We estimate the attainable limits on the coefficients of dimension–6 operators from the analysis of Higgs boson phenomenology, in the framework of a $SU_L(2) \times U_Y(1)$ gauge–invariant effective Lagrangian. Our results, based on the data sample already collected by the collaborations at Fermilab Tevatron, show that the coefficients of Higgs–vector boson couplings can be determined with unprecedented accuracy. Assuming that the coefficients of all “blind” operators are of the same magnitude, we are also able to impose more restrictive bounds on the anomalous vector–boson triple couplings than the present limit from double gauge boson production at the Tevatron collider.

In the framework of effective Lagrangians respecting the local $SU_L(2) \times U_Y(1)$ symmetry linearly realized, the modifications of the couplings of the Higgs field ($H$) to the vector gauge bosons ($V$) are related to the anomalous triple vector boson vertex. The general set of dimension–6 operators involving gauge bosons and the Higgs field, respecting local $SU_L(2) \times U_Y(1)$ symmetry, and $C$ and $P$ conserving contains eleven operators. Some of these operators either affect only the Higgs self–interactions or contribute to the gauge boson two–point functions at tree level and can be strongly constrained from low energy physics. The remaining five “blind” operators can be written as:

\[
\mathcal{L}_{\text{eff}} = \sum_i \frac{f_i}{\Lambda^2} O_i = \frac{1}{\Lambda^2} \left[ f_{WWW} \, \text{Tr}[W_{\mu\nu} W^{\nu\rho} W^{\rho\mu}] + f_W (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) 
+ f_B (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi) + f_{WW} \Phi (D_\mu W^{\mu\nu} \Phi + f_{BB} \Phi (D_\mu B^{\mu\nu} \Phi) \right] \quad (1)
\]
where $\Phi$ is the Higgs field doublet, and $\hat{B}_{\mu \nu} = i (g'/2) B_{\mu \nu}$, $\hat{W}_{\mu \nu} = i (g/2) \sigma^a W^a_{\mu \nu}$, with $B_{\mu \nu}$ and $W^a_{\mu \nu}$ being the field strength tensors of the $U(1)$ and $SU(2)$ gauge fields respectively.

In the unitary gauge, 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, while the operator $O_{WWW}$ solely modifies the gauge boson self–interactions. Searches for deviations on the couplings $WWW$ ($V = \gamma, Z$) have been carried out at different colliders and recent results include the ones by CDF and DØ Collaborations. Forthcoming perspectives on this search at LEP II CERN Collider, and at upgraded Tevatron Collider were also reported.

The operators $O_{WW}$ and $O_{BB}$ only affect $HVV$ couplings, like $HWV$, $HZZ$, $H\gamma\gamma$ and $HZ\gamma$, since their contribution to the $WW\gamma$ and $WWZ$ tree–point couplings can be completely absorbed in the redefinition of the SM fields and gauge couplings. Therefore, one cannot obtain any constraint on these couplings from the study of anomalous trilinear gauge boson couplings. These anomalous couplings were extensively studied in electron–positron collisions.

We consider here Higgs production at the Fermilab Tevatron collider with its subsequent decay into two photons. This channel in the SM occurs at one–loop level and it is quite small, but due to the new interactions, it can be enhanced and even become dominant. We study the associated $HV$ process and the vector boson fusion process, taking into account the 100 pb$^{-1}$ of integrated luminosity already collected by the Fermilab Tevatron collaborations. We focus on the signatures $\ell \nu \gamma \gamma$, ($\ell = e, \mu$), and $jj \gamma \gamma$, coming from the reactions and (3).

Recently, DØ Collaboration has presented their results for the search of high invariant–mass photon pairs in $p \bar{p} \rightarrow \gamma \gamma jj$ events. We show, based on their results, that it may be possible to obtain a significant indirect limit on anomalous $WWV$ coupling under the assumption that the coefficients of the “blind” effective operators contributing to the Higgs–vector boson couplings are of the same magnitude. It is also possible to restrict the operators that involve just Higgs boson couplings, $HVV$, and therefore can not be bounded by the $W^+W^-$ production at LEPII.

