma\gamma) = \frac{\alpha^2 G_F m_H^3}{64\sqrt{2}\,\pi^3}\left|\sum_i A_i Q_i^2\right|^2, \tag{2.1}$$

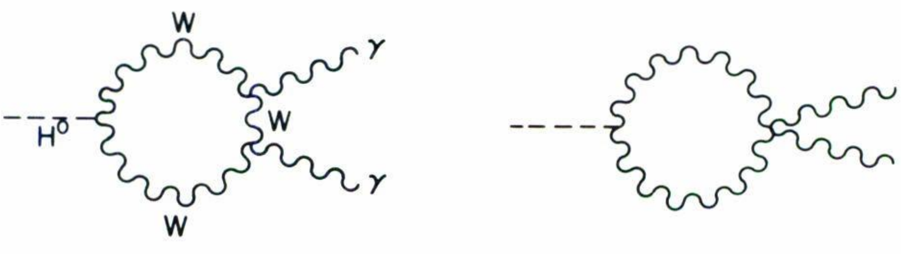

FIGURE 1. Dominant Feynman diagram contributing to $\Gamma(H^0 \to \gamma\gamma, \gamma Z)$.

$$\Gamma_0(H \to \gamma Z) = \frac{\alpha G_{\mathrm{F}}^2 c_{\mathrm{W}}^2 m_H^3 m_{\mathrm{L}}^2}{4\pi^4} \left(1 - \frac{m_Z^2}{m_H^2}\right)^3 \left|\sum_i B_i\right|^2, \tag{2.2}$$

where $i =$ scalar (s), fermion (f), gauge boson (L), Q_i is the respective electric charge for the particle circulating in the loop in units of e, $c_{\mathrm{W}} = \cos\theta_{\mathrm{W}}$ is the weak mixing angle,

$$\begin{aligned} A_{\mathrm{s}} &= \frac{1}{4\tau_{\mathrm{s}}}\left(1 - \frac{1}{4\tau_{\mathrm{s}}} I^2\left(\frac{1}{4\tau_{\mathrm{s}}}\right)\right), \\ A_{\mathrm{f}} &= -\frac{1}{2\tau_{\mathrm{f}}}\left[1 + \left(1 - \frac{1}{4\tau_{\mathrm{f}}}\right) I^2\left(\frac{1}{4\tau_{\mathrm{f}}}\right)\right], \\ A_{\mathrm{L}} &= 2 + \frac{3}{4\tau_{\mathrm{L}}} + \frac{3}{4\tau_{\mathrm{L}}}\left(2 - \frac{1}{4\tau_{\mathrm{L}}}\right) I^2\left(\frac{1}{4\tau_{\mathrm{L}}}\right), \end{aligned} \tag{2.3}$$

$$B_{\mathrm{f}} = \sum_{\mathrm{f}} \frac{-2Q_{\mathrm{f}}(T_{\mathrm{f}}^{3L} - 2Q_{\mathrm{f}} s_{\mathrm{W}}^2)}{c_{\mathrm{W}}} \left[4I_1(\tau_{\mathrm{f}}, \sigma_{\mathrm{f}}) - I_2(\tau_{\mathrm{f}}, \sigma_{\mathrm{f}})\right], \tag{2.4}$$

$$\begin{aligned} B_{\mathrm{L}} = -i\Big\{&(3 - t_{\mathrm{W}}^2) I_2(\tau_{\mathrm{L}}, \sigma_{\mathrm{L}}) \\ &+ \left[(1 + \tfrac{1}{2}\tau_{\mathrm{L}}) t_{\mathrm{W}}^2 - (5 + \tfrac{1}{2}\tau_{\mathrm{L}})\right] I_1(\tau_{\mathrm{L}}, \sigma_{\mathrm{L}})\Big\}, \end{aligned} \tag{2.5}$$

where $\tau_i = m_H^2/m_i^2$, $\sigma_i = M_Z^2/m_i^2$, $i =$ s, f, W_{L}, and the parametric integrals $I(\tau)$, $I_a(\tau_i, \sigma_i)$ are given in the Appendix. It is important to notice that these parametric integrals depend weakly on τ_i and σ_i and that the W_{L}-loop dominates easily both decay widths $\Gamma_0(H \to \gamma\gamma, \gamma Z)$ [8, 14].

