Search for a Fermiophobic Higgs Boson Decaying into Diphotons in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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A search for a narrow diphoton mass resonance is presented based on data from 3.0 fb^{-1} of integrated luminosity from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected by the CDF experiment. No evidence of a resonance in the diphoton mass spectrum is observed, and upper limits are set on the cross section times branching fraction of the resonant state as a function of Higgs boson mass. The resulting limits exclude Higgs bosons with masses below 106 GeV/c^2 at a 95% Bayesian credibility level (C.L.) for one fermiophobic benchmark model.

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The standard model (SM) of particle physics has proven to be an extremely robust theory through its accurate predictions of many experimental results obtained over the last few decades. Although the Higgs mechanism [1] was proposed in the 1960's, the particle it predicts, the Higgs boson (h), has yet to be observed in nature.

The SM prediction for the $h \rightarrow \gamma\gamma$ branching fraction is extremely small (reaching a maximal value of only about 0.2% at a Higgs boson mass (m_h) $\sim$ 120 GeV/c^2) [2]; however, in "fermiophobic" models, where the coupling of the Higgs boson to fermions is suppressed, the diphoton decay can be greatly enhanced. This phenomenon has been shown to arise in a variety of extensions to the SM [3–7], and the resulting collider phenomenology has been described [8–10]. For this fermiophobic case, the diphoton final state dominates at low Higgs boson masses and is therefore the preferred search channel.

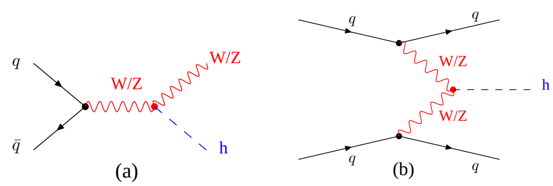

FIG. 1: The dominant production diagrams for the benchmark fermiophobic Higgs boson model: associated production with a vector boson (a), and vector boson fusion (b).

A benchmark fermiophobic model is considered in which the Higgs boson does not couple to fermions, yet retains its SM couplings to bosons. In this model, the fermiophobic Higgs boson production is dominated by two processes: associated production (shown in Fig. 1(a)), and vector boson fusion (abbr. VBF, shown in Fig. 1(b)).

Each of the four experiments [11–14] at the LEP electron-positron collider at CERN place 95% C.L. lower limits on the fermiophobic Higgs boson mass (the most stringent being 105.5 GeV/c^2), while a combination of these results obtains a 95% C.L. limit of 109.7 GeV/c^2 [15]. The CDF and D0 experiments at the Tevatron also searched for a fermiophobic Higgs boson [16, 17]. Most recently, the D0 experiment set limits on the production cross section of the fermiophobic Higgs boson with 1.1 fb^{-1} of data, resulting in a 95% C.L. lower limit on m_h of 100 GeV/c^2 [18]. In this Letter, we search the diphoton mass distribution from the Collider Detector at Fermilab (CDF) for a narrow resonance that could reveal the presence of a fermiophobic Higgs boson.

We use the CDF II detector [19, 20] to identify (ID) photon candidate events produced in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV. The innermost detector component is the silicon vertex tracker [21] which is surrounded by an open-cell drift chamber (COT, [22]). Both sample the trajectories of charged particles and determine their momentum as they curve in the presence of a 1.4 T axial magnetic field. Particles that pass through the COT reach the electromagnetic and hadronic calorimeters [23–25], which are divided into two regions: central ($|\eta| < 1.1$) and forward or "plug" ($1.1 < |\eta| < 3.6$). At the approximate electromagnetic shower maximum, the calorimeters contain fine-grained detectors [26] that measure the shower shape and centroid position in the two dimensions transverse to the shower development. The calorimeters are surrounded by a system of muon chambers [27].

Three levels of real-time event selection (trigger) systems are used to filter events. The trigger paths used here require two clusters of deposited energy in the electromagnetic calorimeter. One path requires that both clusters have a transverse energy $E_T > 12$ GeV [20] and be isolated from other energy clusters in the calorimeter [28]. A second trigger has a cluster transverse energy requirement of $E_T > 18$ GeV without the requirement of cluster isolation. By combining these two trigger paths, virtually all of the identifiable diphoton events are recorded.

