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Search for the Neutral Higgs Boson Decaying to a W boson pair in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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Abstract

We present the results of a search for standard model (SM) Higgs boson production with decay to WW^*, identified through the leptonic final states $e^+e^-\bar{\nu}\nu$, $e^\pm\mu^\mp\bar{\nu}\nu$ and $\mu^+\mu^-\bar{\nu}\nu$. This search uses approximately 360 pb^{-1} of data collected from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV by the upgraded Collider Detector at Fermilab (CDF II). We observe no signal excess and set 95% Bayesian credibility level upper limits on $\sigma(gg \to H)\times$ BR$(H \to WW^*)$. These upper limits range from 8.4 to 3.2 pb, for Higgs boson masses between 110 and 200 GeV/c^2.

The Higgs mechanism is a leading candidate for the mechanism behind electroweak symmetry breaking (EWSB) and consequently for mass generation of the W and Z bosons without violating the local gauge invariance. A manifestation of this mechanism is the existence of a neutral scalar particle, the Higgs boson, which has not been observed to date. Its mass is a free parameter in the SM, but its couplings to other particles of known mass are fully specified at tree level. Direct searches at the CERN e^+e^- collider (LEP) yielded a lower limit for the Higgs boson mass of $m_H > 114.4$ GeV/c^2[1] at 95% CL. Indirect measurements from precision electroweak data fits predict a Higgs boson mass of $m_H = 91^{+45}_{-32}$ GeV/c^2 and provide an upper bound of $m_H \leq 186$ GeV/c^2[2] at 95% CL.

At the Tevatron, the dominant production mechanism for the SM Higgs boson is gluon-gluon fusion through heavy quark loops. There are various decay channels for the SM Higgs with branching fractions dependent on the Higgs mass. For masses below about 135 GeV/c^2 the dominant decay is $H \to b\bar{b}$, while heavier Higgs bosons decay predominantly to WW^* [3]. For low mass Higgs bosons, production in association with vector bosons ($p\bar{p} \to WH/ZH$) provides the most sensitive channels for searches at the Tevatron [4], because one can significantly increase the signal purity using the leptonic decays of the vector boson. For heavier Higgs masses one can achieve the highest sensitivity from single Higgs production using the leptonic W boson decays. The next-to-leading order (NLO)[3] production cross section times branching ratio for a SM Higgs boson, $\sigma(p\bar{p} \to H) \times \mathrm{BR}(H \to WW^*)$, ranges from 0.036 to 0.25 pb over the Higgs mass window 110-200 GeV/c^2.

This Letter presents the results of a search for a Higgs boson in the channel $gg \to H \to WW^* \to \ell^+\nu\ell^-\bar{\nu}$ (ℓ=e, μ, τ), identified by the "dilepton" final states $e^+e^-, e^\pm\mu^\mp$ or $\mu^+\mu^-$. Tau leptons can be included if they decay leptonically, but they are not explicitly identified in this analysis. This is the first search in this channel by the CDF Collaboration. A similar search in this channel was performed by the DØ collaboration using Tevatron Run 2 data[5]. The data sample was collected with the CDF II detector at the Fermilab Tevatron between 2002 and 2004, and corresponds to an integrated luminosity of approximately 360 pb^{-1}[6]. This search is also sensitive to extensions of the SM; for example, a fourth generation fermion family[7] would enhance the observed signal of gluon-gluon fusion Higgs production events.

The CDF II detector is an azimuthally and forward-backward symmetric detector, described in Ref[8]. It consists of a charged-particle tracking system immersed in a 1.4 T magnetic field and segmented electromagnetic and hadronic calorimeters surrounded by muon detectors. A silicon micro-strip vertex detector (SVX) provides tracking for the radial range 1.5 to 28 cm. The radial region from 40 to 137 cm is equipped with a 3.1 m long open-cell drift chamber, the Central Outer Tracker (COT). The electromagnetic and hadronic sampling calorimeters surrounding the solenoid are used to measure the energy of interacting particles in the pseudo-rapidity range $|\eta|$ <3.6[9]. The calorimeters are divided into projective geometry towers. This analysis used both central ($|\eta| < 1.1$) and end-plug detectors (1.2< $|\eta|$ <2.0) to identify electron candidates. A set of drift chambers located outside the central hadron calorimeters and another one behind a 60 cm iron shield help detect muons in the region $|\eta| < 0.6$. Additional drift chambers and scintillation counters detect muons in the region $0.6 \leq |\eta| \leq 1.0$.

A three-level trigger system is used in CDF[10] to select the events for data analysis. The events for this analysis are collected by three triggers: an inclusive central electron ($|\eta| < 1.1$) trigger, requiring an electron $E_T > 18$ GeV[11], an inclusive central muon ($|\eta| < 1.0$) trigger requiring a muon with $P_T > 18$ GeV/c [11], and a trigger for events with a forward electron ($1.2 \leq |\eta| \leq 2.0$), with $E_T > 20$ GeV [12] and large missing energy[13], $\not\!\!E_T > 15$ GeV.

