New Higgs Couplings at Tevatron

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We investigate the potentiality of CERN LEP and Fermilab Tevatron colliders to establish bounds on new couplings involving the bosonic sector of the standard model. A combined exclusion plot for the coefficients of different dimension–6 anomalous operators is presented. We also discuss the sensitivity that can be achieved at the upgraded Tevatron.

EFFECTIVE LAGRANGIANS FOR HIGGS INTERACTIONS

The effective Lagrangian is a model–independent approach to describe new physics that is expected to manifest itself at an energy scale $\Lambda$, larger than the scale where the experiments are performed. The effective Lagrangian can be constructed out of higher dimensional operators and depends only on the particle content of the low energy theory. We consider here the possibility of having a light Higgs boson that should be contained in these operators. Hence, we assume a linearly realized \[SU(2)\times U(1)\] invariant effective Lagrangian to describe the bosonic sector of the SM, keeping the fermionic sector unchanged.

There are eleven dimension–6 operators involving the gauge bosons and the Higgs scalar field which respect local $SU(2)\times U(1)$ and $C$ and $P$ symmetries \[1\]. Six of these operators either affect only the Higgs self–interactions or contribute to the gauge boson two–point functions at tree level and are severely constrained from low energy physics below the present sensitivity of high energy experiments \[2\]. From the remaining five “blind” operators, four affect the Higgs couplings and cannot be constrained by the study of anomalous trilinear gauge boson couplings.

\[\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^2} \left[ f_W(D_\mu \Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu \Phi) + f_B(D_\mu \Phi)^\dagger \tilde{B}^{\mu\nu}(D_\nu \Phi) + f_{WW}(D_\mu \Phi)^\dagger \tilde{W}_\mu^{\mu\nu}\Phi + f_{BB}(D_\mu \Phi)^\dagger \tilde{B}_\mu^{\mu\nu}\Phi \right] \]  \hspace{1cm} (1)

where $\Phi$ is the Higgs field doublet, $\tilde{U}$ and $\tilde{Y}$ strength tensors of the $SU(2)$ and $SU(2)$ gauge fields respectively. Anomalous $H\gamma\gamma$, $HZ\gamma$, and $HZZ$ and $HWW$ couplings are generated by \[1\], which modify the Higgs boson production and decay \[3\]. The field strength tensors of the $U(1)$ and $SU(2)$ gauge fields are

\[\frac{g}{\sqrt{2}} \left[ g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + g_{HZZ} A_{\mu\nu} Z^{\mu\nu} \partial^\alpha H + g_{HW} HA_{\mu\nu} Z^{\mu\nu} + g_{HZZ} Z_{\mu\nu} Z^{\mu\nu} \partial^\alpha H \right] + \left( g_{HWW} W_{\mu\nu} W^{\mu\nu} - \frac{1}{2} g_{HWW} W_{\mu\nu} W_{\mu\nu} \right) \] \hspace{1cm} (2)

where $A(Z)_{\mu\nu} = \partial_\mu A(Z)_\nu - \partial_\nu A(Z)_\mu$. The effective couplings $g_{H\gamma\gamma}$, $g_{HZZ}$, and $g_{HW}$ are related to the coefficients of the operators appearing in (1) and can be found elsewhere \[3\]. Of special interest in our analysis is the Higgs couplings to two photons which is given by

\[g_{H\gamma\gamma} = \left( g \sin^2 \theta_W \frac{M_W}{2\Lambda^2} \right) \left( f_{BB} + f_{WW} \right) \] \hspace{1cm} (3)

Equation (3) also generates new contributions to the triple gauge boson vertex \[1\]. The operators $O_W$ and $O_B$ give rise to both anomalous Higgs–gauge boson couplings and to new triple and quartic self–couplings amongst the gauge bosons. On the other hand $O_{WW}$ and $O_{BB}$ only affect $HVV$ couplings and cannot be constrained by the study of anomalous trilinear gauge boson couplings.