3. LEFT-RIGHT SYMMETRIC MODELS

Since the W_L loop dominates $\Gamma_0(H \to \gamma\gamma, \gamma Z)$, an immediate question arises as far as the W_R loop contribution in LR models is concerned. In fact, it was argued [14] that the branching ratios $B(H^0 \to \gamma\gamma, \gamma Z)$ might be enhanced by about one order of magnitude if there is a new W' gauge boson with the SM coupling to H. This means that in such situation one should expect a $W'W'H$ coupling proportional to $M_{W'}$ and therefore an obvious enhancement of the order $(m_{W'}/m_W)^2$ should arise. In Refs. [12, 13] we addressed this question in the framework of LR models with a minimal Higgs potential and our conclusion was negative, essentially because the $W_R W_R H$ coupling is suppressed by mixing angles and it is not proportional to M_R, but rather to the lighter mass M_L [12].

In LR $SU(2)_L \times SU(2)_R \times U(1)$ models with a minimal Higgs potential [3], each generation of quarks and leptons sits in left- and right-handed doublets. The Higgs sector consists of a bi-doublet Φ and two triplets $\Delta_{L,R}$. The vacuum expectation values (*vev*) necessary to generate masses are given by $\langle \phi_i^{0r} \rangle = k_i$, $i = 1, 2$, $\langle \delta_{L,R}^{0r} \rangle = \nu_{L,R}$, where the neutral fields have been expressed in terms of their real and imaginary components. The SM phenomenology is preserved with the following hierarchy of *vev*, $\nu_L \ll \max(k_i) \ll \nu_R$. It was found [3] that the additional restrictions $\nu_L = k_2 = 0$ and k_1, $\nu_R \neq 0$ reproduce the most natural *vev* scenario in the sense that highly correlated values among the coupling constants are not imposed by the minimization conditions for k_1 and v_R. Furthermore, this scenario leads to all Higgs bosons having positive mass squared and it is consistent with flavor changing neutral currents (FCNC) constraints and unitary requirements on $W_L W_L$ scattering. There is no significant W_L–W_R mixing under these conditions. After the spontaneous symmetry beakdown, there are left 14 physics Higgs bosons: 6 neutral (H^0, h^0, δ_L^{0r}, δ_L^{0i}, ϕ_2^{0r}, ϕ_2^{0i}), 4 singly charged ($h^\pm$, $\delta_L^\pm$), and 4 doubly charged ($\delta_{L,R}^{\pm\pm}$) scalar fields. In the natural *vev* scenario discussed above, $\phi_2^{0r,i}$ and $h^\pm$ are forced to be heavy and will be not experimentally accesible in the near future. H^0 is the LR analogue of the SM neutral Higgs boson H.

In LR models, the calculation of each $W_{L,R}$-loop contribution to $\Gamma(H \to \gamma\gamma, \gamma Z)$ in the linear 'tHooft-Feynman gauge involves the computation of 13 diagrams for the $\gamma\gamma$-decay mode [8] and 29 diagrams for the γZ-mode [14]. Since in the nonlinear R-gauge there are no $G_a W_a \gamma$, $a = L, R$, and $G_R W_R Z(Z')$ vertices, where G_a are the unphysical Goldstone bosons, the number of diagrams reduces to just six for each $W_{L,R}$-loop in the $\gamma\gamma$-mode and three more diagrams for the γZ mode [12], as shown in Fig. 2.

The results for the widths of both $\gamma\gamma$, γZ decay modes in LR models can be expressed in the closed form [12]

$$\Gamma(H \to \gamma\gamma) = \frac{\alpha^2 G_F m_H^3}{64\sqrt{2}\,\pi^3} \left| A_L + A_R \right|^2, \tag{3.1}$$

$$\Gamma(H \to \gamma Z) = \frac{\alpha G_F^2 c_W^2 m_H^3 m_L^2}{4\pi^2} \left(1 - \frac{m_Z^2}{m_H^2}\right)^3 \left| B_L + B_R \right|^2, \tag{3.2}$$

where the $W_{L,R}$-loop contributions are given by the functions $A_{L,R}$ and $B_{L,R}$. The expressions for A_L and B_L reproduce the SM-results given in Eqs. (2.3) and (2.5). The

