
(CDF Collaboration)
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

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Higgs bosons with masses below 106 GeV/c^2 at a 95% Bayesian credibility level 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 1960s, the particle it predicts, the Higgs boson (h), has yet to be observed in nature.

The SM prediction for the h → γγ branching fraction is extremely small (reaching a maximal value of only about 0.2% at a Higgs boson mass (m_h) ~ 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.

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 [abbreviated 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 (|η| < 1.1) and forward or “plug” (1.1 < |η| < 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.

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 [27]. 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 (|η| < 1.05), and the second requires that one photon be located in this region and the other in the plug calorimeter (1.2 < |η| < 2.8). The former will be referred to as central-central (CC) events, and the latter as central-plug (CP) events [28]. The data were recorded between February 2002 and April 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 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_{γγ} > 30 GeV/c^2. Photons are required to pass CDF standard photon ID requirements including the following [27,29]: transverse shower profiles consistent with single photon expectation from test beam studies [30], additional transverse energy in the calorimeter in a cone of angular radius R = (Δφ)^2 + (Δη)^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

![FIG. 1](color online). The dominant production diagrams for the benchmark fermiophobic Higgs boson model: associated production with a vector boson (a), and vector boson fusion (b).
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 4 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 ($E_T^\ast$) 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 ($\sim 25\%$) and events in which either one or both photon candidates are actually quark or gluon jets which were misidentified as photons ($\sim 75\%$). Higgs boson events with only the diphoton decay mode and SM diphoton events were generated using the PYTHIA 6.2 [31] Monte Carlo event generator and a parametrized response of the CDF II detector [32,33]. All PYTHIA samples were made with CTEQ5L [34] parton distribution functions, where the PYTHIA underlying event model is tuned to CDF jet data [35]. 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%) [36], 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 [37]. Other systematic uncertainties were also considered due to uncertainties in photon ID efficiency, the electromagnetic energy scale, and parton distribution functions [38,39]. 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 deter-

<table>
<thead>
<tr>
<th>$m_h$ (GeV$/c^2$)</th>
<th>Acceptance (%)</th>
<th>$\sigma \times \mathcal{B}(h \rightarrow \gamma \gamma)$ (fb)</th>
<th>$\mathcal{B}(h \rightarrow \gamma \gamma)$ (%)</th>
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<tr>
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FIG. 2 (color online). 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 gap in the fit centered at 100 GeV/c\(^2\) represents the signal region for this mass point that was excluded from the fit. The error bands show the statistical uncertainty in the fit. The expected shape of the signal from simulation is shown in the insets.

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 \( \sigma \times B(h \rightarrow \gamma\gamma) \) into limits on \( B(h \rightarrow \gamma\gamma) \). The result excludes the benchmark model predictions (at 95% C.L.) for \( m_h \) of less than 106 GeV/c\(^2\).

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 the 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 in \( \sigma \times B(h \rightarrow \gamma\gamma) \) is obtained by multiplying this likelihood by Gaussian prior densities for the background normalizations and systematic uncertainties leaving the production cross section \( \sigma \) and \( B(h \rightarrow \gamma\gamma) \) with a uniform prior density. A 95% C.L. limit is then determined such that 95% of the posterior density for \( \sigma \times B(h \rightarrow \gamma\gamma) \) falls below the limit [40].

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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[36] We constrain the rate of initial state radiation using Drell-Yan events in data.