Bounds on Higgs and Gauge–Boson Interactions from LEP2 Data

O. J. P. Éboli $^{1,2}$, M. C. Gonzalez-Garcia $^{1,3}$, S. M. Lietti $^{1}$ and S. F. Novaes $^{1}$

$^{1}$ Instituto de Física Teórica, Universidade Estadual Paulista,
Rua Pamplona 145, 01405–900 São Paulo, Brazil.

$^{2}$ Physics Department, University of Wisconsin, Madison, WI 53706, USA.

$^{3}$ Instituto de Física Corpuscular IFIC/CSIC, Departament de Física Teòrica
Universitat de València, 46100 Burjassot, València, Spain.

(February 20, 1998)

Abstract

We derive bounds on Higgs and gauge–boson anomalous interactions using the LEP2 data on the production of three photons and photon pairs in association with hadrons. In the framework of $SU(2)_L \otimes U(1)_Y$ effective Lagrangians, we examine all dimension–six operators that lead to anomalous Higgs interactions involving $\gamma$ and $Z$. The search for Higgs boson decaying to $\gamma \gamma$ pairs allow us to obtain constrains on these anomalous couplings that are comparable with the ones originating from the analyses of $p\bar{p}$ collisions at the Tevatron. Our results also show that if the coefficients of all “blind” operators are assumed to have same magnitude, the indirect constraints on the anomalous couplings obtained from this analyses, for Higgs masses $M_H \lesssim 140$ GeV, are more restrictive than the ones coming from the $W^+W^-$ production.

14.80.Cp, 13.85.Qk

Typeset using REVTEX
In the last few years it has been established that the interactions of the gauge bosons with the fermions are well described by the Standard Model (SM) [1]. However, we are just beginning to directly probe the self–interactions of the electroweak gauge bosons through their pair production at the Tevatron [2] and LEP2 [3] colliders.

On the other hand, we still do not have any experimental evidence on how the symmetry breaking takes place in the SM. A larger symmetry breaking sector can introduce modifications in the interactions of the vector and Higgs bosons predicted by the SM. These possible deviations of the gauge–boson couplings from their SM values can be parametrized through the use of effective Lagrangians. When the $SU(2)_L \otimes U(1)_Y$ symmetry is realized linearly in the effective theory, i.e. when there is a light scalar Higgs doublet in the spectrum, the lowest order anomalous interactions are given by dimension–six operators [4]. These new interactions can alter considerably the low energy phenomenology. For instance, some operators can give rise to anomalous $H\gamma\gamma$ and $HZ\gamma$ couplings which may affect the Higgs boson production and decay [5].

It is important to notice that, since the linearly realized effective Lagrangians relate the modifications in the Higgs couplings to the ones in the vector boson vertex [4–8], the search for Higgs bosons can be used to not only study its properties, but also to place bounds on the gauge–boson self interactions. This approach is more efficient when the analyses is performed for decays of the Higgs boson that are suppressed in the SM, such as $H \rightarrow \gamma\gamma$ that occurs only at one loop level, and are enhanced by new anomalous interactions [9,10].

In this work, we use the recently released LEP data on the production of $\gamma\gamma$ in association with hadrons [11] and $\gamma\gamma\gamma$ [12] to constrain possible Higgs–boson anomalous couplings to vector–bosons. Working with effective operators linearly invariant under the $SU(2)_L \otimes U(1)_Y$, we obtain indirect limits on anomalous gauge–boson interactions from the search of Higgs bosons decaying into two photons. Our results show that, for Higgs masses $M_H \lesssim 140$ GeV, the constraints on anomalous couplings obtained from this analyses are more restrictive than the ones coming from the $W^+W^−$ production.

In the linear representation of the $SU(2)_L \otimes U(1)_Y$ symmetry breaking mechanism, the
SM model is the lowest order approximation while the first corrections, which are of dimension six, can be written as

\[ \mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n \]  

(1)

where the operators \( \mathcal{O}_n \) involve vector–boson and/or Higgs–boson fields with couplings \( f_n \).