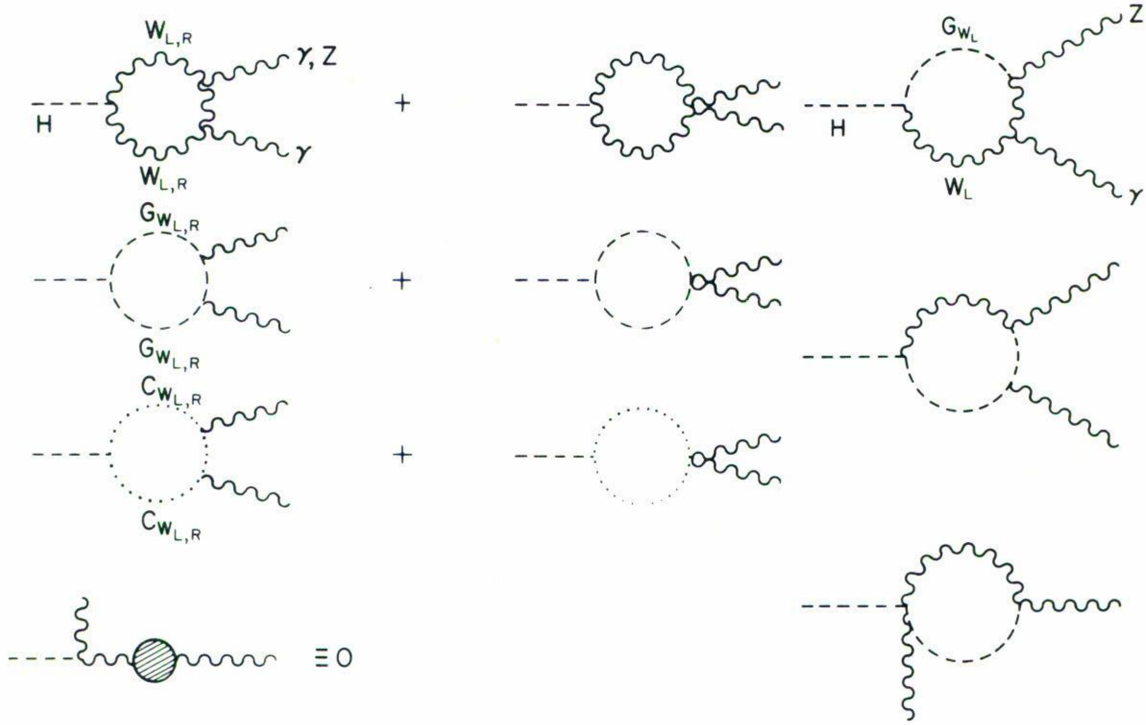

FIGURE 2. (a) Feynman diagrams for the $W_{L,R}$-loop contributions to the decays $H \to \gamma\gamma, \gamma Z$ in the nonlinear R-gauge. (b) Extra Feynman diagrams for the W_L-loop contributions to the decay $H \to \gamma Z$ in LR models. G_W and C_W are the unphysical Goldstone bosons and Faddeev-Popov fields, respectively.

expressions for the W_R-loop functions are given by [12]

$$A_R = \frac{1}{\tau_R}\left[(2 + 3\tau_R + 3\tau_R(2 - \tau_R))I^2(\tau_R)\right], \tag{3.3}$$

$$B_R = -2i\left(\frac{m_L}{m_R}\right)^2 \left[(3 + \tfrac{1}{2}\tau_R)I_1(\tau_R, \sigma_R) - 2I_2(\tau_R, \sigma_R)\right], \tag{3.4}$$

with $\tau_R = m_H^2/m_R^2, \sigma_R = m_Z^2/m_R^2$ and the parametric functions I_i are given in the Appendix.

According to the above results, we get that all the W_R-loop contributions are suppressed with respect to the W_L amplitudes by terms proportional to m_L/m_R. Since this ratio is about 1/10 from constraints obtained by low-energy data [15], the decay widths $\Gamma(H \to \gamma\gamma, \gamma Z)$ in LR models are essentially the same as in the SM. We have also computed in the nonlinear R-gauge the decay widths for the other two low-mass LR neutral Higgs bosons, $h^0(\delta_L^{0r}) \to \gamma\gamma, \gamma Z$. We found [14] that all the W_R-loop contributions are suppressed by LR mixing angles and therefore that only the radiative decays of the SM-like Higgs scalar H are significant in LR models.

