Search for a low-mass neutral Higgs boson with suppressed couplings to fermions using events with multiphoton final states


(CDF Collaboration)
A search for a Higgs boson with suppressed couplings to fermions, \( h_f \), assumed to be the neutral, lower-mass partner of the Higgs boson discovered at the Large Hadron Collider, is reported. Such a Higgs boson could exist in extensions of the standard model with two Higgs doublets, and could be produced via 

\[ p\bar{p} \rightarrow H^+ h_f \rightarrow W^+ h_f h_f \rightarrow 4\gamma + X, \]

where \( H^\pm \) is a charged Higgs boson. This analysis uses all events with

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at least three photons in the final state from proton-antiproton collisions at a center-of-mass energy of 1.96 TeV collected by the Collider Detector at Fermilab, corresponding to an integrated luminosity of 9.2 fb⁻¹. No evidence of a signal is observed in the data. Values of Higgs-boson masses between 10 and 100 GeV/c² are excluded at 95% Bayesian credibility.

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In the standard model (SM) of particle physics, the masses of elementary particles are generated by the spontaneous breaking of the electroweak gauge symmetry [1], which predicts the existence of the Higgs boson. In 2012, the ATLAS and CMS experiments at CERN’s Large Hadron Collider (LHC) discovered a scalar boson with mass of approximately 125 GeV/c² and properties consistent with those expected for the SM Higgs boson [2,3]. Some evidence for such a boson had also been presented by the Tevatron experiments [4]. The detailed phenomenology of the Higgs boson is, however, yet to be investigated. The possibility that the recently observed Higgs boson is part of an extended Higgs sector is attractive because it would address some relevant open questions about the SM such as the generation of matter-antimatter asymmetry in the Universe [5] and it is not ruled out experimentally.

A minimal extension, the “two-Higgs-doublet model” (2HDM) [6], assumes two doublets of Higgs fields. The resulting particle spectrum for the CP-conserving case consists of three electrically neutral Higgs bosons, h⁰, H⁰ and A⁰, and two charged Higgs bosons, H⁺, H⁻, where h⁰ is less massive than H⁰. The acronym CP represents the combined operations of charge-conjugation and parity transformation. An important parameter for predictions from the model is the ratio tan β of the two vacuum-expectation values for the neutral components of the two Higgs doublets. Assuming that the boson discovered recently at the LHC is the h⁰, searches for additional, more-massive neutral Higgs bosons were performed [7,8], yielding exclusion limits on production cross sections.

In this paper, we consider an alternative case in which the newly discovered boson corresponds to the high-mass H⁰ and the lower-mass h⁰ is yet to be observed. This scenario is poorly constrained experimentally if tan β is large and h⁰ has suppressed couplings to fermions at leading order. The h⁰ is referred to as the fermiophobic Higgs boson (hf). Searches performed at various experiments [9–11] have set lower bounds of its mass, m_hf, at 100–150 GeV/c². These mass limits, however, were obtained assuming simplified models in which the couplings between the hf and electroweak-gauge bosons are of the same strength as those in the SM, which is not necessarily true in the 2HDM, as they may be strongly suppressed when tan β is large [12], by a factor of approximately 10⁻² when tan β = 10, for example. A low-mass hf (m_hf ≲ 100 GeV/c²), therefore, could have eluded the previous searches if tan β is large. To fill this gap in exploring the Higgs sector, we focus on the process qq' → W⁺ → hfH⁺, followed by the decay H⁺ → hfW⁺, where q and q' are quarks and antiquarks in the colliding protons and anti-protons taking part in the hard interaction, and W⁺ represents a virtual W boson. This process, involving H⁺, has enhanced production rates for large tan β [13]. By assuming no couplings to fermions, the branching fraction (B) of hf decays to two photons, hf → γγ, is near 100% for m_hf ≲ 95 GeV/c² [13,14]. The production of two hf particles could result in a distinctive multiphoton topology with small background rates. The couplings of the H⁰ to SM particles in this scenario are similar to those of the SM Higgs boson [13] and we perform the analysis assuming that its mass, m_H⁰, is 125 GeV/c². The decay of H⁰ → hf hf, when it is kinematically allowed and when the coupling is sizable, can also lead to multiphoton final states. We conservatively neglect this contribution to the expected signal. We also assume the A⁰ mass, m_A⁰, to be 350 GeV/c², large enough so as not to contribute to H⁺ decays—the specific choice of m_A⁰ has little effect on the final result, and we take tan β = 10. The expected production cross section multiplied by the appropriate branching fractions ranges approximately from 100 pb to 10 fb for the explored m_hf and the H⁺ mass (m_H⁺) values, from 10 to 105 GeV/c² and from 30 to 300 GeV/c², respectively.

