Search for a Higgs Boson in the Diphoton Final State in \( p \bar{p} \) Collisions at \( \sqrt{s} = 1.96 \) TeV
A search for a narrow Higgs boson resonance in the diphoton mass spectrum is presented based on data corresponding to 7.0 fb\(^{-1}\) of integrated luminosity from \(p\bar{p}\) collisions at \(\sqrt{s} = 1.96\) TeV collected by the CDF experiment. No evidence of such a resonance is observed, and upper limits are set on the cross section times branching ratio of the resonant state as a function of Higgs boson mass. The limits are interpreted in the context of the standard model and one fermiophobic benchmark model where the data exclude fermiophobic Higgs bosons with masses below 114 GeV\(\pm\)2 at a 95% Bayesian credibility level.

**DOI:** 10.1103/PhysRevLett.108.011801  
**PACS numbers:** 14.80.Bn, 12.38.Qk, 13.85.Rm, 14.80.Ec

In the standard model (SM) of particle physics, the electromagnetic and weak forces are unified into a single theory known as electroweak theory. However, the measured cross sections for electromagnetic and weak interactions differ by several orders of magnitude due to massive \(W\) and \(Z\) bosons that mediate the weak interactions. These bosons gain mass via electroweak symmetry breaking by way of the Higgs mechanism [1], and the electroweak theory predicts the existence of a boson, known as the Higgs boson, that provides a direct test of the theory.

The SM prediction for the Higgs boson branching ratio into a photon pair \(B(H \rightarrow \gamma\gamma)\) is extremely small, reaching a maximal value of only about 0.2% for a Higgs boson mass \(m_H = 120\) GeV\(\pm\)2 [2]. Even so, a search using the diphoton final state is appealing due to its better mass resolution and reconstruction efficiency relative to dominant decay modes involving \(b\) quarks. The \(H \rightarrow \gamma\gamma\)
channel provides its greatest sensitivity for Higgs boson masses between 110 and 140 GeV/c^2, contributing in a region most useful to combined Tevatron Higgs boson searches [3] and overlapping with a region preferred by electroweak constraints [4]. In addition, in “fermiophobic” Higgs boson models, where the coupling of the Higgs boson to fermions is suppressed, the diphoton decay can be greatly enhanced [5].

The Collider Detector at Fermilab (CDF) and D0 experiments at the Tevatron have searched for both a SM Higgs boson and a fermiophobic Higgs boson h_f decaying to two photons [6–8]. The D0 experiment recently set 95% confidence level (C.L.) upper limits on the cross section times branching ratio $\sigma \times \mathcal{B}(H \rightarrow \gamma \gamma)$ relative to the SM prediction and on $\mathcal{B}(h_f \rightarrow \gamma \gamma)$ using data corresponding to an integrated luminosity $L$ of 8.2 fb$^{-1}$ [9]. The $h_f$ result sets a lower limit on $m_{h_f}$ of 112.9 GeV/c^2, a more stringent limit than that of 109.7 GeV/c^2 obtained from combined searches at the LEP electron-positron collider at CERN [5]. Previously, the CDF experiment set 95% C.L. upper limits on $\mathcal{B}(h_f \rightarrow \gamma \gamma)$ with data corresponding to $L = 3.0$ fb$^{-1}$, resulting in an exclusion of $m_{h_f}$ below 106 GeV/c^2 [10].

In this Letter, we present a search of the diphoton mass distribution from CDF data for a narrow resonance that could reveal the presence of a SM or fermiophobic Higgs boson. This analysis, which uses more than twice the integrated luminosity of the previous CDF $h_f$ analysis [10], implements new techniques to improve the identification of photons and yields a new, improved lower limit on the fermiophobic Higgs boson mass. In addition, this is the first search for the SM Higgs boson at CDF using $H \rightarrow \gamma \gamma$ decays from Run II data.