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. A total of 42 (32) SM (anomalous) Feynman diagrams are involved in the subprocesses of $\ell\nu\gamma\gamma$ for each leptonic flavor, while 1928 (236) participate in $jj\gamma\gamma$ signature. The SM Feynman diagrams were generated by Madgraph in the framework of Helas. The anomalous contributions arising from the Lagrangian were implemented in Fortran routines and were included accordingly. We have used the MRS (G) set of proton structure functions with the scale $Q^2 = \hat{s}$.

The cuts applied on the final state particles are similar to those used by the experimental collaborations. In particular when studying the $\gamma\gamma jj$ final state we have closely followed the results recently presented by DØ Collaboration. We also assumed an invariant–mass resolution for the two–photons of $\Delta M_{\gamma\gamma}/M_{\gamma\gamma} = 0.15/\sqrt{M_{\gamma\gamma}} \pm 0.007$. Both signal and background were integrated over an invariant–mass bin of $\pm 2\Delta M_{\gamma\gamma}$ centered around $M_H$.

The signature of the $jj\gamma\gamma$ process receives contributions from both associated production and $WW/ZZ$ fusion. We isolate the majority of events due to associated production, and the corresponding background, by integrating over a bin centered on the $W$ or $Z$ mass, which is equivalent to the invariant mass cut listed above.

After imposing all the cuts, we get a reduction on the signal event rate which depends on the Higgs mass. For the $jj\gamma\gamma$ final state the geometrical acceptance and background rejection cuts account for a reduction factor of 15% for $M_H = 60$ GeV rising to 25% for $M_H = 160$ GeV. We also include in our analysis the particle identification and trigger efficiencies which vary from 40% to 70% per particle lepton or photon. For the $jj\gamma\gamma$ ($\ell\nu\gamma\gamma$) final state we estimate the total effect of these efficiencies to be 35% (30%). We therefore obtain an overall efficiency for the $jj\gamma\gamma$ final state of 5.5% to 9% for $M_H = 60$–160 GeV in agreement with the results of Ref. 12.

Dominant backgrounds are due to misidentification when a jet fakes a photon what has been estimated to occur with a probability of a few times $10^{-4}$. Although this probability is small, it becomes the main source of background for the $jj\gamma\gamma$ final state because of the very large multijet cross section. In Ref. 12 this background is estimated to lead to $3.5 \pm 1.3$ events with invariant mass $M_{\gamma\gamma} > 60$ GeV and it has been consistently included in our derivation of the attainable limits.

In the $\ell\nu\gamma\gamma$ channel the dominant fake background is $W\gamma j$ channel, when the jet mimics a photon. We estimated the contribution of this channel to
Table 1: Allowed range of $f/\Lambda^2$ in TeV$^{-2}$ at 95% CL, assuming the scenario (i) ($f_{BB} = f_{WW} \gg f_B, f_W$) for the different final states, and for different Higgs boson masses for an integrated luminosity of 100 pb$^{-1}$.

| $M_H$/GeV | 100  | 150  | 200  | 250  |
|-----------|------|------|------|------|
| $\ell\nu\gamma\gamma$ RunI | (-41 - 74) | (-83 - 113) | (< -200 - > 200) | (< -200 - > 200) |
| RunII | (-13 - 36) | (-22 - 46) | (-57 - 135) | (-195 - > 200) |
| TeV33 | (-3.8 - 8) | (-4.8 - 20) | (-28 - 60) | (-45 - 83) |
| $jj\gamma\gamma$ RunI | (-20 - 49) | (-26 - 64) | (-96 - > 100) | (< -100 - > 100) |
| RunII | (-8.4 - 26) | (-11 - 31) | (-36 - 81) | (-64 - > 100) |
| TeV33 | (-4.2 - 6.5) | (-4.5 - 12) | (-19 - 40) | (-28 - 51) |

yield $N_{back} < 0.01$ events at 95% CL. We have also estimated the various QCD fake backgrounds such as jjj, jj$\gamma$ and jj$\gamma\gamma$ with the jet faking a photon and/or electron plus fake missing mass, which are to be negligible.

