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Search for a nonstandard Higgs boson in diphoton events at $p\bar{p}$ 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 coupling. [S0556-2821(98)00111-8]

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Events containing two photons plus large missing transverse energy ($\gamma\gamma\not{E}_T$) 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 $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$, where $\tilde{\chi}_1^0$ 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 $p\bar{p}$ 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 $\sigma(p\bar{p}\to\gamma\gamma\not{E}_T+X)$, 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 $\gamma\gamma\not{E}_T$ 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 $\mathrm{SU}_L(2)\times\mathrm{U}_Y(1)$ 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 $HZ\gamma$, can be written in terms of the Higgs doublet (Φ) as

$$\begin{aligned}\mathcal{L}_{\mathrm{eff}}=&f_{WW}\Phi^{\dagger}\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi+f_{BB}\Phi^{\dagger}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi\\&+f_{W}(D_{\mu}\Phi)^{\dagger}\hat{W}^{\mu\nu}(D_{\nu}\Phi)+f_{B}(D_{\mu}\Phi)^{\dagger}\hat{B}^{\mu\nu}(D_{\nu}\Phi),\end{aligned}\tag{1}$$

where $\hat{B}_{\mu\nu}=i(g'/2)B_{\mu\nu}$ and $\hat{W}_{\mu\nu}=i(g/2)\sigma^{a}W^{a}_{\mu\nu}$, with $B_{\mu\nu}$ and $W^{a}_{\mu\nu}$ being the field strength tensors of the U(1) and SU(2) gauge fields, respectively. Other possible operators like $\Phi^{\dagger}\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$ (not ''blind'' operators) contribute to gauge-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 $p\bar{p}$ collider concentrating on the signature $\gamma\gamma\not{E}_T$, which can originate from the reactions

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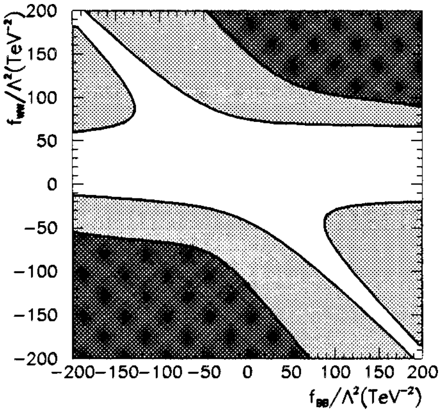

FIG. 1. Excluded region at 95% of C.L. in the $f_{WW}\times f_{BB}$ plane, for an integrated luminosity of 100 pb^{-1}, and for $M_H=80(140)$ GeV [light shadow (dark shadow)].

$$p\bar{p}\to Z(\to\nu\bar{\nu})+H(\to\gamma\gamma)+X,$$

$$p\bar{p}\to W(\to\ell\nu)+H(\to\gamma\gamma)+X, \qquad (2)$$

where in the latter case, the charged lepton ($\ell=e,\mu$) escapes undetected.

We have computed the cross sections (2) taking into account all electroweak subprocess $q\bar{q}'\to\nu\bar{\nu}(\ell\nu)\gamma\gamma$, with $\ell=e,\mu$. The anomalous contributions coming from the Lagrangian (1) and the interference with the SM diagrams were consistently included via modified Helas [17] subroutines. For the proton structure functions, we have employed the Martin-Roberts-Stirling set G [MRS (G)] [18] at the scale $Q^2=\hat{s}$.

In order to compare our predictions with the data collected by the DØ Collaboration, we have applied the same cuts of Ref. [6]. We required that one photon has transverse energy $E_T^{\gamma_1}>20$ GeV and the other $E_T^{\gamma_2}>12$ GeV, each of them with pseudorapidity in the range $|\eta^\gamma|<1.2$ or $1.5<|\eta^\gamma|<2.0$. We further required that $\not{E}_T>25$ GeV. For the $\ell\nu\gamma\gamma$ final state, we imposed that the charged lepton is outside the covered region of the electromagnetic calorimeter and it escapes undetected ($|\eta_e|>2$ or $1.1<|\eta_e|<1.5$, $|\eta_\mu|>1$). After these cuts we find that 80% to 90% of the signal comes from associated Higgs-Z 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 [19]. We estimate the total effect of these efficiencies to be 35%.