The analysis is divided into two independent subsamples according to the position of the photons: the first requires that both photons be located within the fiducial region of the central electromagnetic calorimeter ($|\eta| < 1.05$), and the second requires that one photon be located in this region and the other in the plug calorimeter ($1.2 < |\eta| < 2.8$). The former will be referred to as central-central (CC) events, and the latter as central-plug (CP) events [29]. The data were recorded between February of 2002 and April of 2008, corresponding to an integrated luminosity of 3.0 fb^{-1} for CC and 2.9 fb^{-1} for CP events.

A series of baseline selection criteria helps to remove

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background events and to ID high-energy photon candidates for the analysis. Individual photons are required to have $E_T > 15$ GeV, while the diphoton pair is required to have mass $m_{\gamma\gamma} > 30$ GeV/c^2. Photons are required to pass CDF standard photon ID requirements including the following [28, 30]: transverse shower profiles consistent with single photon expectation from test beam studies [31], additional transverse energy in the calorimeter in a cone of angular radius $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ [20] around the photon candidate be less than 2 GeV, and the scalar sum of the p_T of the tracks in the same cone be less than 2 GeV/c. Central photons must also be isolated in the shower maximum detector.

The above selection criteria define an inclusive diphoton sample. However, the fermiophobic Higgs boson is only produced at a non-negligible rate in association with a W or Z boson or via the VBF process. In order to improve sensitivity, the event selection was further extended to take advantage of the final state features present in these production modes. Associated production dominates the production process (for $m_h = 100$ GeV/c^2 its rate is about four times larger than VBF), so the optimization was carried out on the basis of the associated production process alone. A selection based on the following observables was optimized: diphoton transverse momentum ($p_T^{\gamma\gamma}$), transverse momentum of the second highest p_T jet (p_T^{j2}) for hadronic decays of W/Z, and missing transverse energy ($\not\!\!E_T$) or transverse momentum of an isolated track (p_T^{iso}) for leptonic decays of W/Z.

For the optimization study, a Bayesian method with a flat prior probability was used to estimate the expected limits based on signal and background event expectations in a 10 GeV/c^2 mass window centered at 100 GeV/c^2. The diphoton background is composed of SM diphoton events (~ 25 %) and events in which either one or both photon candidates are actually quark or gluon jets which were misidentified as photons (~ 75 %). Higgs boson events with only the diphoton decay mode and SM diphoton events were generated using the PYTHIA 6.2 [32] Monte Carlo event generator and a parametrized response of the CDF II detector [33, 34]. All PYTHIA samples were made with CTEQ5L [35] parton distribution functions, where the PYTHIA underlying event model is tuned to CDF jet data [36]. The background component arising from jets misidentified as photons was estimated using photon identification control regions from data. The control regions do not overlap with the signal region, as the events in the control region are required to fail at least one of the standard electromagnetic energy fraction or isolation requirements, yet pass a looser set of these requirements.

The optimization shows that a requirement of $p_T^{\gamma\gamma} > 75$ GeV/c is approximately as sensitive as any combination of the other selection criteria. With this requirement on $p_T^{\gamma\gamma}$, roughly 30% of the signal remains (slightly varying with m_h) while more than 99.5% of the background is removed. Although the cut was optimized based on associated production, VBF also has a higher average $p_T^{\gamma\gamma}$ than the background processes and is included in the analysis with the same selection.

The detector acceptance for signal events is calculated using the PYTHIA event generator samples described above. Since a pure sample of reconstructed photons is not available in the data, corrections to the photon identification efficiencies due to imperfections in the detector simulation are derived using electrons from Z boson decays. This is justified since the energy deposition in the EM calorimeter by electrons and photons is almost indistinguishable. The electrons are selected with a slightly modified version of the photon ID requirements to allow the presence of a high p_T track. A correction factor to the ID efficiency of the simulation of 0.97 (0.94) is derived for central (plug) photons by comparing ID efficiencies from the detector simulation with the ID efficiencies measured in data.

