Abstract

We derive bounds on Higgs and gauge–boson anomalous interactions using the CDF data for the process $p\bar{p} \rightarrow \gamma\gamma\gamma + X$. We use a linearly realized $SU_L(2) \times U_Y(1)$ invariant effective Lagrangian to describe the bosonic sector of the Standard Model, keeping the fermionic couplings unchanged. All dimension–six operators that lead to anomalous Higgs interactions involving $\gamma$ and $Z$ are considered. We also show the sensitivity that can be achieved for these couplings at Fermilab Tevatron upgrades.
We certainly expect the Standard Model (SM), despite its astonishing success in describing all the precision high energy experimental data so far [1], to be an incomplete picture of Nature at high energy scales. In particular, the Higgs sector of the model, responsible for the spontaneous electroweak symmetry breaking and for mass generation, is not fully satisfactory since it has to be introduced in an *ad hoc* fashion. Furthermore, this scalar sector has not yet been experimentally verified.

Although we do not know the specific model which will eventually supersede the SM, we can always parametrize its effects at low energies by means of an effective Lagrangian [2] that involves operators with dimension higher than four, containing the relevant fields at low energies and respecting the symmetries of the Standard Model. The effective Lagrangian approach is a model–independent way to describe new physics that can occur at an energy scale $\Lambda$ much larger than the scale where the experiments are performed.

The effective Lagrangian depends on the particle content at low energies and here we will consider the possibility that the Higgs boson can be light, being present in the higher dimensional operators, in addition to the electroweak gauge bosons. Hence we will use a linearly realized $SU_L(2) \times U_Y(1)$ invariant effective Lagrangian to describe the bosonic sector of the Standard Model, keeping the fermionic couplings unchanged. The 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 Lagrangian relates the modifications in the Higgs couplings to the ones in the vector boson vertex [5,3,4], the search for Higgs bosons can be used not only to study its properties, but also to place bounds on the gauge boson self–interactions. This approach is more efficient when the analysis is performed for decays of the Higgs boson that are suppressed in the SM, such as $H \rightarrow \gamma\gamma$ that occurs only at the one loop level, and are enhanced by new anomalous interactions.

Events containing two photons plus additional missing energy, photons or charged fermions represent a signature for several models involving physics beyond the SM such as
some classes of supersymmetric models [6]. Recently, the CDF collaboration have reported
the search for the signature $\gamma\gamma + X$, where $X =$ jets, leptons, gauge bosons ($W$, $Z$, $\gamma$) or
just missing energy in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV [7]. Their analysis indicates a good
agreement with the expectations from the Standard Model (SM). In this way, they were able
to set limits on the production cross section $\sigma(p\bar{p} \rightarrow \gamma\gamma E_T + X)$ in particular in the light
gravitino scenario.

In this work, we point out that the experimental search for $\gamma\gamma\gamma$ events contained in the
CDF analysis can place constraints on new physics in the bosonic sector of the SM. For
instance, associated Higgs–$\gamma$ boson production, with the subsequent decay of the Higgs into
two photons can yield this signature. In the SM, the decay width $H \rightarrow \gamma\gamma$ is very small
since it occurs just at one–loop level [8]. However, the existence of new interactions can
enhance this width in a significant way. These anomalous Higgs boson couplings have also
been studied before in Higgs and $Z$ boson decays [5], in $e^+e^-$ [11,12], $p\bar{p}$ [1,4] and $\gamma\gamma$
colliders [12]. Here we shall show how to bound these new couplings by analyzing their effects on the
process $p\bar{p} \rightarrow \gamma\gamma\gamma + X$ at the Fermilab Tevatron.

In order to write down the most general dimension–6 effective Lagrangian containing
all SM bosonic fields, i.e. $\gamma$, $W^\pm$, $Z^0$, and $H$, we adopt the notation of Hagiwara et al.
[4]. This Lagrangian has eleven independent operators in the linear representation that are
locally $SU_L(2) \times U_Y(1)$ invariant, $C$ and $P$ even. We discard the four operators which affect
the gauge boson two–point functions at tree–level and therefore are strongly constrained by
LEP measurements. We also do not consider the three operators that modify only the Higgs
or vector boson self–interactions, since they are not relevant for our calculations. We are
then left with four independent operators, and the Lagrangian is written as,

$$L_{\text{eff}} = L_{\text{SM}} + \frac{1}{\Lambda^2} (f_{WW}O_{WW} + f_{BB}O_{BB} + f_WO_W + f_BO_B) , \quad (1)$$

with the operators $O_i$ defined as,

$$O_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$$

$$O_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \quad (2)$$
\[\mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi)\]
\[\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi),\]

where \(\Phi\) is the Higgs field doublet, \(\hat{B}^{\mu\nu} = i(g'/2)B^{\mu\nu}\), and \(\hat{W}^{\mu\nu} = i(g/2)\sigma^aW^{a\mu\nu}\), with \(B^{\mu\nu}\) and \(W^{a\mu\nu}\) being the field strength tensors of the \(U(1)\) and \(SU(2)\) gauge fields respectively.

