Search for a nonstandard Higgs boson in diphoton events at $pp$ collisions

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We estimate the attainable limits on the coupling of a nonstandard Higgs boson to two photons taking into account the data collected by the Fermilab collaborations on diphoton events. We based our analysis on a general set of dimension-6 effective operators that give rise to anomalous couplings in the bosonic sector of the standard model. If the coefficients of all “blind” operators have the same magnitude, indirect bounds on the anomalous triple vector-boson couplings can also be inferred, provided there is no large cancellation in the Higgs-gamma-gamma couplings.

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Events containing two photons plus large missing transverse energy ($\gamma\gamma E_T$) represent an important signature for some classes of supersymmetric models [1]. Models that predict the existence of light neutralinos [2] can give rise to this kind of event, when the next to lightest neutralino decays $\tilde{\chi}_2^0 \to \chi_1^0 \gamma$, where $\chi_1^0$ is the lightest supersymmetric particle (LSP). When a light gravitino is present [3], like in models with gauge-mediated low-energy supersymmetry breaking [4], the lightest neutralino is unstable and decays via $\tilde{\chi}_1^0 \to \tilde{G} \gamma$, which also yields an event topology with two photons together with missing energy, since the gravitino ($\tilde{G}$) escapes undetected.

The DØ Collaboration has reported a recent search for diphoton events with large missing transverse energy in $pp$ collisions at $\sqrt{s} = 1.8$ TeV [5–7]. Their analysis indicates a good agreement with the expectations from the standard model (SM). In this way, the DØ Collaboration was able to set limits on the production cross section $\sigma(pp \to \gamma\gamma E_T + X)$, and consequently, to establish an exclusion region in the supersymmetry parameter space and lower bounds on the masses of the lightest chargino and neutralino.

In this work, we point out that the experimental search for $\gamma\gamma E_T$ events is also able to constrain new physics in the bosonic sector of the SM. For instance, associated Higgs-Z boson production, with the subsequent decay of the Higgs boson into two photons and the $Z$ going to neutrinos, can yield this signature. In the SM, the decay width $H \to \gamma\gamma$ is very small since it occurs just at the one-loop level [8]. However, the existence of new interactions can enhance this width in a significant way.

We can describe the deviations of the SM predictions for the couplings in the bosonic sector via effective Lagrangians [9–12]. The new couplings among light states are described by anomalous effective operators representing residual interactions, after the heavy degrees of freedom are integrated out. A complete set of eleven $C$ and $P$ conserving and $SU_L(2) \times SU_Y(1)$ invariant operators can be found in Refs. [10–12]. The dimension-6 operators that alter the $HVV$ couplings, such as $HWW, HZZ, H\gamma\gamma$, and $HZZ\gamma$, can be written in terms of the Higgs doublet ($\Phi$) as

$$L_{\text{eff}} = f_{WW}^1 \hat{W}_{\mu\nu}^1 \Phi + f_{BB}^1 \hat{B}_{\mu\nu}^1 \Phi + f_{W}^1 \hat{W}_{\mu\nu}^1 (D_\nu \Phi) + f_{B}^1 (D_\mu \Phi)^1 \hat{B}_{\mu\nu}^1 (D_\nu \Phi),$$

where $\hat{B}_{\mu\nu} = (g'/2) B_{\mu\nu}$ and $\hat{W}_{\mu\nu} = i(g/2) \sigma^{a} W_{\mu\nu}^a$, with $B_{\mu\nu}$ and $W_{\mu\nu}^a$ being the field strength tensors of the $U(1)$ and $SU(2)$ gauge fields, respectively. Other possible operators like $\Phi^i \hat{B}_{\mu\nu}^i \Phi$ (not “blind” operators) contribute to Higgs-boson two-point functions at tree level and are strongly constrained. The first two operators appearing in Eq. (1) do not modify the $WW\gamma$ and $WWZ$ tree-point couplings, while the operators $\mathcal{O}_W$ and $\mathcal{O}_B$ generate both Higgs-vector boson and self-vector-bosons anomalous couplings. Therefore, the linearly realized effective Lagrangians relate the modifications in the Higgs couplings to those in the vector boson vertex [10–13]. It is important to notice that the coefficient of the operators $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$ cannot be constrained by the $W^+ W^-$ production at LEP2, since they do not generate anomalous triple gauge boson couplings. They can only be studied in processes involving the Higgs boson in electron-positron [13–15] or hadronic collisions [16]. In the latter case, bounds on anomalous Higgs couplings were obtained from the production of two photons accompanied by charged fermions.