This effective Lagrangian describes well the phenomenology of models that are somehow close to the SM since a light Higgs scalar doublet is still present at low energies. Of the eleven possible operators \( \mathcal{O}_n \) that are \( P \) and \( C \) even, only six of them modify the Higgs–boson couplings to vector bosons \[3,8\],

\[ \begin{align*}
\mathcal{O}_{BB} &= \Phi^\dagger \hat{B}^{\mu\nu} \Phi, \\
\mathcal{O}_{WW} &= \Phi^\dagger \hat{W}^{\mu\nu} \Phi, \\
\mathcal{O}_{BW} &= \Phi^\dagger \hat{B}^{\mu\nu} \hat{W}^{\mu\nu} \Phi, \\
\mathcal{O}_{W} &= (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi), \\
\mathcal{O}_{B} &= (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi), \\
\mathcal{O}_{\Phi,1} &= (D_\mu \Phi)^\dagger \Phi^\dagger (D^\mu \Phi),
\end{align*} \]  

(2)

where \( \Phi \) is the Higgs doublet, \( D_\mu \) the covariant derivative, \( \hat{B}^{\mu\nu} = i(g'/2)B^{\mu\nu} \), and \( \hat{W}^{\mu\nu} = i(g/2)\sigma^a W^a_{\mu\nu} \), with \( B^{\mu\nu} \) and \( W^a_{\mu\nu} \) being respectively the \( U(1)_Y \) and \( SU(2)_L \) field strength tensors.

Anomalous \( H\gamma\gamma, HZ\gamma, \) and \( HZZ \) couplings are generated by \[3\], which, in the unitary gauge, are given by

\[ \mathcal{L}_{\text{eff}}^H = g_{H\gamma\gamma} H A_{\mu\nu} A^{\mu\nu} + g_{HZ\gamma}^{(1)} A_{\mu\nu} Z^\mu \partial^\nu H + g_{HZ\gamma}^{(2)} H A_{\mu\nu} Z^{\mu\nu} + g_{HZZ}^{(1)} Z_{\mu\nu} Z^\mu \partial^\nu H + g_{HZZ}^{(2)} H Z_{\mu\nu} Z^{\mu\nu} + g_{HZZ}^{(3)} H Z_{\mu\nu} Z^{\mu\nu}, \]  

(3)

where \( A(Z)_{\mu\nu} = \partial_\mu A(Z)_\nu - \partial_\nu A(Z)_\mu \). The effective couplings \( g_{H\gamma\gamma}, g_{HZ\gamma}^{(1,2)}, \) and \( g_{HZZ}^{(1,2,3)} \) are related to the coefficients of the operators appearing in \(3\) through,

\[ g_{H\gamma\gamma} = -\left( \frac{g_{M_W}}{\Lambda^2} \right) \frac{s^2(f_{BB} + f_{WW} - f_{BW})}{2}, \]

where \( g_{M_W} \) is the weak coupling constant.
\[ g^{(1)}_{HZZ} = \left( \frac{g M_W}{\Lambda^2} \right) \frac{c^2 f_W + s^2 f_B}{2c^2}, \]
\[ g^{(2)}_{HZZ} = -\left( \frac{g M_W}{\Lambda^2} \right) \frac{s^4 f_{BB} + c^4 f_{WW} + c^2 s^2 f_{BW}}{2c^2}, \]
\[ g^{(3)}_{HZZ} = 2 \left( \frac{M_W^3}{g \Lambda^2} \right) \frac{f_{\Phi,1}}{c^2}, \]

with \( g \) being the electroweak coupling constant, and \( s(c) \equiv \sin(\cos)\theta_W \).

The operators \( O_{\Phi,1} \) and \( O_{BW} \) contribute at tree level to the vector–boson two–point functions, and consequently are severely constrained by the low–energy data \[8\]. The present limits on these operators for \( M_H = 100 \text{ GeV} \) and \( m_{\text{top}} = 175 \text{ GeV} \) read \[13\],
\[ \left| \frac{f_{\Phi,1}}{\Lambda^2} \right| = (0.3 \pm 0.16) \text{ TeV}^{-2}, \quad \left| \frac{f_{BW}}{\Lambda^2} \right| = (3.7 \pm 2.4) \text{ TeV}^{-2}. \] (5)

Consequently we will neglect these operators in our analyses. On the order hand, the remaining operators are indirectly constrained via their one–loop contributions to low energy observables, which leads to \( f_i/\Lambda^2 \sim 100 \text{ TeV}^{-2} \). The present data on gauge–boson pair production leads to the following 95\% CL bounds on anomalous couplings \[2,3\],
\[ \left| \frac{f_{W}}{\Lambda^2} \right| < 300 \text{ TeV}^{-2}, \quad \left| \frac{f_{B}}{\Lambda^2} \right| < 390 \text{ TeV}^{-2}. \] (6)

In order to obtain constraints on the anomalous couplings described above, we have used the recent OPAL data \[11,12\] for the reactions,
\[ e^+e^- \rightarrow \gamma \gamma \gamma, \] (7)
\[ e^+e^- \rightarrow \gamma \gamma + \text{ hadrons}. \] (8)

The Feynman diagrams describing the anomalous contributions to the above reactions are displayed in Fig. 1. The scattering amplitudes were generated using Madgraph \[14\] and Helas \[15\], with the anomalous couplings, arising from the operators (2), being implemented as Fortran routines. In Refs. \[11,12\], data taken at several energy points in the range
\[ \sqrt{s} = 130(91)\text{--}172, \] for the \( \gamma\gamma \) (\( \gamma\gamma \) + hadrons) are combined. In our calculation we also combined the expected number of events for the corresponding energies and accumulated luminosities.

