PHYSICAL REVIEW D VOLUME 45, NUMBER 5 1 MARCH 1992

Higgs-boson decay into two photons as a probe of anomalous gauge couplings

Heinz König
Ottawa-Carleton Institute for Physics, Department of Physics, Carleton University, Colonel By Drive, Ottawa, Ontario, Canada K1S 5B6
(Received 3 October 1991)

We present the results of a calculation on the influence of anomalous γWW and $\gamma\gamma WW$ gauge-boson couplings on the decay of the Higgs boson into two photons. In the standard model this decay occurs via penguin diagrams with scalars, fermions, and W bosons within the loop. We show that if new physics comes in at the scale of 1 TeV, anomalous gauge couplings can lead to a large enhancement or suppression of the decay rate compared to the standard-model results depending on the parameter λ_γ and κ_γ in the γWW and $\gamma\gamma WW$ coupling.

PACS number(s): 14.80.Gt, 12.15.Cc, 13.40.Hq

I. INTRODUCTION

In the standard model the decay of the Higgs boson into two photons might be one of the most important decay modes of the Higgs particle because it is the only one that does not have a similar decay mode for the Z boson. Therefore, if the Higgs boson can be produced at energies of the CERN e^+e^- collider LEP or the SLAC Linear Collider (SLC) via reactions such as $e^+e^- \to Z^0H, l^+l^-H$ the two-photon decay mode would play a central role, which is also true for intermediate Higgs-boson mass at the superconducting Super Collider and CERN Large Hadron Collider (LHC).

The decay occurs in the standard model via penguin diagrams with scalars, fermions, and W bosons within the relevant loop diagrams. The result is well known [1,2]. Not only in the standard model does this decay mode appear to be important, but it is also very sensitive to extensions of the standard model [3,4]. For example, the influence of sypersymmetric extensions of the standard model can be found in [5] and the influence of left-right-symmetric theories was considered in [6].

In this paper we study the influence that the anomalous gauge couplings have on the decay mode of the Higgs boson into two photons. Here we use the most general C- and P-parity conserving vector-boson couplings, which have been extensively discussed with their measurable influences in Refs. [7–18], and references therein.

This paper is divided into the following sections. In Sec. II, we present the Lagrangian and the couplings we need for calculating the relevant penguin diagrams given in Fig. 1. We also present the calculation procedure and give the results for the matrix elements. In Sec. III, we present the results of the influence of the anomalous gauge couplings on the decay rate of the Higgs boson into two photons. Finally, in Sec. IV, we give the conclusions.

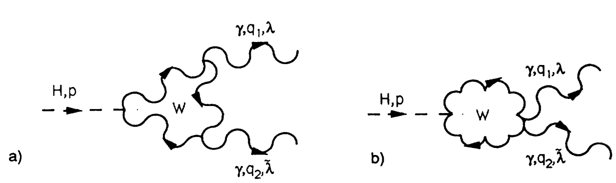

FIG. 1. Feynman diagrams of the anomalous gauge couplings leading to the decay of the Higgs boson into two photons. (a) Three-vertex γWW. (b) Four-vertex $\gamma\gamma WW$.

II. THE LAGRANGIAN AND CALCULATION PROCEDURE

For the Lagrangian we take the most general description for the anomalous couplings with conserving C and P symmetries given by the following parametrization [9–11]:

$$\mathcal{L}=\mathcal{L}_1+\mathcal{L}_2+\mathcal{L}_3\ , \tag{1}$$

$$\mathcal{L}_1=-\tfrac{1}{2}\hat{G}^\dagger_{\mu\nu}\hat{G}^{\mu\nu}-m_W^2W^\dagger_\mu W^\mu-\tfrac{1}{2}m_Z^2Z_\mu Z^\mu\ , \tag{1a}$$

$$\mathcal{L}_2=-\tfrac{1}{4}\sum_{i=\gamma,Z}\hat{F}_{\mu\nu i}\hat{F}_i^{\mu\nu}\ , \tag{1b}$$