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Anomalous Higgs boson couplings have been studied in Higgs and $Z^0$ boson decays \cite{1}, in $e^+e^-$ \cite{4–7} and in $p\bar{p}$ collisions \cite{8–11}. Let us first summarize the combined bounds on anomalous Higgs boson interactions taking into account both Tevatron \cite{12–14} and LEP \cite{15} data on the following signatures:

| Process | Anomalous Higgs Contribution | Exp. Search |
|---------|-----------------------------|-------------|
| $p\bar{p} \rightarrow jj\gamma\gamma$ | $p\bar{p} \rightarrow W(Z)\rightarrow jj + H(\rightarrow \gamma\gamma)$ | DØ \cite{12} |
| $p\bar{p} \rightarrow \gamma\gamma + E_T$ | $p\bar{p} \rightarrow Z^0(\rightarrow \nu\bar{\nu}) + H(\rightarrow \gamma\gamma)$ | DØ \cite{13} |
| $p\bar{p} \rightarrow \gamma\gamma\gamma$ | $p\bar{p} \rightarrow \gamma + H(\rightarrow \gamma\gamma)$ | CDF \cite{14} |
| $e^+e^- \rightarrow \gamma\gamma\gamma$ | $e^+e^- \rightarrow \gamma + H(\rightarrow \gamma\gamma)$ | OPAL \cite{15} |

Events containing two photons plus missing energy, additional photons or charged fermions represent a signature for several theories involving physics beyond the SM and they have been extensively searched for \cite{12–15}. In the framework of anomalous Higgs couplings presented before, they can arise from the production of a Higgs boson which subsequently decays in two photons [second column in Eq.(4)]. In the SM, the decay width $H \rightarrow \gamma\gamma$ is very small since it occurs just at one–loop level but the existence of the new interactions (2) can enhance this width in a significant way. Recent analyses of these signatures showed a good agreement with the expectations from the SM. Thus we can employ these negative experimental results to constrain new anomalous couplings in the bosonic sector of the SM.

FIG. 1. (a) Exclusion region outside the curves in the $f_{BB}/\Lambda^2$ plane, in TeV$^{-2}$, based on the DØ analysis \cite{12} of $\gamma\gamma jj$ production, on the DØ analysis \cite{13} of $\gamma\gamma E_T$, on the CDF analysis \cite{14} of $\gamma\gamma\gamma$ production, and on the OPAL analysis \cite{15} of $\gamma\gamma\gamma$ production, always assuming $M_H = 100$ GeV. The curves show the 95% CL deviations from the SM total cross section. (b) Same as (a) for the combined analysis.

All processes listed in (4) have been the object of direct experimental searches, and in our analysis we have closely followed these searches in order to make our study as realistic as possible. In this way we start by the process $p\bar{p} \rightarrow W(Z)\rightarrow jj + H(\rightarrow \gamma\gamma)$ \cite{8} to constrain the anomalous Higgs boson couplings described in (2). DØ Collaboration reported the results for the search of high invariant–mass photon pairs in $p\bar{p} \rightarrow \gamma\gamma jj$ events \cite{12} at $\sqrt{s} = 1.8$ TeV and 100 pb$^{-1}$ of integrated luminosity where no event with two–photon invariant mass in the range $100 < M_{\gamma\gamma} < 220$ was observed. In our analysis, we applied the same cuts of Ref. \cite{12} and included the particle identification and trigger efficiencies. We have searched for Higgs boson with mass in the range $100 < M_H < 220$, since after the $WW(ZZ)$ threshold is reached the diphoton branching ratio of Higgs is quite reduced.

For events containing two photons plus large missing transverse energy ($\gamma\gamma E_T$) \cite{15} we have used the results from DØ collaborations \cite{13} which reported that no event with two–photon invariant mass in the range $100 < M_{\gamma\gamma} < 2M_W$...
was observed. Anomalous Higgs couplings can give rise to this final state via the contributions listed in the second column, third line of Eq.(4) where in the second subprocess the charged lepton ($\ell = e, \mu$) escapes undetected. In order to compare our predictions with the results of DO Collaboration [13], we have applied the same cuts of last article in Ref. [13]. After these cuts, we find that 80% to 90% of the signal comes from associated Higgs–Z$^0$ production while 10% to 20% arises from Higgs–W. We also include in our analysis the particle identification and trigger efficiencies which vary from 40% to 70% per photon.

We have also analysed events with three photons in the final state and compare our results with the recent search reported by CDF Collaboration [14] for this signature. They looked for $\gamma\gamma\gamma$ events requiring two photons in the central region of the detector, with a minimum transverse energy of 12 GeV, plus an additional photon with $E_T > 25$ GeV. The photons were required to be separated by more than 15$^\circ$.

Finally, for events containing three photons in the final state at electron–positron collisions [3], we have used the recent OPAL results [15] where data taken at several energy points in the range $\sqrt{s} = 130 – 172$ GeV were combined.