The main sources of background to this reaction [6] arise from SM processes containing multijets, direct photon, $W+\gamma$, $W+j$, $Z\to ee$, and $Z\to\tau\tau\to ee$, where photons are misidentified and/or the missing energy is mismeasured. The DØ Collaboration estimate the contribution of all these backgrounds to yield 2.3 ± 0.9 events. DØ Collaboration has observed 2 events that have passed the above cuts in their data sample of 106.3 ± 5.6 pb^{-1}. The invariant mass of the photon pair in these events are 50.4 and 264.3 GeV [7].

In our analysis, we search for Higgs boson with mass in the range $70<M_H\lesssim 2M_W$, since after the W^+W^- threshold is reached, the diphoton branching ratio of Higgs is quite reduced. Since no event with two-photon invariant mass in the range $70<M_{\gamma\gamma}\lesssim 2M_W$ were observed, a 95% C.L. in the determination of the anomalous coefficient f_i, $i=WW,BB,W,B$ of Eq. (1) is attained requiring three events coming only from the anomalous contributions.

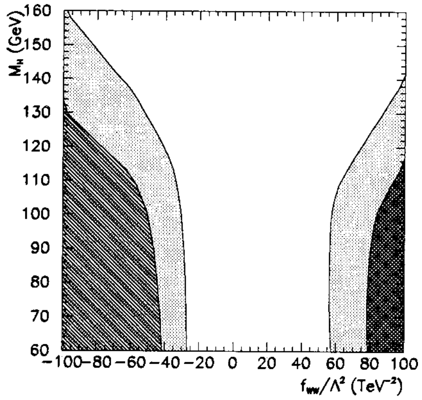

FIG. 2. Excluded region $f_{WW}\times M_H$ plane for $f_BB=0$ for an integrated luminosity of 100 pb^{-1} at 64% (95%) C.L. [light shadow (dark shadow)].

In Fig. 1, we present the exclusion region in the $f_{WW}\times f_{BB}$ 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 $H\to\gamma\gamma$ 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 $H\to\gamma\gamma$ coupling becomes related to the triple vector boson coupling, $WW\gamma$. The coupling $H\gamma\gamma$ derived from Eq. (1) involves the combination $f_{WW}+f_{BB}$ [13]. In consequence, the anomalous signa-

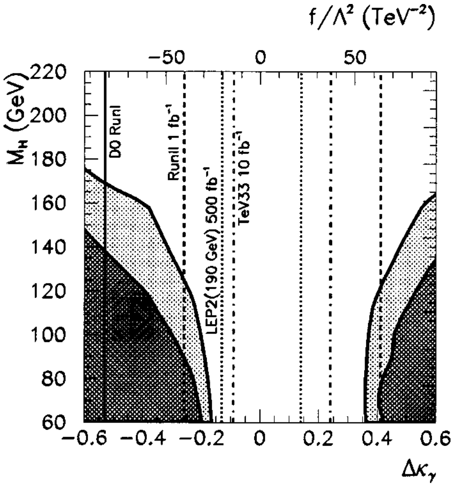

FIG. 3. Excluded region in the $\Delta\kappa_\gamma\times M_H$ plane for an integrated luminosity of 100 pb^{-1}, and for $f\equiv f_{WW}=f_{BB}=f_W=f_B$ ($f\equiv f_{WW}=f_{BB}=-f_W=-f_B$) [light shadow (dark shadow)]. The vertical lines represent the present and future limits on $\Delta\kappa_\gamma$ from different colliders.

ture $\gamma\gamma\not{E}_T$ 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 $f \equiv f_{WW} = f_{BB} = f_W = f_B$ (light shadow) and $f \equiv f_{WW} = f_{BB} = -f_W = -f_B$ (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 $M_H = 127^{+127}_{-72}$ 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 $\gamma\gamma\not{E}_T$ 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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