We examine here the production of anomalously coupled Higgs boson at Fermilab Tevatron $pp$ collider concentrating on the signature $\gamma\gamma E_T$, which can originate from the reactions...
For the proton structure functions, we have employed the
\[ \frac{Q^2}{m^2} \]
sample of 106.3 events that have passed the above cuts in their data
\[ \frac{Q^2}{m^2} \]
consistently included via modified Helas where in the latter case, the charged lepton \((\ell = e, \mu)\) escapes undetected.

We have computed the cross sections of Ref. [17] and the interference with the SM diagrams were
\[ f_{WW} f_{BB} \]
also included in our analysis. We search for Higgs boson with mass in
\[ \Delta m > 2 \]
the range \(70 < M_H < 2 M_W\) were observed, a 95% C.L. in the
determination of the anomalous coefficient \(f_{i.i} = W, B, W, B\) of Eq. (1) is attained requiring three events
coming only from the anomalous contributions.

In Fig. 1, we present the exclusion region in the \(f_{WW} f_{BB}\) plane, when we assume that just these two coefficients
are different from zero. The clear (dark) shadow represents the excluded region, at 95% C.L., for \(M_H = 80(140)\) GeV.
We have used and integrated luminosity of 100 pb\(^{-1}\) . Since the anomalous contribution to \(H \rightarrow \gamma \gamma\) width becomes zero
for \(f_{WW} = -f_{BB}\), a very loose bound is obtained near this axis. We should also notice that the reactions (2) are more sensible to \(f_{WW}\), while the dependence on \(f_{BB}\) is very weak.

In Fig. 2, we show the \(f_{WW}\) values, for vanishing \(f_{BB}\), that can be excluded as a function of the Higgs boson mass at
64% (95%) C.L.

When we assume that all the coefficients of the Lagrangian (1) have the same magnitude, the \(H \rightarrow \gamma \gamma\) coupling becomes
related to the triple vector boson coupling, \(W W \gamma\). The coupling \(H \gamma \gamma\) derived from Eq. (1) involves the combination
\[ f_{WW} f_{BB} \]
In consequence, the anomalous signa-
ture $\gamma \gamma E_T$ is only possible, when those couplings do not cancel each other. In this case, the limits obtained from Higgs production, with the subsequent decay into two photons, are able to generate an indirect bound on $\Delta \kappa_\gamma [10-13,16]$. In Fig. 3, we compare our indirect limit on $\Delta \kappa_\gamma$ with the experimental limit of DØ Collaboration from gauge boson pair production [19] for $f=f_{\gamma \gamma}=f_{BB}=f_W=f_B$ (light shadow) and $f=f_{\gamma \gamma}=f_{BB}=-f_W=-f_B$ (dark shadow). We also display the expected bounds at the upgraded Tevatron (Run II) and at TeV33, assuming 1 and 10 fb$^{-1}$ of integrated luminosity, respectively [20], and the limit that will be possible to extract from the CERN $e^+e^-$ collider LEP II, operating at 190 GeV with an integrated luminosity of 500 fb$^{-1}$ [21]. We can see that, for $M_H \lesssim 170(140)$ GeV, the limit that can be established at 95% C.L. from our analysis based on the present Tevatron luminosity is tighter than the present limit coming from gauge boson production. If the result from the recent global fit to LEP, SLAC Large Detector (SLD), $p\bar{p}$, and low-energy data that favors a Higgs boson with mass $M_H = 127^{+127}_{-10}$ GeV [22] is not substantially modified by the presence of the new operators, our indirect limit on $\Delta \kappa_\gamma$ applies for the most favored Higgs boson masses.

In conclusion, we have shown how to extract important information on anomalous Higgs boson coupling from the analysis of $\gamma \gamma E_T$ events in $p\bar{p}$ collisions. In particular, we were able to establish limits on the coefficients of general effective operators that give rise to the coupling $H \gamma \gamma$. Since linearly realized effective Lagrangians relate the modifications in the Higgs couplings to the ones involving vector boson self-interaction, one can extract indirect limits on the anomalous $WW\gamma$ coupling that are competitive with the bounds from direct searches in gauge boson production at present and future collider experiments.

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[1] For a recent review on the phenomenological aspects of supersymmetry, see for instance X. Tata, in the Proceedings of the IX Jorge André Swieca Summer School: Particles and Fields, São Paulo, Brazil, edited by J. C. A. Barata, A. Malbouisson, and S. F. Novaes (World Scientific, Singapore, 1998), Report No. UH-511-872-97, hep-ph/9706307.