It is important to notice that the dimension-six operators (2) do not induce 4–point anomalous couplings like \( ZZ\gamma\gamma, Z\gamma\gamma\gamma, \) and \( \gamma\gamma\gamma\gamma, \) being these terms generated only by dimension–eight and higher operators. Since the production and decay of the Higgs boson also involve two dimension–six operators, we should, in principle, include in our calculations dimension–eight operators that contribute to the above processes. Notwithstanding, we can neglect the higher order interactions and bound the dimension–six couplings under the naturalness assumption that no cancelation takes place amongst the dimension–six and –eight contributions that appear at the same order in the expansion.

We start our analyses assuming that the only non–zero coefficients are the ones that generate the anomalous \( H\gamma\gamma, \) i.e., \( f_{BB} \) and \( f_{WW}. \) We exhibit in Figs. 2 and 3 the 95% CL exclusion region in the plane \( f_{BB} \times f_{WW} \) obtained from the OPAL data on multiple photon production [12] and diphoton events exhibiting hadrons [11]. In this analyses we set all other anomalous couplings to zero and evaluated only the anomalous contribution as the SM backgrounds were already subtracted in the experimental results. For small Higgs masses (see Fig. 2) the \( Z, \) which decays hadronically, can be produced on mass shell and, therefore, the strongest bounds come from the diphoton production in association with hadrons. Since the anomalous contribution to \( H\gamma\gamma \) is zero for \( f_{BB} = -f_{WW}, \) the bounds become very weak close to this line, as is clearly shown in Fig. 2. For higher Higgs–boson masses (\( M_H \gtrsim 80 \) GeV), the \( Z \) cannot be on–mass shell, and the \( \gamma\gamma \) production accompanied by hadrons is suppressed. In this case, only the \( \gamma\gamma\gamma \) final state is able to lead to new bounds. Moreover, the anomalous production of a \( H\gamma \) pair is also suppressed by the phase space as \( M_H \) increases and the limits worsen, as we can see from Fig. 3. It is interesting to notice that the bounds obtained using the above processes are of the same order of the ones that can be extracted from the Tevatron collider for small Higgs boson masses (\( M_H \lesssim 80 \) GeV). For the sake of comparison, we present in Fig. 4 the contours in the \( f_{BB} \times f_{WW} \) plane from
analyses of $e^+e^-\rightarrow \gamma\gamma\gamma$ and from $p\bar{p}\rightarrow H(\rightarrow \gamma\gamma)+E_T$ [10]. Therefore, LEP2 should lead to more stringent bounds on dimension–six operators with the increase of its accumulated luminosity.

In order to reduce the number of free parameters and, at the same time, relate the anomalous Higgs and the triple vector–boson couplings, one can make the assumption that all blind operators affecting the Higgs interactions have a common coupling $f$, \textit{i.e.}

$$f_W = f_B = f_{WW} = f_{BB} = f,$$

and that $f_{\Phi,1} \simeq f_{BW} \simeq 0$ [3,8,16]. In this scenario, $g_{HZZ}^{(1)} = g_{HZZ}^{(3)} = 0$, and we can relate the Higgs boson anomalous coupling $f$ with the conventional parametrization of the vertex $WWV$ ($V = Z, \gamma$) [17]

$$\Delta \kappa_{\gamma} = \frac{M_W^2}{\Lambda^2} f, \quad \Delta \kappa_Z = \frac{M_Z^2}{2\Lambda^2} (1-2s^2) f, \quad \Delta g_1^Z = \frac{M_Z^2}{2\Lambda^2} f.$$ (10)

We present in Table I the 95\% CL allowed regions of the anomalous couplings in the scenario defined by Eq. (9). In this framework, the bounds become weaker with the increase of the Higgs boson mass. The production of diphotons in association with hadrons is again important only when its is possible to produce a pair $HZ$ on mass shell. Using the relations (10), it is possible to translate these bounds into limits on triple gauge bosons couplings $\Delta \kappa_{\gamma}$, $\Delta \kappa_Z$, and $\Delta g_1^Z$, which we show in Table I for the $\gamma\gamma\gamma$ production. As can be seen from this Table, the search for Higgs bosons decaying into photon pairs leads to limits substantially better then the ones derived from the recent analyses of $W^+W^-$ production at LEP2 [3].