This analysis is based on the entire data set of proton-antiproton collisions at a center-of-mass energy of 1.96 TeV collected with the Collider Detector at Fermilab (CDF II) between February 2002 and September 2011, corresponding to an integrated luminosity of 9.2 fb⁻¹. We select events with multiple photon candidates by applying criteria optimized for achieving the best sensitivity. We compare the observed event yields with background expectations, which are evaluated using a combination of Monte Carlo (MC) simulation and experimental data. A challenge is to estimate the contribution from background events containing clusters of particles (jets) misidentified as photons.

CDF II is a general-purpose detector consisting of tracking devices in a 1.4 T axial magnetic field, surrounded by calorimeters with a projective-tower geometry, and muon detectors surrounding the calorimeters. Gas proportional wire chambers with cathode strips (shower-maximum strip detectors) are located at a depth approximately corresponding to the maximum development of typical electromagnetic (EM) showers to measure precisely
their centroid position and shape in the plane transverse to the shower development. Detailed descriptions of the CDF II detector are in Ref. [15].

The initial data sample is obtained using a real-time event-selection system (trigger) that requires either two EM-energy clusters in the calorimeter, each with $E_T > E \sin \theta > 12$ GeV, or three clusters, each with $E_T > 10$ GeV, where $E$ is the cluster energy measured with the calorimeter, $\theta$ is the polar angle, and $E_T$ is the transverse energy [16]. In the analysis, we select events with at least three EM-energy clusters with $E_T > 15$ GeV. They must be located in the central detector (pseudorapidity magnitude $|\eta| < 1.1$) [16], where reliable tracking of charged particles is available [17]. The photons are also required to be isolated: additional calorimeter $E_T$ in a cone of angular radius $R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.4$ [16] around the photon candidate must be less than 2 GeV, and the scalar sum of transverse momenta of charged particles in the same cone must be less than 2 GeV/c. We then apply photon-identification criteria based on the EM-shower profile, which must be consistent with the expectation for an isolated photon [18]. For photons with $E_T > 15$ GeV in a fiducial region of the central detector, the probability to pass all selections is 80%–90%.

We estimate the reconstruction efficiency for signal events as a function of $m_{jj}$ and $m_{pp}$ using PYTHIA (version 6.4) MC simulation [19]. The generated events are passed through the full detector simulation based on GEANT [20]. The simulation of the EM response of the detector is calibrated by matching the observed energies in samples of $Z \to e^+e^-$ events in the data and the MC simulation [18]. The fractions of generated signal events to pass all event selections are in the range 1%–10% depending on $m_{jj}$ and $m_{pp}$.

Direct triphoton production is a major source of background events. We predict the kinematic distributions from simulated data generated with MADGRAPH (version 5) interfaced with MADEVENT [21] and combined with parton showering from PYTHIA. MADGRAPH provides direct triphoton production using PYTHIA MC and detector simulation, with a final calibration derived by comparing unbiased electrons in $Z \to e^+e^-$ events in the data and the MC simulation. We estimate the probability for misidentifying jets as photons as a function of $E_T$ using isolated jets in data samples collected with inclusive jet triggers. We correct for contributions of genuine photons to the set of objects passing the photon selection in the jet samples based on the differences in the expected distributions of isolation and shower shape variables [18]. Genuine photons tend to be isolated and to have good $\chi^2$ values for the comparison of the observed and expected shower shapes, while misidentified jets show broad distributions in both quantities. These differences enable us to extrapolate the amount of misidentified jets from regions of larger isolation and $\chi^2$ values to the region selected by the photon identification. The fraction of misidentified jets is then estimated to be approximately 30% using the calorimeter-based isolation. The misidentification probability varies from a few percent to 25% depending on the $E_T$.