TABLE I. Couplings of the MSSM neutral Higgs bosons (denoted collectively by Φ) to fermions (u, d type) and gauge bosons (V).

Φ	$g_{\Phi uu}$	$g_{\Phi dd}$	$g_{\Phi VV}$
h	$\dfrac{\cos\alpha}{\sin\alpha}$	$-\dfrac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$
H	$\dfrac{\sin\alpha}{\sin\beta}$	$\dfrac{\cos\alpha}{\cos\beta}$	$\cos(\beta-\alpha)$
A	$\cot\beta$	$\tan\beta$	0

4. MINIMAL SUPERSYMMETRIC MODELS

The minimal supersymmetric standard model (MSSM) requires two Higgs doublets and a singlet Higg field. After spontaneous symmetry breaking, this model has two more parameters than the SM, which can be m_A and $\tan\beta \equiv \nu_2/\nu_1$, where A is a neutral seudoscalar and ν_i are the vacuum expectation values for the neutral components of the two Higgs doublets. The physical Higgs sector contains two charged $H^{\pm}$ and three neutral (h, H, A) scalar bosons. The h and H fields are CP-even Higgs bosons, while A is a CP-odd scalar. Before radiative corrections, the tree-level Higgs potential induces the inequalities $m_A < m_{H^\pm}$, $m_h < m_Z < m_H$, $m_h < m_A < m_H$ [4, 16].

The couplings of (h, H, A) to fermions and gauge bosons depend on the angles β and α, with α a mixing angle used to diagonalize the CP-even scalar mass matrix. They are depicted in Table I. As far as the $\gamma\gamma, \gamma Z$ decay modes are concerned, the MSSM branching rations are smaller than in the SM due to the fact that the decays into $b\bar{b}$ are enhanced for $\tan\beta > 1$ and that the dominant $W_{\rm L}$-loop contribution is suppressed (absent) in the case of the CP-even (odd) Higgs bosons [17]. This result was unexpected in the first calculations for $\Gamma(H \to \gamma\gamma, \gamma Z)$ in the MSSM [11], in particular because it was hoped that the loops induced by heavy SUSY superpartners would produce a clear enhancement. However, it turned out that this was not the case.

5. ANOMALOUS COUPLINGS

Besides the known extensions of the SM (SUSY, LR, GUT, etc.), there is another approach used to characterize the possible effects of physics beyond the SM. It involves a general effective Lagrangian $\mathcal{L}_{\rm eff}$ which is given as an expansion in inverse powers of some energy scale Λ representing the onset of new physical phenomena [9, 10]:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{\alpha_i}{\Lambda^2} O_6^i + \cdots, \tag{5.1}$$

$\mathcal{L}_{\rm SM}$ is the SM Lagrangian, O_6^i are dimension-6 (non-renormalizable) $\mathrm{SU}(2)_{\rm L} \times \mathrm{U}(1)$ invariant operators and α_i are form factors. In this scheme, the operators O_6^i describe possible deviations of the SM, in particular potential non-standard (anomalous) couplings for the boson vertices $WW\gamma(Z)$, WWH, ZZH, etc. Since the decay widths $\Gamma(H \to \gamma\gamma, \gamma Z)$ are expected to be highly sensitive to these couplings, it is therefore interesting to study the above decay widths in the presence of potential anomalous couplings. We follow the approach advocated by de Rújula and collaborators [9] that any modification of the SM dynamics above its symmetry-breaking scale should respect the SU(2) × U(1) SM gauge symmetry. Accordingly, the non-standard $WW\gamma(Z)$, WWH couplings are derived from the SU(2) × U(1) invariant, dimension-6 operators

$$
\begin{aligned}
O_W &= \frac{1}{3!}\varepsilon_{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}, \qquad & O_{W\Phi} &= i(D_\mu\Phi)^\dagger \tau^i (D_\nu\Phi) W^{i\mu\nu}, \\
O_{WB} &= (\Phi^\dagger \tau^i \Phi) W_{\mu\nu}^i B^{\mu\nu}, \qquad & O_{WD} &= (D^\rho W_{\mu\nu}^i)^\dagger (D_\rho W^{i\mu\nu}),
\end{aligned}
\tag{5.2}
$$

where Φ is the SM scalar doublet, τ^i are the Pauli matrices and the field tensors and covariant derivatives are given by

$$
\begin{aligned}
W_{\mu\nu}^i &= \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g\varepsilon_{ijk} W_\mu^j W_\nu^k, \\
B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu, \\
D_\mu &= \partial_\mu - ig\frac{\tau^i}{2} W_\mu^i - ig'\frac{Y}{2} B_\mu.
\end{aligned}
\tag{5.3}
$$