The SM Higgs production mechanisms considered in this study are gluon fusion (GF), associated production (VH) where a Higgs boson is produced in association with a W or Z boson, and vector boson fusion (VBF) with cross sections of 1072.3 fb [11], 240.3 fb [12], and 72.7 fb [13], respectively, for $m_H = 120$ GeV/c^2. A benchmark fermiophobic model is considered in which the Higgs boson does not couple to fermions, yet retains its SM couplings to bosons [5]. In this model, the GF process is suppressed and the fermiophobic Higgs boson production is dominated by VH and VBF. Furthermore, Higgs boson decays to fermions are removed, resulting in increased branching ratios for decays into gauge bosons.

We use the CDF II detector [14] to identify photon candidate events produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The silicon vertex tracker [15] and the central outer tracker [16], contained within a 1.4 T axial magnetic field, measure the trajectories of charged particles and determine their momenta. Particles that pass through the central outer tracker reach the electromagnetic (EM) and hadronic calorimeters [17–19], which are divided into two regions: central ($|\eta| < 1.1$) [20] and forward or "plug" ($1.1 < |\eta| < 3.6$). The EM calorimeters contain fine-grained shower maximum detectors [21], which measure the shower shape and centroid position in the two dimensions transverse to the direction of the shower development.

Events with two photon candidates are selected, and the data are divided into four categories according to the position and type of the photons. In central-central (CC) events, both photon candidates are located within the fiducial region of the central EM calorimeter ($|\eta| < 1.05$); in central-plug (CP) events, one photon candidate is located in this region and the other is in the fiducial region of the plug calorimeter ($1.2 < |\eta| < 2.8$); in central-central events with a conversion (C’C), both photon candidates are in the central region, but one photon converts and is reconstructed from its $e^+e^-$ decay products; and, in central-plug events with a conversion (C’P), there is one central conversion candidate together with a plug photon candidate.

The events are selected by a three-level trigger system that requires an isolated cluster of energy deposited in the EM calorimeter with a transverse energy $E_T > 25$ GeV [22]. The trigger efficiency for events accepted into the final sample is determined from simulation and found to be essentially 100% for the most sensitive event category (CC) and above 90% for all other categories.

A set of selection criteria is used to remove background events and to identify high-energy photon candidates for this analysis. All reconstructed photon candidates are required to have $E_T > 15$ GeV. Plug photon candidates are identified using standard CDF requirements described elsewhere [23,24]. A new neural network (NN) technique is used to identify photons in the central region. Central photon candidates are first required to satisfy loose selection requirements, as described in Ref. [25]. After additional track requirements are applied to remove electrons, the remaining candidates are required to have a NN output value above a threshold that is selected to maximize $H \rightarrow \gamma \gamma$ sensitivity. As more than half of the events in the data with two photon candidates contain either one or two jets misidentified as a prompt photon [26], the NN discriminant is trained using photon and jet Monte Carlo (MC) samples and constructed from several detector variables that distinguish true photons from these jet backgrounds [27]. These variables include the ratio of energy in the shower maximum detector to that in the calorimeter cluster associated with the photon, the ratio of hadronic to EM transverse energy, calorimeter and track isolation [25], and a $\chi^2$ value calculated by comparing the measured transverse shower profile to that of a single EM shower [28]. This NN method increases the photon signal efficiency by $\sim 5\%$ and background rejection by $\sim 12\%$ compared to the standard selection requirements for central photons [25], which improves $H \rightarrow \gamma \gamma$ sensitivity by about 9%.

As photons pass through the CDF detector material, EM interactions with a nucleus cause about 15% of central
photon pairs. In order to recover these conversion photons, we search for a central electron with a nearby track corresponding to a particle of opposite charge. The proximity of the two tracks is first determined by requiring the transverse distance between the two tracks to be less than 0.2 cm at the radial location where they are parallel. The difference in \( \cot \theta \) between the two tracks must be less than 0.04, where \( \cot \theta = p_x / p_T \). Backgrounds are further removed by requiring the ratio of \( E_T \) to \( p_T \) of the reconstructed conversion photon to be between 0.1 and 1.9 and calorimeter isolation to be less than 2.6 GeV, where cut boundaries are optimized to maximize \( H \rightarrow \gamma \gamma \) sensitivity. The direction of the conversion photon’s momentum is obtained by taking the vector sum of the individual track momenta.