After the event reconstruction, event selection criteria which retain high $H \to WW$ signal efficiency while minimizing the effect of background contamination are applied. Some selection requirements are mass dependent, as the event kinematics and topology change when varying m_H. We investigated ten Higgs masses ranging from 110 to 200 GeV/c^2 in 10 GeV/c^2 increments.

The selection requires two oppositely signed leptons from the same vertex, with transverse momenta $P_T > 20$ GeV/c for the trigger lepton and $P_T > 10$ GeV/c for the second one. The leptons are required to be isolated in both the calorimeter [14] and the tracking chamber [15] in order to reject jets misidentified as leptons or leptons from semileptonic decays of heavy quarks. The dilepton invariant mass $m_{\ell\ell}$ is required to be greater than 16 GeV/c^2, to remove events from the $c\bar{c}/b\bar{b}$ continuum spectrum.

After removal of cosmic ray events and electrons from photon conversions, the jets in the event are counted. A jet is defined as a cluster of calorimeter towers above an energy threshold of 3 GeV, with fixed radius $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$. The raw jet transverse energy is corrected for the calorimeter response and multiple interactions[16]. We require that the jets have $E_T > 15$ GeV and $|\eta| < 2.5$. Signal events do not typically have high-E_T jets in the final state, but can occasionally have lower-E_T jets from initial state gluon radiation. On the other hand, the $t\bar{t}$ pairs decay primarily to $W^+W^-b\bar{b}$ and thus tend to have at least two jets in the final state. This background is reduced by selecting only events satisfying one of the following criteria: no jets with E_T >15 GeV, or only one jet with $E_T <$ 55 GeV, or 2 jets, each with $E_T <$ 40 GeV. Events with more than two jets with E_T >15 GeV are also rejected.

After the cuts described above, the dominant surviving background is due to Z/γ^*, which is suppressed by requiring that $\not{E}_T > m_H/4$. The events with missing energy due to a mis-measurement of the jet energy, or $Z \to \tau\tau$ events with missing energy arising from a leptonic decay are removed by requiring that $\not{E}_T$ vector be at least 20° from the closest jet or lepton. This requirement is applied only if $\not{E}_T <$ 50 GeV and is very efficient for low Higgs masses. To further reduce the large Z/γ^* background, the dilepton invariant mass is required to be $m_{\ell\ell} < (m_H/2 - 5)$ GeV/c^2. Finally, the sum of the P_T of the two leptons and the $\not{E}_T$ is required to be below the Higgs mass.

The topological cuts to try to separate the signal from SM WW production are motivated by the fact that the Higgs boson is a spin-zero particle with its decay to WW conserving the spin. Due to helicity conservation in the W boson leptonic decay, the final state electrons and muons tend to be more collinear than for SM WW production. The same is true for the neutrinos in the event. This implies that the signal events tend to have larger missing energy, smaller azimuthal angle between leptons and a smaller dilepton invariant mass, $m_{\ell\ell}$, as compared with WW production.

The acceptance for identifying $H \to WW^* \to \ell\nu\ell\nu$ events with the above selection criteria is calculated as a function of the Higgs boson mass using PYTHIA 6.2[17] Monte Carlo samples, after a GEANT-based[18] simulation of the CDF detector response. The total acceptance is a product of the geometric and kinematic acceptance, the lepton identification efficiencies, the trigger efficiencies and the topological cut efficiencies. It does not include the branching fraction of W leptonic decays. The total acceptance ranges from 2.0% to 6.5%, depending on the Higgs mass and is summarized in Table I. Approximately 25% of the expected signal are ee events, 25% $\mu\mu$, and 50% $e\mu$.

The systematic uncertainty on the acceptance of 6% results from uncertainties in the modeling of the initial state radiation by PYTHIA (3%), uncertainty on the gluon parton distribution functions (4%)[19], jet energy scale (1%), track isolation (<2%), electron and muon trigger efficiencies(<1%), electron and muon identification efficiencies (2%). In addition there is an uncertainty on the integrated luminosity (6%), which applies to signal and any backgrounds.

TABLE I: The branching ratio BR($H \to WW^*$), the total acceptance of the signal after all the cuts, with respect to the signal dilepton events $WW^* \to \ell^+\nu\ell^-\bar{\nu}$ produced.

M_H (GeV/c^2)	120	140	160	180	200
BR(H$\to WW^*$)	0.13	0.48	0.90	0.94	0.74
Total acceptance(%)	3.15	4.58	6.48	6.43	6.06

TABLE II: The expected number of signal and SM background events are presented. The number of events observed in the data are also shown.