$$\mathcal{L}_3=\sum_{i=\gamma,Z}\frac{ig_i\lambda_i}{m_W^2}\hat{F}_{\mu\nu}\hat{G}^{\dagger\mu\rho}\hat{G}_\rho^{\ \nu}\ , \tag{1c}$$

$$\hat{G}_{\mu\nu}=(\partial_\mu-ig_\gamma A_\mu-ig_Z Z_\mu)W_\nu -(\partial_\nu-ig_\gamma A_\nu-ig_Z Z_\nu)W_\mu\ , \tag{1d}$$

$$\hat{F}^i_{\mu\nu}=F^i_{\mu\nu}+ig_i\kappa_i(W^\dagger_\mu W_\nu-W^\dagger_\nu W_\mu)\ , \tag{1e}$$

$$F^i_{\mu\nu}=\partial_\mu i_\nu-\partial_\nu i_\mu\ , \tag{1f}$$

$$g_\gamma=g_2\sin\theta_W=e\ , \tag{1g}$$

$$g_Z=g_2\cos\theta_W\ . \tag{1h}$$

The anomalous magnetic moment and the electric quadrupole moment of the W gauge boson are then given by

$$\mu_{iW}=(1+\kappa_i-\lambda_i)\frac{g_i}{2m_W}\ , \tag{2}$$

$$Q_{iW}=-(\kappa_i+\lambda_i)\frac{g_i}{m_W^2)}\ . \tag{3}$$

In the standard model $\lambda_i=0$ and $\kappa_i=1$ at tree level. The contributions of several kinds of models such as the two-Higgs-doublet model or broken supersymmetric extensions of the standard model to the parameters μ_W and

Q_W can be found in [19–21].

The Feynman rules for the three- and four-vertex gauge-boson couplings derived from (1) are listed in Table 1 in [10] and are given below for those we use to calculate the decay of the Higgs boson into two photons. The relevant Feynman diagrams we have to consider are shown in Fig. 1 and the Feynman rules in Fig. 2, where we have made the definitions

$$\Gamma^{\rm St}_{\mu\nu\lambda} = -g_{\mu\nu}(k_1+k_2)_\lambda + g_{\nu\lambda}(k_2-q_1)_\mu + g_{\mu\lambda}(k_1+q_1)_\nu \ , \tag{4}$$

$$\begin{aligned}\Gamma^{\rm NSt}_{\mu\nu\lambda} = \frac{\lambda_\gamma}{m_W^2}[&q_{1\nu}k_{2\mu}k_{1\lambda} - q_{1\mu}k_{2\lambda}k_{1\nu} + (q_1k_2)(k_{1\nu}g_{\mu\lambda} - k_{1\lambda}g_{\mu\nu}) \\ &+ (q_1k_1)(k_{2\lambda}g_{\mu\nu} - k_{2\mu}g_{\nu\lambda}) + (k_1k_2)(q_{1\mu}g_{\nu\lambda} - q_{1\nu}g_{\mu\lambda})] + \Delta\kappa_\gamma(q_{1\nu}g_{\mu\lambda} - q_{1\mu}g_{\nu\lambda}) \ ,\end{aligned} \tag{5}$$

$$\Delta\kappa_\gamma \equiv \kappa_\gamma - 1 \ .$$

Here $k_{1,2}$ are the momenta of the W bosons within the loop and q_1 is the momenta of the outgoing photon. A similar equation is obtained for the outgoing photon with momenta q_2.