Summarizing, in this work we have estimated the limits on anomalous dimension–six Higgs boson interactions that can be derived from the existing data on the search for Higgs bosons decaying into two photons at LEP2. The bounds that arise from the anomalous Higgs boson searches at LEP2 are as restrictive as the ones obtained at the Tevatron for small Higgs masses ($M_H \lesssim 80$ GeV). Under the assumption of equal coefficients for all anomalous Higgs operators, these bounds also lead to limits on triple–gauge–boson couplings. Our results show that the limits obtained through this search are more restrictive than the ones derived from the $W$ pair production analyses.
ACKNOWLEDGMENTS

We would like to thank Kirsten Sachs and Peter Maettig from valuable discussions. M. C. G–G is grateful to the Instituto de Física Teórica for its kind hospitality. O. J. P. E. is grateful to the Physics Department of University of Wisconsin, Madison for its kind hospitality. This work was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), by DGICYT under grant PB95-1077, by CICYT under grant AEN96–1718, and by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, and by the U.S. Department of Energy under Grant No. DE-FG02-95ER40896.
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TABLES

| $M_H$(GeV) | $e^+e^- \rightarrow \gamma\gamma\gamma$ | $e^+e^- \rightarrow q\bar{q}\gamma\gamma$ |
|------------|--------------------------------------|--------------------------------------|
| 60         | (−56, 50)                            | (−24, 35)                            |
| 80         | (−53, 49)                            | (−107, 128)                          |
| 100        | (−64, 57)                            | (−730, 750)                          |
| 120        | (−82, 70)                            | —                                     |
| 140        | (−192, 175)                          | —                                     |

**TABLE I.** Allowed range of $f/\Lambda^2$ in TeV$^{-2}$ at 95% CL coming from the processes $e^+e^- \rightarrow \gamma\gamma\gamma$ and $e^+e^- \rightarrow q\bar{q}\gamma\gamma$ at LEP2. We assumed the scenario defined by Eq. (9).

| $M_H$(GeV) | $\Delta\kappa_\gamma$ | $\Delta\kappa_Z$ | $\Delta g_1^Z$ |
|------------|------------------------|-------------------|----------------|
| 60         | (−0.36, 0.32)          | (−0.13, 0.11)     | (−0.23, 0.21)  |
| 80         | (−0.34, 0.32)          | (−0.12, 0.11)     | (−0.22, 0.21)  |
| 100        | (−0.41, 0.37)          | (−0.15, 0.13)     | (−0.26, 0.24)  |
| 120        | (−0.53, 0.45)          | (−0.19, 0.16)     | (−0.34, 0.29)  |
| 140        | (−1.24, 1.13)          | (−0.44, 0.40)     | (−0.80, 0.73)  |

**TABLE II.** 95% CL allowed range of $\Delta\kappa_\gamma$, $\Delta\kappa_Z$, and $\Delta g_1^Z$ obtained from the analyses of $\gamma\gamma\gamma$ production, assuming the scenario defined by Eq. (9).
FIG. 1. Anomalous contribution for the $\gamma\gamma\gamma$ production (a) and $\gamma\gamma$ in association with hadrons (b).
FIG. 2. Contour plot of $f_{BB} \times f_{WW}$, in TeV$^{-2}$. The curves show the 95% CL deviations from the SM total cross section, for $e^+e^- \rightarrow \gamma\gamma\gamma$ (dark lines) and $e^+e^- \rightarrow q\bar{q}\gamma\gamma$ (light lines) for (a) $M_H = 60$ GeV and (b) $M_H = 80$ GeV. The excluded regions are outside the lines.
FIG. 3. Contour plot of $f_{BB} \times f_{WW}$, in TeV$^{-2}$. The curves show the 95% CL deviations from the SM total cross section, for $e^+e^- \rightarrow \gamma\gamma\gamma$ with $M_H = 100$ GeV (dark lines), and $M_H = 120$ GeV (light lines).
FIG. 4. Contour plot of $f_{BB} \times f_{WW}$, in TeV$^{-2}$. The curves show the 95% CL deviations from the SM total cross section, for $e^+e^- \rightarrow \gamma\gamma\gamma$ with $M_H = 80$ GeV (dark lines) and $p\bar{p} \rightarrow \gamma\gamma + E_T$ at Tevatron with $M_H = 80$ GeV (light lines).