Reconstruction of photon conversions in this analysis provides an improvement of about 13\% in sensitivity to a Higgs boson signal [29].

The above selection criteria define an inclusive diphoton sample for the SM Higgs boson search. In order to improve sensitivity for the fermiophobic Higgs boson search, the event selection is extended by taking advantage of the final-state features present in the VH and VBF processes. Because the Higgs boson from these processes will be produced with a \( W \) or \( Z \) boson or with two jets, the transverse momentum of the diphoton system \( p_T^{\gamma\gamma} \) is generally higher relative to the diphoton backgrounds. A requirement of \( p_T^{\gamma\gamma} > 75 \) GeV/c forms a region of high \( h_f \) sensitivity, retaining roughly 30\% of the signal while removing 99.5\% of the background [10]. Two lower \( p_T^{\gamma\gamma} \) regions are additionally included and provide about 15\% more \( h_f \) sensitivity: \( p_T^{\gamma\gamma} < 35 \) GeV/c and \( 35 \) GeV/c < \( p_T^{\gamma\gamma} < 75 \) GeV/c. With four diphoton categories (CC, CP, C'C, and C'P) and three \( p_T^{\gamma\gamma} \) regions, twelve independent channels are included for the fermiophobic Higgs boson search.

The efficiency times detector acceptance \( \epsilon A \) for signal events in each event category (CC, CP, C'C, and C'P) for \( m_H = 120 \) GeV/c\(^2\), as a percentage of the total number of \( H \rightarrow \gamma \gamma \) decays for each production mechanism. For the \( h_f \) search, results for VH and VBF are shown for the high[medium]low \( p_T^{\gamma\gamma} \) regions as described in the text.

<table>
<thead>
<tr>
<th>( \epsilon A ) (%)</th>
<th>( H_{SM} ) Search</th>
<th>( h_f ) Search</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GF</td>
<td>VH</td>
</tr>
<tr>
<td>CC</td>
<td>10.0</td>
<td>10.2</td>
</tr>
<tr>
<td>CP</td>
<td>12.0</td>
<td>10.9</td>
</tr>
<tr>
<td>C'C</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>C'P</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Total</td>
<td>25.8</td>
<td>24.6</td>
</tr>
</tbody>
</table>

**FIG. 1.** The invariant mass distribution of the data for CC photon pairs is shown in (a) for the entire \( p_T^{\gamma\gamma} \) region used in the SM Higgs boson search and (b) for the highest \( p_T^{\gamma\gamma} \) region (the most sensitive region) used in the \( h_f \) search. Each distribution shows a fit to the data for the hypothesis of a \( m_H \) of 120 GeV/c\(^2\). The gap in the fit centered at 120 GeV/c\(^2\) represents the signal region for this mass point that was excluded from the fit. The expected shape of the signal from simulation is shown in the inset of (a).
The signal. Fits for a shown in Fig. 1. The statistical uncertainties on the total boson search and 12% background in the signal region, taken from the fit, are 8%.

The decay of a Higgs boson into a photon pair would appear as a very narrow peak in the invariant mass distribution of the two photons (see Fig. 1 as an example for the CC sample). The diphoton mass resolution, as determined from simulation and checked using $Z \rightarrow e^+ e^-$ decays in data, is better than 3 GeV/$c^2$ for the Higgs boson mass regions and diphoton channels studied here and is limited by the energy resolution of the EM calorimeters. The mass resolution is also sensitive to the selection of the correct primary vertex of the $p\bar{p}$ interaction, determined by selecting the vertex with the highest sum of associated track momenta. The locations of the vertex and EM energy cluster are used to derive the photon's momentum. For GF (VH and VBF) signal samples, the primary vertex is misidentified in roughly 16% (4%) of nonconversion channel (CC and CP) events, which degrades the resolution of the reconstructed Higgs boson mass [37]. This effect is studied using $Z$ decays in the data and found to be well-modeled in the simulation.