For the four-vertex $\gamma\gamma WW$ coupling we have

$$\Gamma^{\rm St}_{\mu\nu\lambda\bar\lambda} = 2g_{\lambda\bar\lambda}g_{\mu\nu} - g_{\mu\lambda}g_{\nu\bar\lambda} - g_{\mu\bar\lambda}g_{\nu\lambda} \ , \tag{6}$$

$$\begin{aligned}\Gamma^{\rm NSt}_{\mu\nu\lambda\bar\lambda} = \frac{\lambda_\gamma}{m_W^2}\{&g_{\mu\nu}g_{\lambda\bar\lambda}(q_1+q_2)(k_2-k_1) + g_{\mu\lambda}g_{\nu\bar\lambda}(q_2k_1-q_1k_2) + g_{\mu\bar\lambda}g_{\nu\lambda}(q_1k_1-q_2k_2) \\ &+ g_{\mu\nu}[q_{1\bar\lambda}(k_1-k_2)_\lambda + q_{2\lambda}(k_1-k_2)_{\bar\lambda}] + g_{\lambda\bar\lambda}[k_{1\nu}(q_1+q_2)_\mu - k_{2\mu}(q_1+q_2)_\nu] \\ &+ g_{\mu\lambda}[q_{1\nu}(k_1+k_2)_{\bar\lambda} - q_{2\nu}k_{1\bar\lambda} - q_{1\bar\lambda}k_{1\nu}] + g_{\mu\bar\lambda}[q_{2\nu}(k_1+k_2)_\lambda - q_{1\nu}k_{1\lambda} - q_{2\lambda}k_{1\nu}] \\ &- g_{\nu\lambda}[q_{1\mu}(k_1+k_2)_{\bar\lambda} - q_{2\mu}k_{2\bar\lambda} - q_{1\bar\lambda}k_{2\mu}] - g_{\nu\bar\lambda}[q_{2\mu}(k_1+k_2)_\lambda - q_{1\mu}k_{2\lambda} - q_{2\lambda}k_{2\mu}]\} \ .\end{aligned} \tag{7}$$

To compute the Feynman diagrams shown in Fig. 1, we take the W-boson propagator in the unitary gauge

$$-\frac{i}{k_i^2-m_W^2}(g_{\mu\nu} - k_{i\mu}k_{i\nu}/m_W^2) \ .$$

As was already pointed out in [12], the calculations show that the longitudinal component of the W-boson propagator $(k_\mu k_\nu/m_W^2)$ does not contribute to the λ_i term but gives the most singular contribution to the $\Delta\kappa_i$ terms.

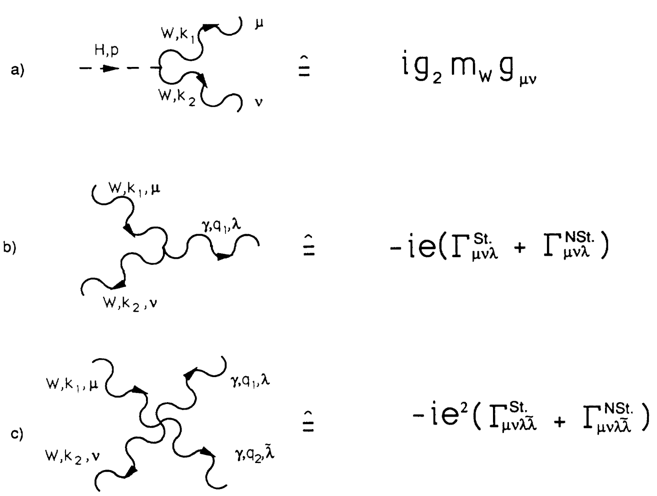

FIG. 2. (a) Feynman rules for the Higgs-boson–W-boson coupling. (b) Feynman rules for the three-vertex γWW coupling. (c) Feynman rules for the four-vertex $\gamma\gamma WW$ coupling.

The highest divergencies, which occur in the considered Feynman diagrams, are quadratic. To keep the matrix element finite we therefore introduce a cutoff parameter Λ, where we suppose the new physics is coming in. This cutoff parameter is introduced via the usual power-law form factor [11] by multiplying the quadratically divergent part of the matrix element with the factor $\Lambda^4/[(k_1^2-\Lambda^2)(k_2^2-\Lambda^2)]$. In the calculation we will keep only the most divergent terms, which are quadratic divergent [that means we neglect all terms $\ll(\Lambda/m_W)^2$, e.g., $\ln(\Lambda/m_W)^2$, $(m_H/\Lambda)^2, \ldots$].