In particular, de Rújula and collaborators found [9] that the operators O_{WB} induce a tree-level anomalous vertex $H\gamma\gamma$ with an amplitude $A_{WB} = 8\pi s_{\rm W}^2/g\alpha$. Our point of view is that a complete estimate —to first order in the coefficients of the new operators ε_{WB}, ε_W, $\varepsilon_{W\Phi}$, ε_{WD}, which are expected to behave as Λ^{-2}, $\varepsilon_i \equiv \alpha_i/\Lambda^2$— of the nonstandard deviations of $\Gamma(H \to \gamma\gamma)$ has to include the effects generated by the anomalous vertices $WW\gamma$, WWH in the one-loop diagrams as shown in Fig. 3. We performed this calculation [13] in the Feynman-'tHooft gauge, the respective Feynman diagrams are shown in Fig. 4. The decay width obtained is given by

$$
\Gamma(H^0 \to \gamma\gamma) = \Gamma_0(H \to \gamma\gamma)\left|1 + \frac{(A_{WB} + A_{W\Phi})g\varepsilon_{W\Phi} + 12A_W g^2 \varepsilon_{WB}}{A_0}\right|^2, \tag{5.4}
$$

where Γ_0 and A_0 are the SM results [8] and

$$
\begin{aligned}
A_{W\Phi} = {} & \left(7 + \frac{4}{\tau_{\rm L}}\right)\ln\left(\frac{\Lambda^2}{M_W^2}\right) + \frac{73}{6} + 2\tau_{\rm L} + 8\tau_{\rm L} \\
& + 2\left(\tau_{\rm L} - 4 - \frac{4}{\tau_{\rm L}}\right)\sqrt{\tau_{\rm L} - 1}\, I(\tau_{\rm L}) - (16 + \tau_{\rm L}) I^2(\tau_{\rm L}),
\end{aligned}
\tag{5.5}
$$

$$
A_W = 4\ln\left(\frac{\Lambda^2}{M_W^2}\right) + 10 - 2\sqrt{\tau_{\rm L} - 1}\, I(\tau_{\rm L}) + 2(3 - \tau_{\rm L}) I^2(\tau_{\rm L}). \tag{5.6}
$$

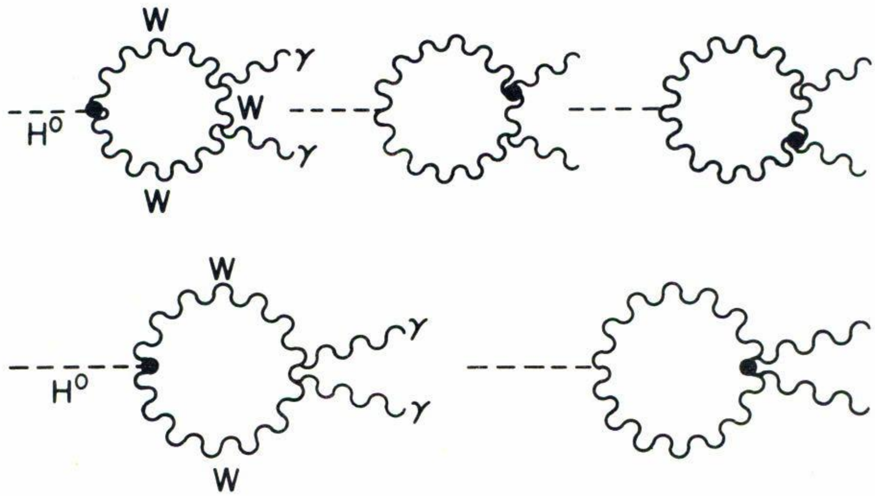

FIGURE 3. Feynman diagrams for the anomalous contribution (black dots) to $\Gamma(H \to \gamma\gamma)$.