The total background prediction is estimated from a fit made to the data using a binned log-likelihood ($\log \ell$) method [38]. The fit is performed for each $m_H$ hypothesis in 5 GeV/$c^2$ steps from 100 to 150 GeV/$c^2$. At each step, a 12 GeV/$c^2$ mass window centered on the point is excluded, where 12 GeV/$c^2$ is chosen to include 95% of the signal. Fits for a $m_H$ hypothesis of 120 GeV/$c^2$ are shown in Fig. 1. The statistical uncertainties on the total background in the signal region, taken from the fit, are 8% or less for the channels associated with the SM Higgs boson search and 12% or less for the channels associated with the fermiophobic Higgs boson search (except for the high-$p_T^Z$ bins with conversion photons, where it is 27%).

No obvious evidence of a narrow peak or any other anomalous structure is visible in the diphoton mass spectrum. We calculate a Bayesian C.L. limit for each Higgs boson mass hypothesis based on a combination of binned likelihoods for all channels using six bins in the 12 GeV/$c^2$ signal region (2 GeV/$c^2$ bin width) of each mass distribution. We use a flat prior in $\sigma \times \mathcal{B}(H \rightarrow \gamma\gamma)$ and integrate over the priors for the systematic uncertainties. A 95% C.L. limit is determined such that 95% of the posterior density for $\sigma \times \mathcal{B}(H \rightarrow \gamma\gamma)$ falls below the limit [39]. The expected 95% C.L. limits are calculated assuming no signal, based on expected backgrounds only, as the median of 2000 simulated experiments. The observed 95% C.L. on $\sigma \times \mathcal{B}(H \rightarrow \gamma\gamma)$ are calculated from the data. The limit results are displayed in Table II and graphically in Fig. 2. For a SM Higgs boson, the results are shown relative to the theory prediction, where theoretical cross section uncertainties of 14% on the GF process, 6% on the VH process, and 5% on the VBF process are included in the limit calculation [40,41]. Limits are also provided on $\sigma \times \mathcal{B}(H \rightarrow \gamma\gamma)$ without including theoretical cross section uncertainties. The inclusion of systematic uncertainties in the SM (fermiophobic) limit calculation degrades the limit on $\sigma \times \mathcal{B}(H \rightarrow \gamma\gamma)$ by 15% (9%), where the effect of the uncertainty on the background estimate is dominant at 10% (6%).

For the SM limit at $m_H = 120$ GeV/$c^2$, we observe a deviation of greater than 2.5$\sigma$ from the expectation [42]. After accounting for the trials factor associated with performing the search at 11 mass points, the significance of this discrepancy decreases to less than 2$\sigma$. When the analysis is optimized for the fermiophobic benchmark model, no excess is observed. For the $h_f$ model, SM cross sections and uncertainties are assumed (GF excluded) and used to convert limits on $\sigma \times \mathcal{B}(H \rightarrow \gamma\gamma)$ to limits on $\mathcal{B}(h_f \rightarrow \gamma\gamma)$. Table II gives the predicted $\mathcal{B}(h_f \rightarrow \gamma\gamma)$ for this model as calculated using HDECAY [2]. We obtain a lower limit on $m_{h_f}$ of 114 GeV/$c^2$ by linear interpolation between the sampled values of $m_{h_f}$ based on the intersection of the observed limit and the model prediction.

This Letter presents the results of a search for a narrow resonance in the diphoton mass spectrum using data taken by the CDF II detector at the Tevatron. We