The result of the calculation of the first diagram in Fig. 1 is then given by

$$\begin{aligned}M_a = +i\frac{e^2g_2}{(4\pi)^2}m_W\frac{\Lambda^2}{m_W^4}&(q_1q_2g_{\lambda\bar\lambda} - q_{1\bar\lambda}q_{2\lambda}) \\ &\times\epsilon_1^{*\lambda}\epsilon_2^{*\bar\lambda}\{\lambda_\gamma^2 + \tfrac{1}{2}(\Delta\kappa_\gamma)^2 + 3\Delta\kappa_\gamma\} \ .\end{aligned} \tag{8}$$

The second diagram leads to

$$M_b = +i\frac{e^2g_2}{(4\pi)^2}m_W\frac{\Lambda^2}{m_W^4}(q_1q_2g_{\lambda\bar\lambda} - q_{1\bar\lambda}q_{2\lambda})\epsilon_1^{*\lambda}\epsilon_2^{*\bar\lambda}\{-4\lambda_\gamma\}. \tag{9}$$

As a final point we want to mention that the terms proportional to Λ^2 of diagrams with one scalar particle and two W bosons within the loop are proportional to q_1^2 or q_2^2 and therefore identical to zero.

III. THE DECAY RATE OF THE HIGGS BOSON INTO TWO PHOTONS

In the standard model the penguin diagrams with scalars, fermions, and gauge bosons lead to the decay rate [2]

$$\Gamma(H \xrightarrow{\text{St}} \gamma\gamma) = \frac{\alpha^2 G_F m_H^3}{64\sqrt{2}\pi^3} \left| \sum_i N_{ci} e_i^2 F_i \right|^2 \equiv \frac{\alpha^3}{128\pi^2 \sin^2\Theta_W} \frac{m_H^3}{m_W^2} \left| \sum_i N_{ci} e_i^2 F_i \right|^2 , \tag{10}$$

where i = scalars, fermions, and gauge bosons, e_i the electric charge in units of e, and N_{ci} the color factor:

$$\begin{aligned} F_s &= \tau_s(1-\tau_s I^2) , \\ F_f &= -2\tau_f[1+(1-\tau_f)I^2] , \\ F_g &= 2+3\tau_g+3\tau_g(2-\tau_g)I^2 , \end{aligned} \tag{11}$$

with $\tau_i = 4(m_i/m_H)^2$ and

$$I = \begin{cases} \arctan\dfrac{1}{\sqrt{\tau-1}}, & \tau > 1 , \\ \dfrac{1}{2}\left[\pi + i\ln\left[\dfrac{\eta_+}{\eta_-}\right]\right], & \tau < 1 , \end{cases}$$

$$\eta_\pm = 1 \pm \sqrt{1-\tau} .$$

The new couplings given in (5) and (7) change the decay rate of (10) to

$$\Gamma(H \xrightarrow{\text{St+NSt}} \gamma\gamma) = \frac{\alpha^3}{128\pi^2 \sin^2\Theta_W} \frac{m_H^3}{m_W^2} \left| \sum_i N_{ci} e_i^2 F_i + \left[\frac{\Lambda}{m_W}\right]^2 [3\Delta\kappa_\gamma - 4\lambda_\gamma + \lambda_\gamma^2 + \tfrac{1}{2}(\Delta\kappa_\gamma)^2] \right|^2 . \tag{12}$$

In the standard model the scalars and fermions lead to negative F_i, whereas the W bosons give a positive value for F; if we take for the mass of the top quark 140 GeV and for the Higgs-boson mass 100 GeV, the summation over all fermions leads for the real part of F to $\sum_f N_{cf} e_f^2 F_f \approx -3.5$ (the largest contribution comes from the top quark). The addition of the W boson contribution changes the value to $\sum_{i=f,W} N_{ci} e_i^2 F_i \approx +4.2$ and the further addition of the Higgs boson finally gives us the value $+3.8$. The imaginary part is about -0.2. The highest contribution therefore comes from the W bosons.

