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Search for a Low-Mass Neutral Higgs Boson with Suppressed Couplings to Fermions Using Events with Multiphoton Final States

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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 $p\bar{p}\to H^{\pm}h_f \to W^{*}h_f h_f \to 4\gamma + X$, where $H^{\pm}$ is a charged Higgs boson. This analysis uses all events with 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/c^2 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/c^2 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 and it is not ruled out experimentally.

A minimal extension, the "two-Higgs-doublet model" (2HDM) [5], assumes two doublets of Higgs fields. The resulting particle spectrum for the *CP*-conserving case consists of three electrically neutral Higgs bosons, h^0, H^0 and A^0, and two charged Higgs-bosons, H^+, H^-, where h^0 is less massive than H^0. The acronym *CP* represents the combined operations of charge-conjugation and parity transformation. An important parameter for predictions from the model is the ratio $\tan\beta$ 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 h^0, searches for additional, more-massive neutral Higgs bosons were performed [6, 7], yielding exclusion limits on production cross sections.

In this Letter, we consider an alternative case in which the newly-discovered boson corresponds to the high-mass H^0 and the lower-mass h^0 is yet to be observed. This scenario is poorly constrained experimentally if $\tan\beta$ is large and h^0 has suppressed couplings to fermions at leading order. The h^0 is referred to as the fermiophobic Higgs boson (h_f). Searches performed at various experiments [8–10] have set lower bounds of its mass, m_{h_f}, at 100–150 GeV/c^2. These mass limits, however, were obtained assuming simplified models in which the couplings between the h_f 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 $\tan\beta$ is large [11], by a factor of approximately 10^{-2} when $\tan\beta = 10$, for example. A low-mass h_f ($m_{h_f} \lesssim 100$ GeV/c^2), therefore, could have eluded the previous searches if $\tan\beta$ is large. To fill this gap in exploring the Higgs sector, we focus on the process $q\bar{q}' \to W^* \to h_f H^{\pm}$, followed by the decay $H^{\pm} \to h_f W^*$, where q and $\bar{q}'$ are quarks and antiquarks in the colliding protons and antiprotons taking part in the hard interaction, and W^* represents a virtual W boson. This process, involving $H^{\pm}$, has enhanced production rates for large $\tan\beta$ [12]. By assuming no couplings to fermions, the branching fraction ($\mathcal{B}$) of h_f decays to two photons, $h_f \to \gamma\gamma$, is near 100% for $m_{h_f} \lesssim 95$ GeV/c^2 [12, 13]. The production of two h_f particles could result in a distinctive multiphoton topology with small background rates. The couplings of the H^0 to SM particles in this scenario are similar to those of the SM Higgs boson [12] and we perform the analysis assuming that its mass, m_{H^0}, is 125 GeV/c^2. We also assume the A^0 mass, m_{A^0}, to be 350 GeV/c^2, large enough so as not to contribute to $H^{\pm}$

decays – the specific choice of m_{A^0} has little effect on the final result, and we take $\tan\beta = 10$.

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. [14].

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 $E_T \equiv E\sin\theta > 12$ GeV, or three clusters, each with $E_T > 10$ GeV, where E is the cluster energy measured with the calorimeter, θ is the polar angle, and E_T is the transverse energy [15]. In the analysis, we select events with at least three EM energy clusters with $E_T > 15$ GeV in the central detector (pseudorapidity magnitude $|\eta| < 1.1$) [15]. The photons are also required to be isolated: additional calorimeter E_T in a cone of angular radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ [15] 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.

We estimate the reconstruction efficiency for signal events as a function of m_{h_f}, from 10 to 105 GeV/c^2 with a typical step size of 5 GeV/c^2, and of the $H^\pm$ mass, $m_{H^\pm}$, from 30 to 300 GeV/c^2 with a typical step size of 10 GeV/c^2, using PYTHIA (version 6.4) MC simulation [16]. The generated events are passed through the full detector simulation based on GEANT [17]. 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 efficiencies, before applying any further selection criteria to increase the search sensitivity, are within 1–10%, depending on m_{h_f} and $m_{H^\pm}$.

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 [19] and combined with parton showering from PYTHIA. MadGraph provides direct triphoton production with up to two additional jets. The generated events are passed through the full detector simulation and we apply the same photon selection as that used for data.