Anomalous \(H\gamma\gamma\), \(HZ\gamma\), and \(HZZ\) couplings are generated by (1), which, in the unitary gauge, are given by

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

(3)

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

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

\[g^{(1)}_{HZ\gamma} = \left(\frac{gM_W}{\Lambda^2}\right) \frac{s(f_W - f_B)}{2c},\]

\[g^{(2)}_{HZ\gamma} = \left(\frac{gM_W}{\Lambda^2}\right) \frac{s[2s^2f_{BB} - 2c^2f_{WW}]}{2c},\]
\[g^{(1)}_{HZZ} = \left(\frac{gM_W}{\Lambda^2}\right) \frac{c^2f_W + s^2f_B}{2c^2},\]
\[g^{(2)}_{HZZ} = -\left(\frac{gM_W}{\Lambda^2}\right) \frac{s^4f_{BB} + c^4f_{WW}}{2c^2},\]

(4)

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

The calculation of the reaction \(p\bar{p} \rightarrow \gamma\gamma\gamma\) was performed using the Helas package [13]. We have constructed new subroutines in order to incorporate the anomalous contributions. The irreducible background subprocesses \(q\bar{q} \rightarrow \gamma\gamma\gamma\) for \(q = u, d, s\) were generated by MadGraph [14] and the new contributions were included. In this way, all the anomalous contributions and their respective interference with the SM were evaluated. We convoluted this subprocess cross sections, using a Monte Carlo integration [15], with the corresponding parton distributions using the MRS (G) [16] set of proton structure functions with the scale given by the parton–parton center–of–mass energy.
The CDF Collaboration [7] search for anomalous $\gamma\gamma$ events has included events that have two photons in the central region of the detector ($|\eta| < 1$), 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 an angle larger the 15°. After applying these cuts, no event was observed, while the expect number from the background is $0.1 \pm 0.1$ in the 85 pb$^{-1}$ collected. Therefore, at 95 % CL this experimental result implies that the signal should have less than 3 events. The efficiency of identification of an isolated photon is $68 \pm 3\%$, for $E_T > 12$ GeV, and grows to $84 \pm 4\%$, for $E_T > 22$ GeV. We have taken into account these efficiencies in our estimate.

It is important to notice that the dimension-six operators (1) 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 analysis by examining which are the bounds that can be placed on the anomalous coefficients from the negative search of 3 photon events made by the CDF Collaboration. We start by assuming that the only non–zero coefficients are the ones that generate the anomalous $H\gamma\gamma$, i.e., $f_{BB}$ and $f_{WW}$. Our results for the 95% CL exclusion region in the plane $f_{BB} \times f_{WW}$, obtained from the CDF data, are presented in Fig. 1. For $f_{BB} = -f_{WW}$ the anomalous contribution to $H\gamma\gamma$ becomes zero, independently of the values of $f_W$ and $f_B$, and the bounds become very weak in this region.

As mentioned above, the coupling $H\gamma\gamma$ derived in Eq. (4) involves $f_{WW}$ and $f_{BB}$. In consequence, the anomalous $\gamma\gamma$ signature is only possible when those couplings are non–vanishing. The couplings $f_B$ and $f_W$, on the other hand, affect the production mechanisms for the Higgs boson. 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.
In this scenario we can relate the Higgs boson anomalous coupling $f$ with the LEP conventional parametrization of the vertex $WWV$ ($V = Z, \gamma$) \[17\] can be written as,

$$\alpha = \alpha_{B\Phi} = \alpha_{W\Phi} = \frac{M_W^2}{2\Lambda^2} f.$$ \hspace{1cm} (5)

Table [1] shows the 95\% CL allowed region of the anomalous couplings in the above scenario. As could be expected, these bounds become weaker as the Higgs boson mass increases. We also show the related bounds in $\alpha = \alpha_{B\Phi} = \alpha_{W\Phi}$ in Table [1].

We now extend our analysis to the upgraded Tevatron collider. We first study the possible improvements in the kinematical cuts in order to get better sensitivity to the anomalous coefficients. First of all, we order the three photons according to their transverse energy, i.e. $E_{T_1} > E_{T_2} > E_{T_3}$, and we adopt a preliminary cut of $E_{T_i} > 12 \text{ GeV}$ and $|\eta_i| < 1$, for all the three photons. In Fig. [4], we show the transverse energy distribution for the three photons for $\sqrt{s} = 2 \text{ TeV}$. Comparison is made between the SM background and the new anomalous distribution for $f = 100 \text{ TeV}^{-2}$, and for a Higgs boson mass of 100 GeV.