Considering (12), we see that mainly the linear terms in $\Delta\kappa_\gamma$ and λ_γ lead to a contribution to the decay rate of the decay of the Higgs boson into two photons, whereas the λ_γ^2 and $(\Delta\kappa_\gamma)^2$ terms can usually be neglected. They only become important if $\lambda_\gamma \approx \Delta\kappa_\gamma$ because of an accidental cancellation between the λ_γ and $\Delta\kappa_\gamma$ terms due to a relative minus sign.

Because $\sum_{i=s,f,W} N_{ci} e_i^2 F_i$ is of order 1 and $(\Lambda/m_W)^2$ of order 100, if we set the scale of new physics at 1 TeV, even small values λ_γ, $\Delta\kappa_\gamma < 0.01$ will have a large influence on this decay. In Figs. 3–7, we show the decay rate of the Higgs boson into two photons in units of keV as a function of the Higgs-boson mass for different values of λ_γ and $\Delta\kappa_\gamma$. In all figures we have taken a top mass of 140 GeV.

In Fig. 3 we have taken $\lambda_\gamma = 0.01$ and $\Delta\kappa_\gamma = 0$ (dashed line) and $\lambda_\gamma = 0$ and $\Delta\kappa_\gamma = 0.01$ (dashed-dotted line). The values of the standard model are given by the solid line. We see that due to a relative plus or minus sign of the new terms compared to the standard model, we get a

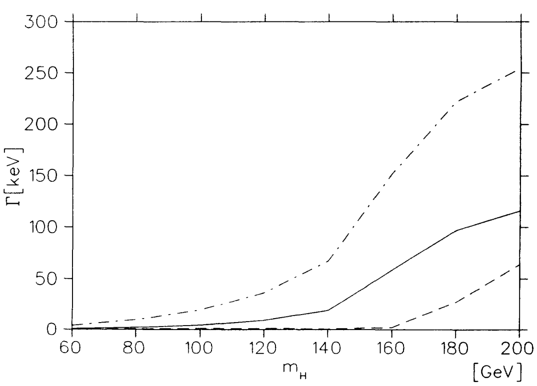

FIG. 3. $\Gamma(H \xrightarrow{\text{St+NSt}} \gamma\gamma)$ in keV as a function of the Higgs-boson mass m_H in GeV for $m_{\text{top}} = 140$ GeV: Standard model (solid line); $\lambda_\gamma = 0.01$ and $\Delta\kappa_\gamma = 0$ (dashed line); $\lambda_\gamma = 0$ and $\Delta\kappa_\gamma = 0.01$ (dashed-dotted line).

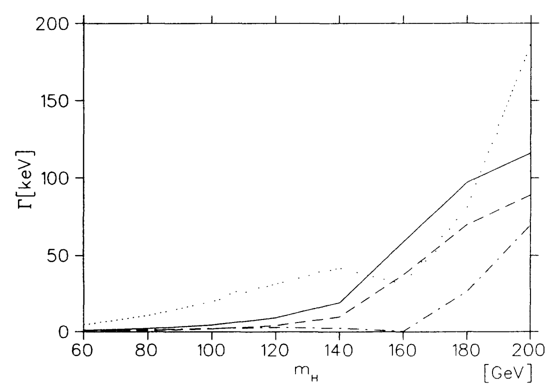

FIG. 4. Same as in Fig. 3: Standard model (solid line); $\lambda_\gamma \equiv \Delta\kappa_\gamma$ with $\Delta\kappa_\gamma = 0.01$ (dashed line), $\Delta\kappa_\gamma = 0.05$ (dashed-dotted line), and $\Delta\kappa_\gamma = 0.1$ (dotted line).