The largest systematic uncertainties on the expected number of Higgs boson events arise from the luminosity measurement (6%), varying the parameters controlling the amount of initial and final state radiation from the parton shower model of PYTHIA (4%) [37], and the PYTHIA modeling of the shape of the $p_T^{\gamma\gamma}$ distribution for the signal (4%). The latter uncertainty was obtained by studying the effect on the acceptance from the differences in the shape of the $p_T^{\gamma\gamma}$ distribution from leading-order, next-to-leading-order, and PYTHIA predictions [38]. Other systematic uncertainties were also considered due to uncertainties in photon ID efficiency, the electromagnetic energy scale, and parton distribution functions [39, 40]. The signal acceptances are included in Table I and they have a relative uncertainty of 8% (9%) for CC (CP).

The decay of a Higgs boson into a diphoton pair appears as a very narrow peak in the invariant mass distribution of these two photons. The diphoton mass resolution as determined from simulation is better than 3% for the Higgs boson mass region studied here and is limited by the energy resolution of the electromagnetic calorimeters. The simulated resolution was compared with data using electrons from Z boson decays and is found to model the detector well. The diphoton invariant mass distribution shown in Fig. 2 could be sensitive to a resonance in the context of the fermiophobic benchmark model (see the inserts in Fig. 2 for the signal shape expected from simulation). No evidence of such a resonance is apparent in the data. As a background prediction to be used for setting limits on a diphoton resonance, the data is fit to a sum of two exponentials multiplied by a fractional degree polynomial, where the degree of one term is a parameter of the fit. The fit, excluding a 10 GeV/c^2 mass window centered at each test m_h, is performed for each m_h hypothesis (10-GeV/c^2 steps from 70 to 150 GeV/c^2). The fit for a m_h of 100 GeV/c^2 is

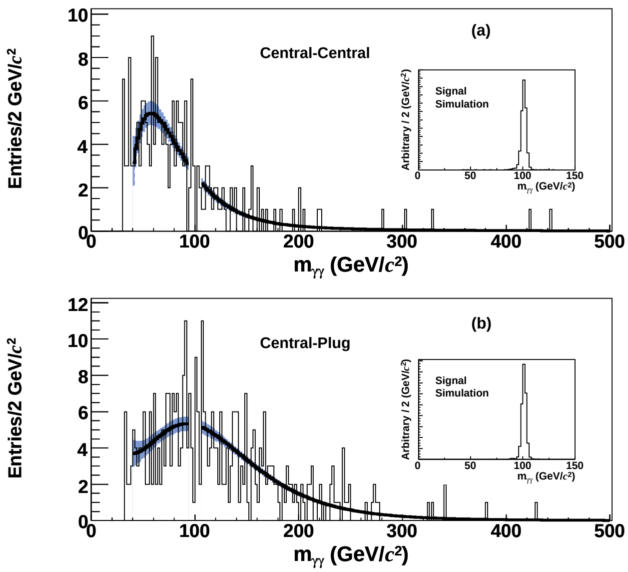

FIG. 2: The invariant mass distribution of central-central (a) and central-plug (b) photon pairs after the requirement of $p_T^{\gamma\gamma} > 75$ GeV/c, shown with the fit to the data for the hypothesis of a m_h of 100 GeV/c^2. The error bands represent the statistical uncertainty in the fit. The expected shape of the signal from simulation is shown in the inserts.

shown in Fig. 2.

After the background fit for each mass hypothesis has been determined, the presence or absence of a Higgs boson signal is ascertained on the basis of a binned likelihood method incorporating the simulated signal shape and the systematic uncertainties. We calculate a Bayesian C.L. limit for each mass hypothesis based on the combined binned likelihood of the mass distributions for the CC and CP samples. A posterior density is obtained by multiplying this likelihood by Gaussian prior densities for the background normalizations and systematic uncertainties leaving the production cross section ($\sigma \times \mathcal{B}(h \to \gamma\gamma)$) with a uniform prior density. A 95% C.L. limit is then determined such that 95% of the posterior density for $\sigma \times \mathcal{B}(h \to \gamma\gamma)$ falls below the limit [41].