A third source of background events arises from electroweak processes containing $Z(\to ee)\gamma$, $W(\to ev)\gamma$, $Z(\to \tau\tau)\gamma$, or $W(\to\tau\nu)\gamma$ decays with additional misidentified jets or other photonlike particles that result in the $\gamma\gamma\gamma$ signature. We predict these backgrounds using PYTHIA MC and detector simulation, after normalizing the cross sections to observed $W$ and $Z$ yields in the data.

The total expected number of background events at this stage is $10.3 \pm 0.2$, where the uncertainty is statistical. We observe ten events in the data, which is consistent with the background expectation. None of the observed events contains four or more photons.

In order to further improve the search sensitivity, we apply an additional criterion on the summed $E_T$ of the two highest-$E_T$ photons, $E_T^{p} + E_T^{j}$. To quantify the search sensitivity, we calculate Bayesian [22] expected limits on the product of the cross section and the branching fraction,

$$\sigma(p\bar{p} \to h_jH^\pm) \times B(H^\pm \to h_jW^+) \times [B(h_j \to \gamma\gamma)]^2,$$

with respect to theoretical predictions by integrating posterior probability density functions based on the
predicted number of background events. We assume a uniform prior probability density for the signal rate. The theoretical cross sections at leading order are computed using PYTHIA with an enhancement factor of 1.4 to approximate higher-order contributions. This factor is taken to be the ratio of the $W$ boson production cross section measured by CDF [17] to the corresponding prediction by PYTHIA. This is similar to a calculation of the ratio of the next-to-leading-order prediction to the leading-order prediction of $1.3 \pm 0.3$ for Higgs boson pair production in Drell-Yan-like processes at the LHC [23], and we note that the central values, which are expected to be similar, are within the theoretical uncertainty on the Higgs boson pair production prediction, which is much larger than the experimental uncertainty on the $W$ boson enhancement factor. Because the $h_f$ signal production process under study begins with $W$ boson production, we use the measured $W$ boson production enhancement factor, but we use the uncertainty on the theoretical prediction, $\pm 0.3$, as an estimate of the uncertainty in extrapolating the enhancement factor from one process to the other. The branching fractions are calculated with the 2HDMC program (version 1.6.5) [24]. The expected limit is the median in a large set of simulated experiments based on the Poisson fluctuation of the background events. We choose $E_T^{\gamma} + E_T^{\gamma} > 90$ GeV as the final requirement because it provides the best expected limit. Figure 1 shows the predicted and observed distributions of $E_T^{\gamma} + E_T^{\gamma}$ and includes the requirement defining the signal region. We compare the background distribution and the expected signal distribution for a signal point having $m_{h_f} = 75$ GeV/c$^2$ and $m_{H^\pm} = 120$ GeV/c$^2$.

The main systematic uncertainty on the signal efficiency comes from that on the estimation of the identification efficiency for three photons, which is 8% of the total efficiency based on studies comparing $Z \rightarrow e^+e^-$ in data and simulation [18] by assuming full correlation among three photons. Other sources of systematic uncertainties include those on the parton momentum distributions in the colliding hadrons, the initial- and final-state radiation of a gluon, and the renormalization scale, which are each found to contribute less than 3% of the total efficiency [18].