The coupling $H\gamma\gamma$ derived from (1) involves $f_{WW}$ and $f_{BB}$. In consequence, the anomalous signature $ff\gamma\gamma$ 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 what follows, we present our results for three different scenarios of the anomalous coefficients: (i) Suppressed $VVV$ couplings compared to the $H\gamma\gamma$ vertex: $f_{BB,WW} = f \gg f_{B,W}$; (ii) all coupling with the same magnitude and sign: $f_{BB,WW,B,W} = f$; (iii) all coupling with the same magnitude but different relative sign: $f_{BB,WW} = f = -f_{B,W}$.

In order to establish the attainable bounds on the coefficients, we imposed an upper limit on the number of signal events based on Poisson statistics. For the $jj\gamma\gamma$ final state we use the results from Ref. 12, where no event has been reported in the 100 pb$^{-1}$ sample. For the other cases, the limit on the number of signal events was conservatively obtained assuming that the number of observed events coincides with the expected background.

Table shows the range of $f/\Lambda^2$ that can be excluded at 95% CL with the present Tevatron luminosity in the scenario (i). We should remind that this scenario will not be restricted by LEP II data on $W^+W^-$ production since there is no trilinear vector boson couplings involved. As seen in the table, the best limits are obtained for the $jj\gamma\gamma$ final state and they are more restrictive than the ones coming from $e^+e^- \rightarrow \gamma\gamma\gamma$ or $b\bar{b}\gamma$ at LEP II.

For the scenarios (ii) and (iii), the limits derived from our study lead to constraints on the triple gauge boson coupling parameters. The most general parametrization for the $WWV$ vertex can be found in Ref. 14. When only the operators (1) are considered, it contains three independent parameters. If it
Figure 1: Excluded region in the $\Delta \kappa \gamma \times M_H$ plane for an integrated luminosity of 100 pb$^{-1}$, and for scenarios (ii) (clear shadow) and (iii) (dark shadow). The present and future bounds on $\Delta \kappa \gamma$ are also shown (see text for details).

is further assumed that $f_B = f_W$, only two free parameters remain, which are usually chosen as $\Delta \kappa \gamma$ and $\lambda \gamma$. This is usually quoted in the literature as the HISZ scenario.$^5$

Since we are assuming $f_B = f_W$, our results can be compared to the derived limits from triple gauge boson studies in the HISZ scenario. In Fig. 1 we show the region in the $\Delta \kappa \gamma \times M_H$ that can be excluded through the analysis of the present Tevatron data, accumulated in Run I, with an integrated luminosity of 100 pb$^{-1}$,$^1$ for scenarios (ii) and (iii).

For the sake of comparison, we also show in Fig. 1 the best available experimental limit on $\Delta \kappa \gamma$,$^7$ and the expected bounds, from double gauge boson production, from an updated Tevatron Run II, with 1 fb$^{-1}$, and TeV33 with 10 fb$^{-1}$,$^8$, and from LEP II operating at 190 GeV with an integrated luminosity of 500 fb$^{-1}$.$^9$ In all cases the results were obtained assuming the HISZ scenario. We can see that, for $M_H \leq 200[170]$ GeV, the limit that can be established at 95% CL from the Higgs production analysis for scenario (ii) [(iii)], based on the present Tevatron luminosity is tighter than the present limit coming from gauge boson production.

When the same analysis is performed for the upgraded Tevatron, a more severe restriction on the coefficient of the anomalous operators is obtained. For
instance, from $p\bar{p} \to jj\gamma\gamma$, in scenario (ii) we get, for $M_H = 150$ GeV: For RunII with $1 \text{ fb}^{-1}$ $-9 < f < 25 (-0.06 < \Delta\kappa_\gamma < 0.16)$; For TeV33 with $10 \text{ fb}^{-1}$ $-4 < f < 15 (-0.03 < \Delta\kappa_\gamma < 0.1)$.

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