Few comments are in order. The amplitudes $A_{W\Phi,W}$ depend weakly on M_H and Λ. In particular, the leading divergence is logarithmic and, according to (5.1), they decouple as $\Lambda \to \infty$ and the SM predictions are recovered in this limit. In this respect, our calculation can be considered also as an illustrative example of how the full $SU(2) \times U(1)$ gauge invariance of the operators O_6 provides a useful bookkeeping of electromagnetic gauge invariance as well as a test of the decoupling nature of the non-standard quantum (one-loop) corrections induced by O_6. The latter situation does not arise in a specific calculation of $\Gamma(H \to \gamma\gamma)$ when use is made of an anomalous vertex $WW\gamma$ which is not explicitly $SU(2) \times U(1)$ gauge invariant [18]. A similar situation arises for the decay width $\Gamma(H \to \gamma Z)$, with the only complication that it is necessary to consider a greater number of Feynman diagrams [19].

De Rújula *et al.* [9] found that the new tree-level anomalous coupling A_{WB} induces an enhancement of the ratio $\Gamma(H^0 \to \gamma\gamma)/\Gamma_0(H^0 \to \gamma\gamma)$ of 5.6 to 19 in the interval $|\varepsilon_{WB}| \leq 0.01$. We have found that the same ratio —including the one-loop anomalous contributions $A_{W\phi}$ and A_W— varies from 0.166 to 7.6 for $m_H = 100$ GeV and $\lambda = 1$ TeV when we use the bounds obtained in Ref. [9] from well-measured observables at tree level $-0.008 < \varepsilon_{WB} < 0.01$ and $-0.024 < \varepsilon_{DW} < 0.014$. Our results for the anomalous one-loop contributions $A_{W\phi}$ and A_W change smoothly with M_H and $\Gamma(H^0 \to \gamma\gamma)/\Gamma_0(H^0 \to \gamma\gamma)$ and the difference with respect to our results cannot be explained by the anomalous one-loop contributions. The discrepancy with respect to de Rújula's result may lie just in an erroneous calculation of their tree level contribution.

On the other hand, we can get bounds on ε_{DW} and ε_{WB} by requiring that the anomalous contributions to $\Gamma(H^0 \to \gamma\gamma)$ should be lower than the SM decay width $\Gamma_0(H^0 \to \gamma\gamma)$. This approach is consistent with the expected decoupling nature of the non-standard quantum corrections as $\Lambda \to \infty$ and $\varepsilon_i \to \Lambda^{-2}$. What is relevant now is to find if the new bounds improve those already found from the existing low-energy data [9]. Assum-

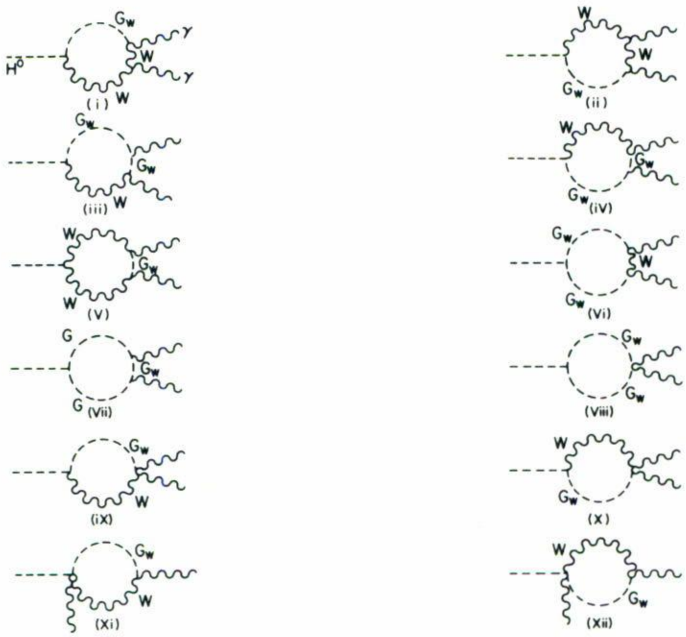

FIGURE 4. Feynman diagrams with non-standard couplings in the Feynman-'t-Hooft gauge involving the Goldstone boson G_W.

ing no accidental cancelations among the anomalous terms, we get $|\varepsilon_{WB}| \approx |\varepsilon_{W\phi}| \leq |4A_0/g(A_{WB} + |A_{W\Phi})|$ and $|\varepsilon_{DW}| \leq |A_0/3g^2 A_W|$, which are equivalent to the bounds $|\varepsilon_{DW}| \leq 0.2$ and $|\varepsilon_{WB}| \leq 0.009$.