These distributions strongly suggest that a cut on the transverse energy of the most energetic photon with a simultaneous cut in transverse energy of the two softest photons can improve the sensitivity. We tried two sets of cuts: (a) $E_{T_1} > 40 \text{ GeV}$ while $E_{T_{2,3}} > 25 \text{ GeV}$, and (b) $E_{T_1} > 40 \text{ GeV}$, with $E_{T_{2,3}} > 12 \text{ GeV}$. Cut (a) leads to a large background reduction of a factor 5.5 but it also reduces the number of signal events by a factor two. So the significance of the signal over the background ($S = N_{\text{Signal}}/\sqrt{N_{\text{Background}}}$) is enhanced only by 17\%. Cut (b) however leads to a smaller background rejection of a factor of 2 without significantly changing the signal. The significance is now improved by a factor of 41\%, so we present our results considering this set of cuts. We always require the photons to be in the central region of the detector ($|\eta_i| < 1$) where there is sensitivity for electromagnetic showering. In our estimates we assume the same detection efficiency for photons as the present CDF efficiencies given above.

After applying the cuts, we obtain the 95\% CL exclusion region in the plane $f_{BB} \times f_{WW}$.
shown in Fig. 1. We have assumed that the upgraded Tevatron collider will reach a centre–of–mass energy of $\sqrt{s} = 2$ TeV with an integrated luminosity of 1 fb$^{-1}$, in the Run II, and of 10 fb$^{-1}$, in the TeV33 run [18]. Again, the $f_{BB} = -f_{WW}$ line is unbounded since the anomalous contribution to $H\gamma\gamma$ is zero in this case.

In Table I, we present the 95% CL limit of the anomalous couplings when all couplings are taken to be equal, for different Higgs boson masses. The associated bounds in $\alpha = \alpha_{B\Phi} = \alpha_{W\Phi}$ are also shown in Table I. These bounds are comparable with the preliminary results of the combinations of measurements from the individual LEP and DØ experiments [19], $\alpha_{B\Phi} = -0.05^{+0.22}_{-0.20}$, and $\alpha_{W\Phi} = -0.03^{+0.06}_{-0.06}$. The comparison is to be taken with a pinch of salt as the LEP–DØ bounds are given for only one coupling different from zero while our bounds hold for $\alpha_{B\Phi} = \alpha_{W\Phi}$.

Summarizing, in this work we have estimated the limits on anomalous dimension–six Higgs boson interactions that can be derived from the investigation of three photon events at the Fermilab Tevatron. We have used the present data from the CDF collaboration and we have estimated the attainable sensitivity at the upgraded Tevatron. Under the assumption of equal coefficients for all anomalous Higgs operators, these bounds also lead to limits on triple–gauge–boson couplings.

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FIG. 1. Exclusion region outside the curves in the $f_{BB} \times f_{WW}$ plane, in TeV$^{-2}$, based on the CDF analysis \cite{7} and Tevatron upgrades of $\gamma\gamma\gamma$ production, assuming $M_H = 100$ GeV. The curves show the 95% CL deviations from the SM total cross section. The outermost curves are based on the CDF analysis, the intermediate curves on the Tevatron Run II analysis, and the innermost curves are based on the Tevatron TeV33 upgrade.
FIG. 2. Transverse momentum distribution of the three photons for $\sqrt{s} = 2$ TeV, for the SM background (dotted line) and for the anomalous contributions (full line). We have taken $M_H = 100$ GeV, and $f_i/\Lambda^2 = 100$ TeV$^{-2}$. 
TABLES

| $M_H$(GeV) | $f/\Lambda^2$(TeV$^{-2}$) | CDF | Tevatron Run II | Tevatron TeV33 |
|------------|-----------------------------|-----|-----------------|----------------|
| 100        | (−61.7, 64.5)              | (−23.2, 23.3) | (−13.7, 13.9) |
| 120        | (−75.5, 76.9)              | (−25.0, 25.0) | (−14.4, 14.5) |
| 140        | (−92.0, 93.2)              | (−29.1, 29.5) | (−15.3, 15.7) |
| 160        | (−113, 115)                | (−34.0, 35.8) | (−16.1, 17.8) |

TABLE I. The minimum and maximum values (min, max) of $f/\Lambda^2$, at 95% CL, from $\gamma\gamma\gamma$ production at CDF and Tevatron upgrades, assuming that all $f_i$ are equal.

| $M_H$(GeV) | $\alpha = \alpha_{B\Phi} = \alpha_{W\Phi}$ | CDF | Tevatron Run II | Tevatron TeV33 |
|------------|-----------------------------------------|-----|-----------------|----------------|
| 100        | (−0.197, 0.206)                        | (−0.074, 0.075) | (−0.044, 0.044) |
| 120        | (−0.242, 0.246)                        | (−0.080, 0.080) | (−0.046, 0.046) |
| 140        | (−0.294, 0.298)                        | (−0.093, 0.094) | (−0.049, 0.050) |
| 160        | (−0.362, 0.368)                        | (−0.109, 0.115) | (−0.052, 0.057) |

TABLE II. The minimum and maximum values (min, max) of $\alpha = \alpha_{B\Phi} = \alpha_{W\Phi}$, at 95% CL, from $\gamma\gamma\gamma$ production at CDF and Tevatron upgrades, assuming that all $f_i$ are equal.