The results of the limit calculation are included in Table I and displayed graphically in Fig. 3. The SM cross sections assumed in the benchmark fermiophobic model are used to convert the limits on $\sigma \times \mathcal{B}(h \to \gamma\gamma)$ into limits on $\mathcal{B}(h \to \gamma\gamma)$. The result excludes the benchmark model predictions (at 95% C.L.) for m_h of less than 106 GeV/c^2.

This Letter presents the results of a search for a narrow resonance in the diphoton mass spectrum using data comprising 3.0 fb^{-1} of integrated luminosity from the CDF II detector at the Tevatron. Selected events include two photons in the central detector or one photon in the central and one in the plug detector. There is no evidence of a narrow resonance. Limits are placed on the production cross section and the branching fraction for the Higgs boson decay into a photon pair and compared to the predictions of a benchmark fermiophobic model resulting in a limit on the Higgs boson mass of $m_h > 106$ GeV/c^2 at the 95% C.L. This mass limit is approximately as strong as any previous single experiment, and the result significantly extends the excluded region of $\sigma \times \mathcal{B}(h \to \gamma\gamma)$ and $\mathcal{B}(h \to \gamma\gamma)$ for m_h above 106 GeV/c^2.

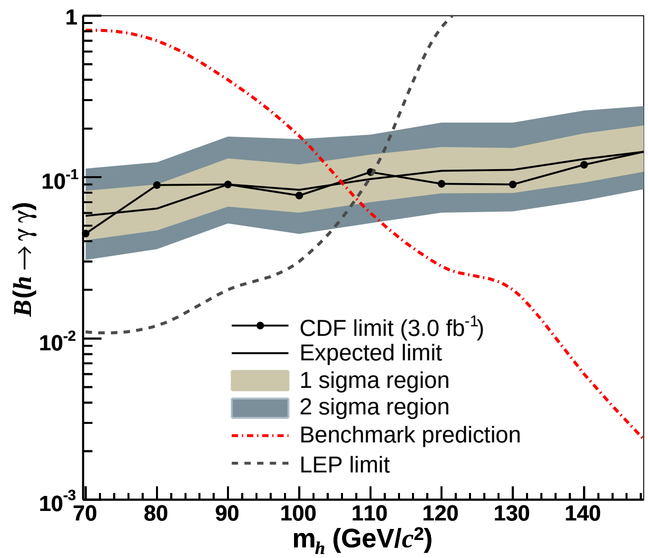

FIG. 3: The 95% C.L. upper limit on the branching fraction for the fermiophobic Higgs boson decay to diphotons, as a function of m_h. The shaded regions represent the one and two sigma probability of fluctuations of the observed limit away from the expected limit based on the distribution of possible experimental outcomes. For reference, the 95% C.L. limits from LEP are also included.

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TABLE I: Observed and expected 95% C.L. limits on the production cross section and branching fraction and theory predictions for the fermiophobic benchmark Higgs boson model. Total signal acceptance is also included. Note that the CP channel is not included for the 90 GeV/c^2 point [29].

		$\sigma\times\mathcal{B}(h\rightarrow\gamma\gamma)$ (fb)			$\mathcal{B}(h\rightarrow\gamma\gamma)$ (%)		
	Acceptance (%)	Limits			Limits		
m_h (GeV/c^2)	(CC +CP)	Expected	Observed	Theory [2]	Expected	Observed	Theory
70	4.8	88.1	68.2	1240	5.8	4.5	81
80	6.2	68.3	95.4	749	6.4	8.9	70
90	4.4	70.7	70.8	312	7.4	11.3	40
100	8.8	48.3	44.5	104	8.3	7.7	18
110	10	41.8	46.2	25.8	9.7	10.7	6.0
120	11	36.3	30.2	9.3	10.9	9.1	2.8
130	12	27.8	22.6	5.0	11.0	9.0	2.0
140	13	26.6	24.4	1.2	12.0	11.9	0.6
150	15	23.5	23.9	0.3	14.6	14.9	0.2

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