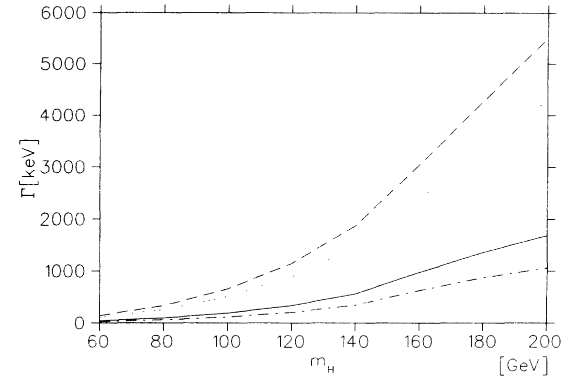

FIG. 5. Same as in Fig. 3: $\lambda_\gamma=0$ with $\Delta\kappa_\gamma=0.05$ (solid line) and $\Delta\kappa_\gamma=0.1$ (dashed line); $\lambda_\gamma=0.01$ with $\Delta\kappa_\gamma=0.05$ (dashed-dotted line) and $\Delta\kappa_\gamma=0.1$ (dotted line).

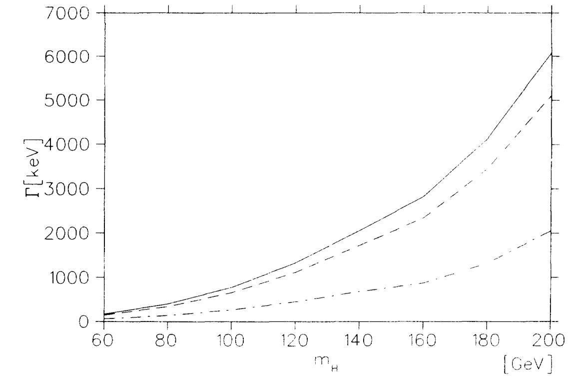

FIG. 7. Same as in Fig. 3: $\lambda_\gamma=0.1$ with $\Delta\kappa_\gamma=0$ (solid line), $\Delta\kappa_\gamma=0.01$ (dashed line), and $\Delta\kappa_\gamma=0.05$ (dashed-dotted line).

large suppression or enhancement of the decay rate relative to the standard model. In Fig. 4 we show the results for $\lambda_\gamma\equiv\Delta\kappa_\gamma$ in the cases of $\lambda_\gamma=0.01$ (dashed line), $\lambda_\gamma=0.05$ (dashed-dotted line), and $\lambda_\gamma=0.1$ (dotted line). The values of the standard model are again given by the solid line. Again we see the suppression of enhancement of the decay rate relative to the standard model.

In Fig. 5 we have taken $\lambda_\gamma=0$ with $\Delta\kappa_\lambda=0.05$ (solid line) and $\Delta\kappa_\gamma=0.1$ (dashed line) and $\lambda_\gamma=0.01$ with $\Delta\kappa_\gamma=0.05$ (dashed-dotted line), and $\Delta\kappa_\gamma=0.1$ (dotted line). In Fig. 6 we have $\lambda_\gamma=0.05$ with $\Delta\kappa_\gamma=0$ (solid line), $\Delta\kappa_\gamma=0.01$ (dashed line), and $\Delta\kappa_\gamma=0.1$ (dashed-dotted line). Finally, in Fig. 7 we have plotted the results for $\lambda_\gamma=0.1$ with $\Delta\kappa_\gamma=0$ (solid line), $\Delta\kappa_\gamma=0.01$ (dashed line) and $\Delta\kappa_\gamma=0.05$ (dashed-dotted line). In the last three figures we see that, even if one parameter is identical to zero, the decay rate is enhanced by a factor of at least 10 compared to the values in the standard model. The enhancement is at the highest when $\lambda_\gamma\neq\Delta\kappa_\gamma$ and both parameters are unequal to zero.