The anomalous magnetic dipole and electric quadrupole moments of the W boson can be expressed in terms of the ε_i form factors evaluated at zero momentum transfer:

$$\mu_W = \frac{\left[1 + \frac{1}{8}g(\varepsilon_{W\Phi} + \varepsilon_W)\right]e}{2M_W}, \tag{5.7}$$

$$Q_W = -\frac{g(\varepsilon_{W\Phi} - \varepsilon_W)e}{8M_W^2}. \tag{5.8}$$

The SM predictions correspond to $\varepsilon_i \equiv 0$. According to our bounds on ε_i, we get $\delta\mu_W \leq 0.02$ and $\delta Q \leq 4 \times 10^{-3}$, which are more stringent that the experimental values [20] $\mu_W = 1 + 2.6\,(-2.2)$ and $Q_W = 0 + 1.7\,(-1.8)$, but just comparable to the bounds obtained by the Rújula *et al.* [9].

6. HIGGS BOSON SEARCHES

The $d = 6$ operators O_6 given in Eq. (5.2) induce anomalous vertices $WW\gamma(Z)$, HZZ, HWW which may generate deviations on the search techniques for the SM Higgs boson. In particular, we have computed [21] the expected deviations of the branching ratios (BR)

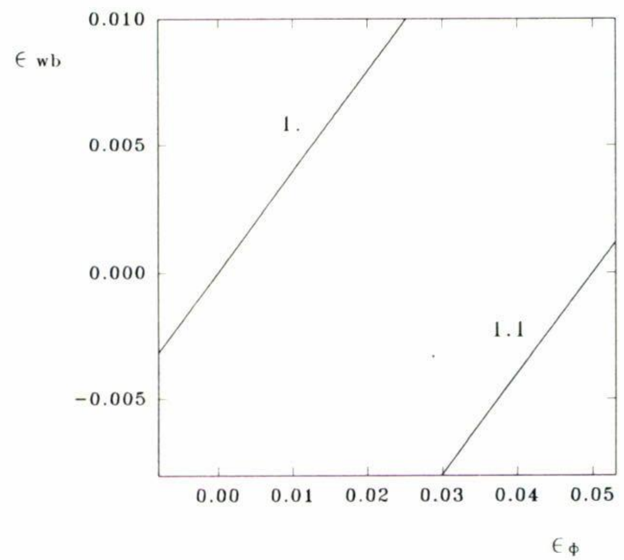

FIGURE 5. Dependence of the ratio $R_\Gamma = \Gamma(H \to ZZ)/\Gamma_0(H \to ZZ)$ with respect to the anomalous coefficients ε_{WB} and ε_Φ, for $m_H = 200$ GeV.

of the decay modes $H \to ZZ, WW$ for $m_H \geq 200$ GeV. We have used also these anomalous vertices to compute the cross section $\sigma(e^+e^- \to Z* \to ZH)$ at LEP II energies.

We show in Figs. 5 y 6 the results for $R_\sigma = \sigma(e^+e^- \to ZH)/\sigma_0(e^+e^- \to ZH)$ and $R_\Gamma = \Gamma(H \to ZZ)/\Gamma_0(H \to ZZ)$ in the $\varepsilon_\Phi - \varepsilon_{WB}$ plane of parameter space. We find that these ratios are very close to the SM prediction, which means that the anomalous coupling HZZ induces minimal deviations. As a consequence, the bounds obtained on m_H from LEP are only slightly modified. Similarly, we have found that the reaction $e^+e^- \to Z + H$, which will be searched at LEP II, has a cross section that differs from the SM result by only a fraction of a percent. On the other hand, the search for a heavy Higgs boson can be still done at hadron colliders through the decay $H \to ZZ$. As expected, our values for $\mathrm{BR}(H \to \gamma\gamma)$ are higher than the SM prediction and this result confirms the expectations that this decay mode can be used to detect a SM Higgs boson in the intermediate mass range.