We compare the MADGRAPH cross section with MCFM [25] calculations that take into account different higher-order contributions and take the resulting difference of 0.83 events as a systematic uncertainty on the yield of direct triphoton events. The systematic uncertainty from the renormalization scale, that from the initial- and final-state radiation, and that from the luminosity measurement [26] range from 0.16 to 0.21 events. We estimate the total systematic uncertainty on the expected yield of events with misidentified jets to be 0.17 events, which includes the contribution from the measurement of the misidentified-jet probability and that from the possible difference of the probabilities between jets originating from quarks and gluons. The dominant uncertainty on the electroweak contribution originates from the limited size of the simulated event samples used to estimate the small probability to find an extra photonlike particle in the $W(\rightarrow e\nu)\gamma\gamma$ events.

Table I shows the expected number of background events and the number of events found in data after the final selection. We find five candidate events in data, which is consistent with the expected number of background events.

We check the background predictions using background-rich control samples. In events containing one lower-quality photon candidate that passes the loose selection but fails the full selection, the predicted and observed numbers of events are $372 \pm 68$ and $370$, respectively. In events with $E_T^{\gamma} + E_T^{\gamma} < 90$ GeV, $6.6 \pm 1.7$ events are predicted and five events observed. The observed agreement supports the reliability of the background estimation.

We perform a Bayesian limit calculation restricted to events observed in the signal region, $E_T^{\gamma} + E_T^{\gamma} > 90$ GeV,

![Graph showing distribution of $E_T^{\gamma} + E_T^{\gamma}$ in events containing three or more photons for data, SM background prediction, and hypothetical signal for a signal point having $m_{h_f} = 75$ GeV/c$^2$ and $m_{H^\pm} = 120$ GeV/c$^2$.]

**Table I.** Expected number of background events compared to the observed number of events after the final event selection. The first contribution to the uncertainty is statistical and the second is systematic.

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Events in signal region $(E_T^{\gamma} + E_T^{\gamma} &gt; 90$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct triphoton</td>
<td>$2.60 \pm 0.04 \pm 0.93$</td>
</tr>
<tr>
<td>Misidentified jets</td>
<td>$0.32 \pm 0.07 \pm 0.17$</td>
</tr>
<tr>
<td>Electroweak</td>
<td>$0.04 \pm 0.01 \pm 0.03$</td>
</tr>
<tr>
<td>Total</td>
<td>$2.96 \pm 0.08 \pm 0.94$</td>
</tr>
<tr>
<td>Data</td>
<td>5</td>
</tr>
</tbody>
</table>
as a function of $m_{h_f}$, ranging from 10 to 105 GeV/$c^2$, and $m_{H^+}$, ranging from 30 to 300 GeV/$c^2$. We include systematic uncertainties due to the signal efficiency, the predicted number of background events, and the luminosity, as well as the theoretical uncertainty of 20% on the cross section of Higgs boson production [23]. Figure 2 shows the expected and the observed cross section limits at 95% credibility for a particular choice of $m_{h_f}$ and $m_{H^+}$, with possible variations of the expected limits obtained by assuming 68% or 95% of Poisson fluctuations of the number of background events. From Fig. 2, the $m_{h_f}$ region between 14 and 62 GeV/$c^2$ is excluded for $m_{H^+} = 75$ GeV/$c^2$. Connecting the boundary regions of the excluded $m_{h_f}$ region for various values of $m_{H^+}$ in the $m_{h_f}$ vs $m_{H^+}$ plane, we form contours of the excluded mass regions and present them in Fig. 3. The region of parameters given by $m_{h_f}$ between 10 and 100 GeV/$c^2$ and $m_{H^+}$ between 30 and 170 GeV/$c^2$ is excluded for tan $\beta = 10$. This is the first search for a fermiophobic neutral Higgs boson with mass smaller than the boson discovered at the LHC in the two-Higgs-doublet model.

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[16] CDF uses a cylindrical coordinate system with \( +z \) in the proton beam direction, \( \theta \) and \( \phi \) are the polar and azimuthal angles, respectively, and \( \eta \) is the pseudorapidity defined by \( \eta = -\ln \tan(\theta/2) \).