Another source of background is the production of events with jets misidentified as photons. For estimating this contribution, we introduce a loose photon selection by choosing a subset of the selection criteria. In a sample of three-photon candidates selected with the loose selection, there are eight possible combinations of E_T-ordered photons and EM-like jets, $\gamma\gamma\gamma$, $\gamma\gamma j$, $\cdots$, where j represents an EM-like jet. The numbers of these events are unknown and we express them by a vector $\boldsymbol{n}^*$ of event counts ($n^*_{\gamma\gamma\gamma}$, $n^*_{\gamma\gamma j}$, $\cdots$). By applying the full set of criteria for the photon selection, we categorize the events in eight classes depending on whether each of the photon candidates in a given event passes (p) or fails (f) the full photon selection (n_{ppp}, n_{ppf}, $\cdots$), denoted by $\boldsymbol{n}$. The components of $\boldsymbol{n}^*$ are obtained by solving eight linear equations $\boldsymbol{n} = \boldsymbol{E}\boldsymbol{n}^*$, where $\boldsymbol{E}$ is an 8×8 matrix, the elements of which are calculated from the probability for a genuine photon or jet that meets the loose selection to also meet the full photon selection. Once $\boldsymbol{n}^*$ is obtained by inverting the matrix $\boldsymbol{E}$, we estimate the misidentified-jet contribution to n_{ppp} using $\boldsymbol{E}$ and the calculated elements of $\boldsymbol{n}^*$ except $n^*_{\gamma\gamma\gamma}$. Statistical uncertainties are propagated to $\boldsymbol{n}^*$. 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 objects passing the photon selection in the jet samples, which is approximately 70%, based on the differences in the expected distributions of isolation and shower shape between the misidentified jets and genuine photons. 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 $Z(\to ee)\gamma$, $W(\to e\nu)\gamma$, $Z(\to\tau\tau)\gamma$, or $W(\to\tau\nu)\gamma$ decays with additional misidentified jets or other photon-like particles that result in the $\gamma\gamma\gamma$ signature. We investigate these processes using MC simulation and calibrate the rates with experimental data.

The total expected number of background events at this stage is 10.3±0.2, where the uncertainty is statistical. We observe 10 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, $E_T^{\gamma_1} + E_T^{\gamma_2}$. To quantify the search sensitivity, we calculate Bayesian [20] expected limits on the product of the cross section and the branching fraction

$$\sigma(p\bar{p} \to h_f H^{\pm}) \times \mathcal{B}(H^{\pm} \to h_f W^*) \times [\mathcal{B}(h_f \to \gamma\gamma)]^2 ,$$

with respect to theoretical predictions by integrating posterior probability density functions based on predicted number of background events. We assume a uniform prior probability densityfor 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, based on theoretical estimation and cross-section measurements of known processes [21]. The branching fractions are calculated with the 2HDMC program (version 1.6.5) [22]. The expected limit is the median in a large set of simulated experiments based on the Poisson fluctuation of the background events. We choose $E_T^{\gamma_1} + E_T^{\gamma_2} > 90$ GeV as the final requirement because it provides the best expected limit. Figure 1 shows the predicted and observed distributions of $E_T^{\gamma_1} + E_T^{\gamma_2}$ 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 $Z \to e^+e^-$ 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.

We compare the MadGraph cross section with MCFM [23] 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 [24] 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

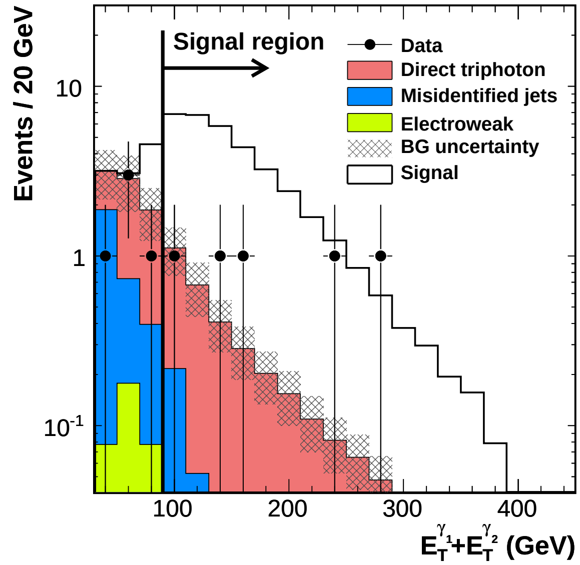

FIG. 1. Distribution of $E_T^{\gamma_1} + E_T^{\gamma_2}$ in events containing three or more photons for data, SM background prediction, and hypothetical signal for a signal point having $m_{h_f} = 75$ GeV$/c^2$ and $m_{H^{\pm}} = 120$ GeV$/c^2$.

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.

	Events in signal region ($E_T^{\gamma_1} + E_T^{\gamma_2} > 90$ GeV)
Direct triphoton	2.60 ± 0.04 ± 0.93
Misidentified jets	0.32 ± 0.07 ± 0.17
Electroweak	0.04 ± 0.01 ± 0.03
Total	2.96 ± 0.08 ± 0.94
Data	5

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 photon-like particle in the $W(\to e\nu)\gamma$ events.