For the sake of simplicity we have chosen only positive values for λ_γ, and $\Delta\kappa_\gamma$. As can be seen from (12) and Fig. 3, if we choose the cases $\lambda_\gamma<0$ with $\Delta\kappa_\gamma<0$ or >0 or $\lambda_\gamma>0$ with $\Delta\kappa_\gamma<0$, this would not change our results

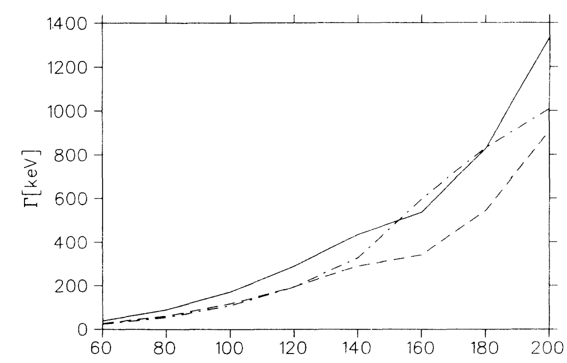

FIG. 6. Same as in Fig. 3: $\lambda_\gamma=0.05$ with $\Delta\kappa_\lambda=0$ (solid line), $\Delta\kappa_\gamma=0.01$ (dashed line), and $\Delta\kappa_\gamma=0.1$ (dashed-dotted line).

very much. Depending only on the relative minus or plus sign of the new terms compared to the standard model we always obtain a large suppression or enhancement of the decay rate relative to the standard model even for small values of λ_γ or $\Delta\kappa_\gamma$. If $|\lambda_\gamma|$ or $|\Delta\kappa_\gamma|$ are large (≥ 0.05) and $\lambda_\gamma\neq\Delta\kappa_\gamma$, we always obtain

$$\Gamma H\xrightarrow{\text{St}+\text{NSt}}\gamma\gamma)\gg\Gamma(H\xrightarrow{\text{St}}\gamma\gamma)$$

because then the nonstandard couplings mostly contribute to the decay rate. This is also true if we would have chosen for the scale of new physics $\Lambda=10$ TeV, where the contribution of the nonstandard coupling is enhanced by a further factor of 100 due to the $(\Lambda/m_W)^2$ factor.

IV. CONCLUSION

In this paper we have shown the contribution of the nonstandard couplings given in (5) and (7) to the decay rate of the Higgs-boson decay into two photons. We have seen that, even for small values of λ_γ and $\Delta\kappa_\gamma$ (<0.01), the nonstandard couplings lead to a large enhancement or suppression of the decay rate compared to the standard model. This is also valid for negative values of λ_γ and Δ_{κ_γ}.

If $\lambda_\gamma,\Delta\kappa_\gamma>0.05$ and $\lambda_\gamma\neq\Delta\kappa_\gamma$, the nonstandard couplings give the largest contribution to the two-photon decay rate and enhance it by more than a factor of 10 compared to the standard-model prediction to the decay rate, which is also true for $\lambda_\gamma,\Delta\kappa_\gamma<-0.05$.

A final point we want to mention is that we can use our result given in (8) and (9) for the decay of the Higgs boson into a Z boson and photon if we replace the curly brackets in M_a with

$$\{\lambda_\gamma\lambda_Z+\tfrac{1}{2}\Delta\kappa_\gamma\Delta\kappa_Z+\tfrac{3}{4}(\Delta\kappa_\gamma+3\Delta\kappa_Z)\}$$

and in M_b with $-2(\lambda_\gamma+\lambda_Z)$ and multiply M_a+M_b by an overall factor $-\cot\Theta_W$.

The result of this decay rate within the standard model is given in [22]. But because of the large backgrounds coming from continuum $q\bar{q}\rightarrow Z\gamma$ and $gg\rightarrow Z\gamma$ production [4,23], we do not consider the decay of the Higgs boson into a Z boson and one photon.