7. Concluding remarks

We have found that —even with the stringent bounds on ε_i obtained from low-energy data [9]— the $\gamma\gamma$-decay width may be enhanced by an order of magnitude with respect to the SM result $\Gamma_0(H \to \gamma\gamma)$ given in Eq. (2.1). This result confirms the expected sensitivity of the one-loop diagrams on the structure of the $WW\gamma$, WWH vertices. We have also verified that the $\mathrm{SU}(2) \times \mathrm{U}(1)$ gauge invariant $d = 6$ operators given in Eq. (5.2) induce only logarithmic divergences in the $\gamma\gamma$-decay width. As a consequence, the effective Lagrangian (5.1) restores the decoupling nature of the non-standard quantum corrections in the limit $\Lambda \to \infty$.

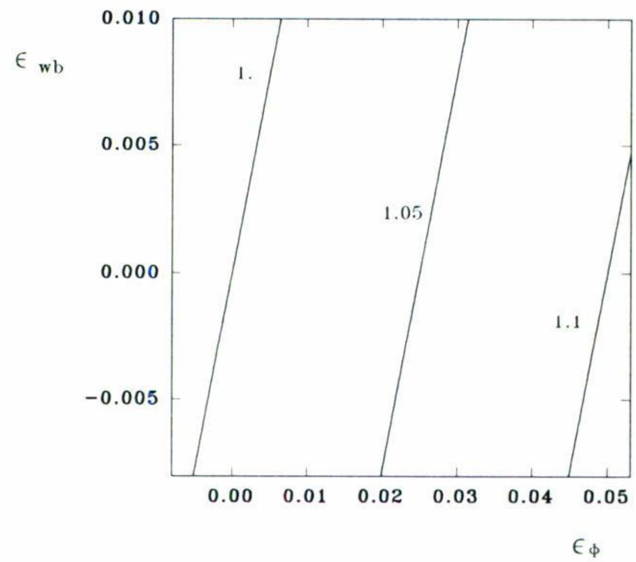

FIGURE 6. Dependence of the ratio $R_\sigma = \sigma(e^+e^- \to ZH)/\sigma_0(e^+e^- \to ZH)$ with respect to the anomalous coefficients ε_{WB} and ε_Φ, for $m_H = 70$ GeV.

On the other hand, we found that the LR phenomenology forces the LR prediction for $\Gamma(H \to \gamma\gamma, \gamma Z)$ to be as close as possible to the SM result, while the MSSM prediction for these decay widths are somewhat suppressed as compared to $\Gamma_0(H \to \gamma\gamma, \gamma Z)$. We have therefore, in conclusion, that a measurement of these decay modes for the neutral Higgs boson may be used to distinguish among minimal extensions of the standard model.

APPENDIX

The decay widths $\Gamma(H \to \gamma\gamma, \gamma Z)$ depend on the following parametric integrals:

$$I(\tau) = \begin{cases} \tan^{-1}\left[\dfrac{1}{\sqrt{\tau - 1}}\right], & \tau > 1, \\ \\ \dfrac{1}{2}\left[\pi + i \ln \dfrac{1 + \sqrt{1-\tau}}{1 - \sqrt{1-\tau}}\right], & \tau < 1. \end{cases} \tag{A.1}$$

$$I_1(\tau,\sigma) = \frac{1}{2(\tau - \sigma)} + \frac{2}{(\tau-\sigma)^2}[f(\sigma^{-1}) - f(\tau^{-1})] + \frac{\tau}{(\tau-\sigma)^2}[g(\sigma^{-1}) - g(\tau^{-1})], \tag{A.2}$$

$$I_2(\tau,\sigma) = -\frac{2}{(\tau-\sigma)}[f(\sigma^{-1}) - f(\tau^{-1}], \tag{A.3}$$

$$f(a) = \begin{cases} -\left[\sin^{-1}(1/2\sqrt{a})\right]^2, & 4a > 1, \\ \\ \frac{1}{4}\left[\ln(b_+/b_-) + i\pi\right]^2, & 4a < 1. \end{cases} \tag{A.4}$$

$$g(a) = \begin{cases} \sqrt{4a-1}\,\sin^{-1}(1/2\sqrt{a}), & 4a > 1, \\ \\ \frac{1}{2}\sqrt{1-4a}\,[\ln(b_+/b_-) + i\pi], & 4a < 1. \end{cases} \tag{A.5}$$

$$b^{\pm} = \tfrac{1}{2}\left(1 \pm \sqrt{1-4a}\right). \tag{A.6}$$

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