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### Table II

<table>
<thead>
<tr>
<th>$m_H$(GeV/$c^2$)</th>
<th>100</th>
<th>105</th>
<th>110</th>
<th>115</th>
<th>120</th>
<th>125</th>
<th>130</th>
<th>135</th>
<th>140</th>
<th>145</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma \times \mathcal{B}(H \rightarrow \gamma\gamma)/\text{SM}$ Expected</td>
<td>16.4</td>
<td>14.8</td>
<td>14.2</td>
<td>13.8</td>
<td>13.3</td>
<td>13.6</td>
<td>14.4</td>
<td>15.8</td>
<td>17.7</td>
<td>20.8</td>
<td>27.5</td>
</tr>
<tr>
<td>Observed</td>
<td>15.1</td>
<td>13.9</td>
<td>8.5</td>
<td>14.6</td>
<td>28.7</td>
<td>19.2</td>
<td>19.2</td>
<td>14.8</td>
<td>23.1</td>
<td>21.9</td>
<td>21.4</td>
</tr>
<tr>
<td>$\sigma \times \mathcal{B}(H \rightarrow \gamma\gamma)$ (fb) Expected</td>
<td>57.3</td>
<td>50.8</td>
<td>47.9</td>
<td>43.2</td>
<td>39.0</td>
<td>36.0</td>
<td>32.8</td>
<td>30.6</td>
<td>28.5</td>
<td>26.7</td>
<td>26.1</td>
</tr>
<tr>
<td>Observed</td>
<td>52.9</td>
<td>47.8</td>
<td>28.8</td>
<td>44.8</td>
<td>84.4</td>
<td>50.4</td>
<td>44.7</td>
<td>29.4</td>
<td>36.9</td>
<td>28.0</td>
<td>20.2</td>
</tr>
<tr>
<td>$\mathcal{B}(h_f \rightarrow \gamma\gamma)$ (%) Expected</td>
<td>4.4</td>
<td>4.9</td>
<td>5.2</td>
<td>5.8</td>
<td>6.0</td>
<td>6.4</td>
<td>6.8</td>
<td>7.4</td>
<td>7.7</td>
<td>8.1</td>
<td>8.7</td>
</tr>
<tr>
<td>Observed</td>
<td>4.8</td>
<td>5.4</td>
<td>2.8</td>
<td>4.2</td>
<td>7.3</td>
<td>5.5</td>
<td>6.6</td>
<td>6.6</td>
<td>5.7</td>
<td>7.8</td>
<td>8.1</td>
</tr>
</tbody>
</table>

The fermiophobic benchmark model prediction for $\mathcal{B}(h_f \rightarrow \gamma\gamma)$ is also shown for comparison.
have improved upon the previous CDF analysis by implementing a neural network discriminant to improve central photon identification, recovering central photons that have converted to an $e^+e^-$ pair, and more than doubling the amount of data analyzed. There is no significant evidence of a resonance in the data. Limits are placed on the production cross section times branching ratio for Higgs boson decay into a photon pair and compared to the predictions of the standard model and a benchmark fermiophobic model. The latter result excludes fermiophobic Higgs boson masses below 114 GeV/$c^2$ at the 95% C.L., which is the strongest limit to date on this model by a single experiment.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science, and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean World Class University Program and the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/ CNRS of France; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; the Academy of Finland; and the Australian Research Council (ARC).

FIG. 2 (color online). (a) As a function of $m_H$, the 95% C.L. upper limit on cross section times branching ratio for the SM Higgs boson decay to two photons, relative to the SM prediction. (b) The 95% C.L. upper limit on the branching ratio for the fermiophobic Higgs boson decay to two photons, as a function of $m_{h_f}$. For reference, the 95% C.L. limits from LEP are also included. The shaded regions represent the 1σ and 2σ probability of fluctuations of the observed limit away from the expected limit based on the distribution of simulated experimental outcomes.
[20] CDF uses a cylindrical coordinate system with $+z$ in the proton beam direction. $\theta$ and $\phi$ are the polar and azimuthal angles, respectively, and pseudorapidity is $\eta = -\ln \tan(\theta/2)$.
[22] The transverse energy $E_T$ and transverse momentum $p_T$ are defined as $E \sin \theta$ and $|p| \sin \theta$, respectively.
[26] Typically, this occurs when a jet fragments into a $\pi^0$ or $\eta$ particle that subsequently decays to multiple photons, which are then reconstructed as a single photon.
[27] The variables also allow the NN method to be applied to electrons, which are used to calibrate ID efficiencies.
[34] We constrain the rate of initial-state radiation using Drell-Yan events in data.
[36] The natural width of the Higgs boson is negligible.
[37] In CC (CP) events, the resolution degrades by 15(15)%.
[38] The combined natural width of the Higgs boson is negligible.
[39] We constrain the rate of initial-state radiation using Drell-Yan events in data.
with a plug photon have a non-negligible contamination from $Z$ boson decays and additionally include a Breit-Wigner function to model this background.