Furthermore, we can also use the result for the decay of the Z boson into the Higgs boson and one photon, if the Higgs-boson mass is smaller than the Z-boson mass. In the usual parametrization of this decay mode [24], we obtain

$$A_{\Lambda} = +\cos\Theta_W \{ \lambda_\gamma \lambda_Z + \tfrac{1}{2}\Delta\kappa_\gamma \Delta\kappa_Z + \tfrac{3}{4}(\Delta\kappa_\gamma + 3\Delta\kappa_Z) - 2(\lambda_\gamma + \lambda_Z) \} \frac{\Lambda^2}{m_W^2} \; . \tag{13}$$

This can be much larger than the contribution coming from the W bosons with $A_W \approx -4.6 - \frac{1}{4}(m_H/m_W)^2$. But because of the lower experimental mass bound of the Higgs boson, this decay rate is only interesting in the small mass range of the Higgs boson from 60 GeV to m_Z. This decay mode is also suppressed by the kinematic factor of $\beta^3 = (1 - m_H^2/m_Z^2)^3$. Therefore, if the Higgs boson will be discovered at LEP or SLC in the near future, the decay of the Higgs boson into two photons will be the most important mode for analyzing extensions of the standard model.

ACKNOWLEDGMENTS

I would like to thank S. Godfrey for useful advice. This research was supported by the Deutsche Forschungsgemeinschaft.

[1] L. Resnick, M. K. Sundaresan, and P. J. S. Watson, Phys. Rev. D **8**, 172 (1973).

[2] A. J. Vainstein, M. B. Voloshin, V. I. Zakharov, and M. A. Shifman, Yad. Fiz. **30**, 1368 (1979) [Sov. J. Nucl. Phys. **30**, 711 (1979)].

[3] J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. **B106**, 292 (1976).

[4] J. F. Gunion, G. L. Kane, and J. Wudka, Nucl. Phys. **B299**, 231 (1988).

[5] R. Bates, J. N. Ng, and P. Kalyniak, Phys. Rev. D **34**, 172 (1986).

[6] R. Martínez, M. A. Pérez, and J. J. Toscana, Phys. Rev. D **40**, 1722 (1989).

[7] A. Grau and J. A. Grifols, Phys. Lett. **154B**, 283 (1985).

[8] R. Alcorta, J. A. Grifols, and S. Peris, Mod. Phys. Lett. A **2**, 23 (1987).

[9] J. A. Grifols, S. Peris, and J. Solá, Phys. Lett. B **197**, 437 (1987).

[10] J. A. Grifols and S. Peris, Int. J. Mod. Phys. A **3**, 225 (1988).

[11] G. L. Kane, J. Vidal, and C. P. Yuan, Phys. Rev. D **39**, 2617 (1989).

[12] F. Boudjema, K. Hagiwari, C. Hamzaoui, and K. Mumata, Phys. Rev. D **43**, 2223 (1991).

[13] G. Bélanger, F. Boudjema, and D. London, Phys. Rev. Lett. **65**, 2943 (1990).

[14] F. Boudjema, C. P. Burgess, C. Hamzaoui, and J. A. Robinson, Phys. Rev. D **43**, 3683 (1991).

[15] G. Couture, S. Godfrey, and R. Lewis, Phys. Rev. D **45**, 777 (1992).

[16] S. Godfrey, Report No. OCIP-91-2, 1991 (unpublished).

[17] E. Yehudai, Phys. Rev. D **41**, 33 (1990).

[18] E. Yehudai, Phys. Rev. D **44**, 3434 (1991).

[19] G. Couture and J. N. Ng, Z. Phys. C **35**, 65 (1987).

[20] G. Couture, J. N. Ng, J. L. Hewett, and T. G. Rizzo, Phys. Rev. D **36**, 859 (1987).

[21] G. Couture, J. N. Ng, J. L. Hewett, and T. G. Rizzo, Phys. Rev. D **38**, 860 (1988).

[22] J. F. Gunion, H. E. Haber, G. L. Kane, and S. Dawson, *The Higgs Hunter's Guide* (Addison-Wesley, Redwood City, CA, 1990).

[23] J. J. van de Bij and E. W. N. Glover, Phys. Lett. B **206**, 701 (1988).

[24] H. König, Z. Phys. C **44**, 401 (1989).