We have included in our calculations all SM (QCD plus electroweak), and anomalous contributions that lead to these final states. The SM one-loop contributions to the $H\gamma\gamma$ and $HZ\gamma$ vertices were introduced through the use of the effective operators with the corresponding form factors in the coupling. Neither the narrow–width approximation for the Higgs boson contributions, nor the effective $W$ boson approximation were employed. We consistently included the effect of all interferences between the anomalous signature and the SM background. For $p\bar{p}$ processes, we have used the MRS (G) [16] set of proton structure functions with the scale $Q^2 = \hat{s}$.

![f/Λ² (TeV⁻²)](image)

FIG. 2. Excluded region in the $f \times M_H$ plane from the combined analysis of the LEPII and Tevatron searches.

The coupling $H\gamma\gamma$ [3] involves $f_{WW}$ and $f_{BB}$ [3]. In consequence, the anomalous signature $f \bar{f} \gamma\gamma$ is only possible when those couplings are not vanishing. The couplings $f_B$ and $f_W$, on the other hand, affect the production mechanisms for the Higgs boson. In Fig. 1.a we present our results for the excluded region in the $f_{WW}, f_{BB}$ plane from the different channels studied for $M_H = 100$ GeV, assuming that these are the only non–vanishing couplings. Since the anomalous contribution to $H\gamma\gamma$ is zero for $f_{BB} = -f_{WW}$ (see Eq. (3)), the bounds become very weak close to this line, as is clearly shown in Fig. 1. In order to establish these bounds, we imposed an upper limit on the number of signal events based on Poisson statistics. In the absence of background this implies $N_{\text{signal}} < 1 (3)$ at 64% (95%) CL. In the presence of background events, we employed the modified Poisson analysis.

The results obtained from the analysis of the four reactions (4) can be statistically combined in order to constrain the value of the coefficients $f_i$, $i = WW, BB, W, B$ of Eq. (1) [11]. We exhibit in Fig. 1.b the 95% CL exclusion region in the plane $f_{BB} \times f_{WW}$ obtained from combined results.
In order to reduce the number of free parameters one can make the assumption that all blind operators affecting the Higgs interactions have a common coupling $f$, i.e. $f = f_W = f_B = f_{WW} = f_{BB}$. In Fig 2 we present the combined limits for the coupling constant $f = f_{BB} = f_{WW} = f_B = f_W$ for Higgs boson masses in the range of $100 \leq M_H \leq 220$ GeV.

### ATTAINABLE BOUNDS AT FUTURE TEVATRON RUNS

The effect of the anomalous operators becomes more evident with the increase of energy, and therefore, higher sensitive to smaller values of the anomalous coefficients can be achieved by studying their contribution to different processes at the upgraded Tevatron collider. We have considered the Tevatron Run II upgrade, with 1 fb$^{-1}$, and the TeV33 upgrade with 10 fb$^{-1}$. For the reactions $p\bar{p} \rightarrow \gamma\gamma E_T$ and $p\bar{p} \rightarrow \gamma\gamma jj$, we assumed the same cuts and detection efficiencies than at Tevatron Run I. For the $\gamma\gamma$ final state we have studied the improvement on the sensitivity to the anomalous coefficients by implementing additional kinematical cuts. Best results are obtained for the following set of cuts: $E_T > 40$ GeV, with $E_T > 12$ GeV, where we have ordered the three photons according to their transverse energy, i.e. $E_T > E_{T2} > E_{T3}$. We always required the photons to be in the central region of the detector ($|\eta| < 1$) where there is sensitivity for electromagnetic showering. In our estimate, we assumed the same detection efficiency for photons as considered by CDF Collaboration [14] for the Run I.

| $M_H$(GeV) | $f/\Lambda^2$(TeV$^{-2}$) | $p\bar{p} \rightarrow \gamma\gamma$ | $p\bar{p} \rightarrow \gamma\gamma + E_T$ | $p\bar{p} \rightarrow \gamma\gamma jj$ | Combined |
|-----------|-----------------|------------------|-----------------|-----------------|--------|
| 100       | (−24, 24) −13, 15 | (−16, 36) −9.4, 26 | (−9.2, 22) −3.3, 5.6 | (−7.6, 19) −3.0, 5.6 |         |
| 120       | (−26, 26) −14, 14 | (−20, 39) −15, 27 | (−8.6, 21) −3.4, 5.9 | (−7.4, 18) −3.3, 5.9 |         |
| 140       | (−30, 31) −15, 16 | (−25, 44) −14, 30 | (−10, 23) −4.5, 8.9 | (−9.1, 20) −4.0, 8.7 |         |
| 160       | (−36, 38) −17, 19 | (−29, 50) −14, 33 | (−11, 24) −6.0, 14 | (−9.9, 22) −5.1, 13 |         |
| 180       | (−3, −) −63, 72 | −46, 53 | (−26, 34) −16, 24 | (−24, 33) −16, 24 |         |
| 200       | (−3, −) −87, 90 | −50, 53 | (−33, 40) −17, 23 | (−32, 39) −17, 23 |         |
| 220       | (−3, −) −42, 45 | −19, 26 | (−42, 45) −19, 26 | (−42, 45) −19, 26 |         |