[2] S. Ambrosanio et al., Phys. Rev. Lett. 76, 3498 (1996); Phys. Rev. D 55, 1372 (1997).

[3] S. Ambrosanio et al., Phys. Rev. D 54, 5395 (1996); J. Kim et al., ibid. 57, 373 (1998).

[4] P. Fayet, Phys. Lett. 70B, 461 (1977); S. Dimopoulos et al., Phys. Rev. Lett. 76, 3494 (1996); H. Baer, M. Brhlik, C. Chen, and X. Tata, Phys. Rev. D 55, 4463 (1997).

[5] DØ Collaboration, S. Abachi et al., Phys. Rev. Lett. 78, 2070 (1997).

[6] DØ Collaboration, B. Abbott et al., Phys. Rev. Lett. 80, 442 (1998).

[7] See also the DØ Collaboration public Web page: http://www-d0.fnal.gov/public/new/analyses/gauge/welcome.html

[8] J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B106, 292 (1976); M. A. Shifman, A. I. Vainshtein, M. B. Voloshin, and V. I. Zakharov, Sov. J. Nucl. Phys. 30, 711 (1979).

[9] K. Hagiwara, H. Hikasa, R. D. Peccei, and D. Zeppenfeld, Nucl. Phys. B282, 253 (1987).

[10] C. J. C. Burguess and H. J. Schnitzer, Nucl. Phys. B228, 464 (1983); C. N. Leung, S. T. Love, and S. Rao, Z. Phys. C 31, 433 (1986); W. Buchmüller and D. Wyler, Nucl. Phys. B268, 621 (1986).

[11] A. De Rujula, M. B. Gavela, P. Hernandez, and E. Masso, Nucl. Phys. B384, 3 (1992); A. De Rujula, M. B. Gavela, O. Pene, and F. J. Vegas, ibid. B357, 311 (1991).

[12] K. Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld, Phys. Lett. B 283, 353 (1992); Phys. Rev. D 48, 2182 (1993); K. Hagiwara, T. Hatsukano, S. Ishihara, and R. Szalapski, Nucl. Phys. B496, 66 (1997).

[13] K. Hagiwara, R. Szalapski, and D. Zeppenfeld, Phys. Lett. B 318, 155 (1993).

[14] K. Hagiwara and M. L. Ston, Z. Phys. C 62, 99 (1994); B. Grzadkowski and J. Wudka, Phys. Lett. B 364, 49 (1995); G. J. Gounaris, J. Layssac, and F. M. Renard, Z. Phys. C 65, 245 (1995); G. J. Gounaris, F. M. Renard, and N. D. Vlachos, Nucl. Phys. B459, 51 (1996).

[15] S. M. Lietti, S. F. Novaes, and R. Rosenfeld, Phys. Rev. D 54, 3266 (1996); F. de Campos, S. M. Lietti, S. F. Novaes, and R. Rosenfeld, Phys. Lett. B 389, 93 (1996); Phys. Rev. D 56, 4384 (1997); S. M. Lietti and S. F. Novaes, hep-ph/9708443.

[16] F. de Campos, M. C. Gonzalez-Garcia, and S. F. Novaes, Phys. Rev. Lett. 79, 5210 (1997).

[17] H. Murayama, I. Watanabe, and K. Hagiwara, KEK Report No. 91-11 (unpublished).

[18] A. D. Martin, W. J. Stirling, and R. G. Roberts, Phys. Lett. B 354, 155 (1995).

[19] DØ Collaboration, B. Abbott et al., Phys. Rev. Lett. 79, 1441 (1997).

[20] D. Amidei et al., Future Electroweak Physics at the Fermilab Tevatron: Report of the TeV-2000 Study Group, Report No. FERMILAB-PUB-96-082 (1996).

[21] T. Barklow et al., in New Directions for High-Energy Physics, Proceedings of the Snowmass Summer Study, Snowmass, Colorado, 1996, edited by D. Cassel (SLAC, Stanford, 1997), hep-ph/9611454.

[22] The LEP Collaborations ALEPH, DELPHI, L3, OPAL, and the LEP Electroweak Working Group, in ICHEP 96, Proceedings of the 28th International Conference on High-Energy Physics, Warsaw, Poland, 1996, edited by Z. Ajduk and A. Wroblewski (World Scientific, Singapore, 1997); contributions to the 1997 Winter Conferences, Report No. LEPEWWG/97-01 (1997).