Table I shows the expected number of background events and the number of events found in data after the final selection. We find 5 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

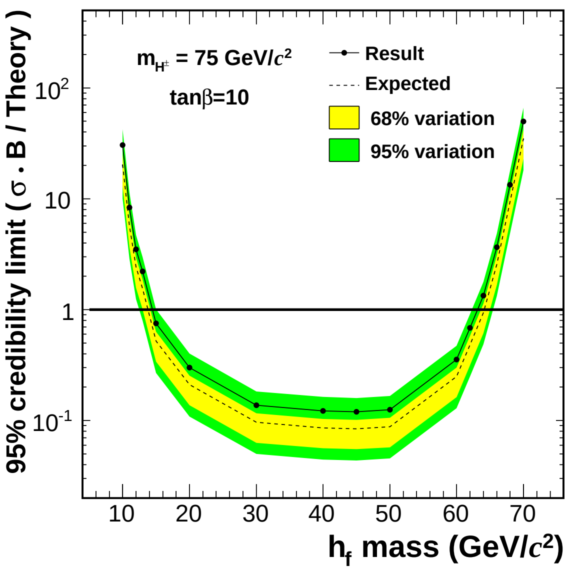

FIG. 2. Upper limit at 95% credibility on the cross-section ratio with respect to theory predictions, calculated for the final selection, including the $E_T^{\gamma_1} + E_T^{\gamma_2} > 90$ GeV requirement. The solid line is the obtained limit, the dashed line is the expected limit, and the shaded regions cover the 68% and 95% of possible variations of expected limit values based on the Poisson statistics of the expected number of background events.

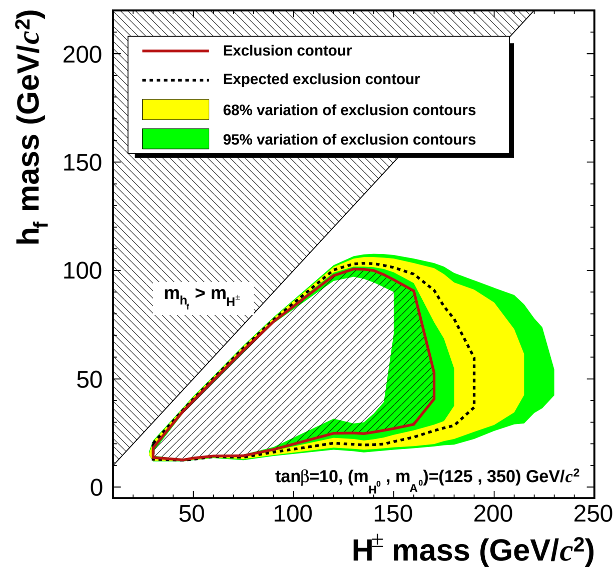

FIG. 3. Excluded mass region at a 95% credibility, calculated for the final selection. The solid curve is the contour enclosing the exclusion region, the dashed line encloses the median expected exclusion region, and the shaded regions cover the 68% and 95% of possible variations of expected contours based on the Poisson statistics of the expected number of background events.

the loose selection but fails the full selection, the predicted and observed numbers of events are 372 ± 68 and 370, respectively. In events with $E_T^{\gamma_1} + E_T^{\gamma_2} < 90$ GeV, 6.6 ± 1.7 events are predicted and 5 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, $E_T^{\gamma_1} + E_T^{\gamma_2} > 90$ GeV, as a function of m_{h_f}, ranging from 10 to 105 GeV/c^2, and $m_{H^\pm}$, 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 [21]. Figure 2 shows the expected and the observed cross section limits at 95% credibility for a particular choice of m_{h_f} and $m_{H^\pm}$, 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 $m_{H^\pm} = 75$ GeV/c^2. Connecting the boundary regions of the excluded m_{h_f} region for various values of $m_{H^\pm}$ in the m_{h_f} vs. $m_{H^\pm}$ 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 $m_{H^\pm}$ between 30 and 170 GeV/c^2 is excluded. The result does not change significantly if we repeat the analysis by assuming $\tan\beta = 30$, while the excluded region shrinks by approximately 20 GeV/c^2 for both of m_{h_f} and $m_{H^\pm}$ for $\tan\beta = 3$.

In conclusion, we report on a search for the fermiophobic Higgs boson in the two-Higgs-doublet model using events with at least three photons in the final state, resulting from the hypothetical process $p\overline{p}\to h_f H^\pm$ followed by $H^\pm \to h_f W^*$ and $h_f \to \gamma\gamma$. The observed number of signal candidate events in data is consistent with the expected number of background events. We calculate the upper limit on the product of the cross section and the branching fraction at 95% Bayesian credibility for m_{h_f} values ranging from 10 to 105 GeV/c^2 and for $m_{H^\pm}$ values ranging from 30 to 300 GeV/c^2, and then translate these limits into an excluded region in the m_{h_f} vs. $m_{H^\pm}$ plane, shown in Fig. 3. The region of parameters given by m_{h_f} between 10 and 100 GeV/c^2 and $m_{H^\pm}$ 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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