**TABLE I.** 95% CL allowed range for $f/\Lambda^2$, from $\gamma\gamma$, $\gamma\gamma + E_T$, $\gamma\gamma jj$ production at Tevatron Run II [TeV33] assuming all $f_i$ to be equal. We denote by ‘—’ limits worse than $|f| = 100$ TeV$^{-2}$.

In Table I, we present the 95% CL limit on the anomalous couplings for Tevatron Run II and TeV33 for each individual process. All couplings are assumed equal ($f = f_{BB} = f_{WW} = f_B = f_W$) and the Higgs boson mass is varied in the range $100 \leq M_H \leq 220$ GeV. Combination of the results obtained from the analysis of the first three reactions in Eq. (1) leads to the improved bounds given in the last column of Table I. Comparing these results with those in Fig. 2 we observe an improvement of about a factor $\sim 2–3$ ($\sim 4–6$) for the combined limits at Run II (TeV33).

As mentioned above for the conventional realization of effective Lagrangians, the modifications introduced in the Higgs and in the vector boson sector are related to each other. In consequence the bounds on the new Higgs couplings should also restrict the anomalous gauge–boson self interactions. Under the assumption of equal coefficients for all anomalous Higgs operators, we can relate the common Higgs boson anomalous coupling $f$ with the conventional parametrization of the vertex $WWV$ ($V = Z^0, \gamma$) [17],

$$\Delta\kappa = \frac{M_Z^2}{\Lambda^2} f = \frac{2\cos^2\theta_W}{1 - 2\sin^2\theta_W} \Delta\kappa_Z = 2\cos^2\theta_W \Delta g_1^Z$$

(5)

A different set of parameters has been also used by the LEP Collaborations in terms of three independent couplings, $\alpha_{B\Phi}$, $\alpha_{W\Phi}$, and $\alpha_W$. These parameters are related to the parametrization of Ref. [17] through $\alpha_{B\Phi} \equiv \Delta\kappa - \Delta q_1^2 \cos^2\theta_W$, $\alpha_{W\Phi} \equiv \Delta g_2^Z \cos^2\theta_W$, $\alpha_W \equiv \lambda$. The current experimental limit on these couplings from combined results on double gauge boson production at Tevatron and LEP II [18] is $-0.15 < \Delta\kappa < 2\alpha < 0.41$ at 95% CL. This limit is derived under the relations given in Eq. (3) [19].

In Table II, we present the 95% CL limit of the anomalous coupling $\Delta\kappa$, using the limits on $f/\Lambda^2$ obtained through the analysis of the processes [20]. We also present the expected bounds that will be reachable at the upgraded Tevatron. Our results show that the present combined limit from the Higgs production analysis obtained in this paper is comparable with the existing bound from gauge boson production for $M_H \leq 170$ GeV.
\[ \Delta \kappa_\gamma = 2 \alpha = 2 \alpha B \Phi = 2 \alpha W \Phi \]

| Process                              | \[ -0.084, 0.204 \] | \[ -0.048, 0.122 \] | \[ -0.020, 0.036 \] |
|--------------------------------------|-------------------|-------------------|-------------------|
| Combined Tevatron Run I + LEP II     |                   |                   |                   |
| Combined Tevatron Run II             |                   |                   |                   |
| Combined Tevatron TeV33              |                   |                   |                   |

TABLE II. 95% CL allowed range for the anomalous triple gauge boson couplings derived from the limits obtained for the anomalous Higgs boson coupling \( f \) for \( M_H = 100 \) GeV.

Summarizing, we have estimated the limits on anomalous dimension–six Higgs boson interactions that can be derived from the investigation of three photon events at LEP2 and Tevatron and diphoton plus missing transverse energy events or dijets at Tevatron. Under the assumption that the coefficients of the four “blind” effective operators contributing to Higgs–vector boson couplings are of the same magnitude, the study can give rise to a significant indirect limit on anomalous \( WWV \) couplings. We have also studied the expected improvement on the sensitivity to Higgs anomalous couplings at the Fermilab Tevatron upgrades.

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