M_H (GeV/c^2)	120	140	160	180	200
WW	5.49 $\pm$ 0.66	7.98 $\pm$ 0.96	9.79 $\pm$ 1.18	9.89 $\pm$ 1.19	9.19 $\pm$ 1.11
Z/γ^*	1.63 $\pm$ 0.42	1.01 $\pm$ 0.26	0.76 $\pm$ 0.20	0.83 $\pm$ 0.21	0.96 $\pm$ 0.25
W+jets/γ/Multi-jets	4.57 $\pm$ 0.90	3.49 $\pm$ 0.81	2.48 $\pm$ 0.69	1.70 $\pm$ 0.46	1.20 $\pm$ 0.37
$WZ + ZZ$	0.25 $\pm$ 0.03	0.37 $\pm$ 0.05	0.40 $\pm$ 0.05	0.49 $\pm$ 0.07	1.16 $\pm$ 0.15
$t\bar{t}$	0.12 $\pm$ 0.01	0.21 $\pm$ 0.02	0.35 $\pm$ 0.04	0.46 $\pm$ 0.05	0.58 $\pm$ 0.06
Total Background	12.07 $\pm$ 1.19	13.08 $\pm$ 1.28	13.78 $\pm$ 1.38	13.37 $\pm$ 1.30	13.09 $\pm$ 1.21
$H \to WW^*$	0.09 $\pm$ 0.008	0.32 $\pm$ 0.03	0.58 $\pm$ 0.05	0.41 $\pm$ 0.03	0.21 $\pm$ 0.02
Data	7	14	16	19	17

After all selection requirements, the background events come predominantly from WW pair production (about 70% of the total for $m_H = 160$ GeV/c^2), Z/γ^*, W+jets, and W+γ. Smaller backgrounds include WZ, ZZ and $t\bar{t}$ production. A summary of these contributions as a function of Higgs mass is given in Table II. The diboson (WW, WZ, ZZ) and $t\bar{t}$ backgrounds are determined using PYTHIA samples, followed by the CDF II detector simulation. We normalize the total number of events for these processes to the latest theoretical cross-sections. For $t\bar{t}$ we use a cross-section of 6.7 pb, for m_t= 175 GeV/c^2[20]. To estimate the W+γ background we use a matrix element generator[21] that includes initial and final state photon radiation and the $WW\gamma$ vertex diagram; we use PYTHIA for the initial state QCD radiation and hadronization.

The background from W+jets, where a jet is misidentified as a lepton (electron/muon), is completely determined from the data. First we determine the probability for a jet with a large fraction of the energy deposited in electromagnetic calorimeter be misidentified as an electron, or for a minimum ionizing track be misidentified as a muon. This probability is termed as the fake rate. The fake rate is calculated using an average of four inclusive jet samples (triggered with at least one jet with $E_T > 20$ GeV, 50 GeV, 70 GeV or 100 GeV). We remove the sources of real leptons, W and Z decays, and parametrize the fake rate as a function of jet transverse energy (for electrons) or track transverse momentum (for muons). The background is determined by weighting the jets from the data sample of $Wj \to \ell\nu$+jet events by the fake rate. To check the fake background estimate we compare the number of observed same-sign dilepton events to the fake background prediction and find good agreement.

For data events passing the previously described selection criteria, we search for an excess of events with small azimuthal angle between the leptons, denoted as $\Delta\phi$. A binned likelihood is used to compare the azimuthal angle distribution in the data with a combination of expected distributions from the SM background processes. Figure 1 shows the azimuthal angle distributions for SM backgrounds, for the SM Higgs masses of 130 and 170 GeV/c^2, and for the data. Since no excess is observed over the SM expectations, we calculate upper limits on the production cross section times branching ratio $\sigma(p\bar{p} \to H)\times$ BR$(H \to WW^*)$ using a Bayesian procedure. We consider three components in the data: $H \to WW^*$, WW and other SM processes (WZ, ZZ, Drell Yan, W+jets/γ) labeled as "others". The expected number of events in each $\Delta\phi$ bin is

$$\mu = f_{WW} \cdot n_{WW} + f_{others} \cdot n_{others} + f_{HWW} \cdot (\epsilon \cdot \mathcal{L} \cdot \sigma_{HWW} \cdot BR(H \to WW^*)), \qquad (1)$$

where f_{WW}, f_{others} and f_{HWW} represents the expected fraction of events in each $\Delta\phi$ bin, n_{WW}, n_{others} are the expected numbers of WW and non-WW background events, while ϵ, $\mathcal{L}$ and σ_{HWW} correspond to efficiency, integrated luminosity and $H \to WW^*$ cross-section. A posterior density is obtained by multiplying the Poisson likelihood function with Gaussian prior densities for the integrated luminosity, background normalizations, and the signal efficiency.

$$L = \prod_{i=1}^{N_{bins}} \frac{\mu_i^{n_i} \cdot e^{-\mu_i}}{n_i!} \times G(n_{WW}, \sigma_{WW}) \times G(n_{others}, \sigma_{others}) \times G(\epsilon, \sigma_\epsilon) \times G(\mathcal{L}, \sigma_{\mathcal{L}}) \qquad (2)$$

where n_i is the number of events observed in the data and $G(n, \sigma_n)$ are Gaussian constraints for parameter n with uncertainty σ_n. The prior density for $\sigma(p\bar{p} \to H)\times$ BR$(H \to WW^*)$ is assumed uniform. The posterior density is then integrated over all parameters except $\sigma(p\bar{p} \to H)\times$ BR$(H \to WW^*)$, for which a 95% credibility level (CL) upper limit is obtained by calculating the 95$^{\text{th}}$ percentile of the resulting distribution.

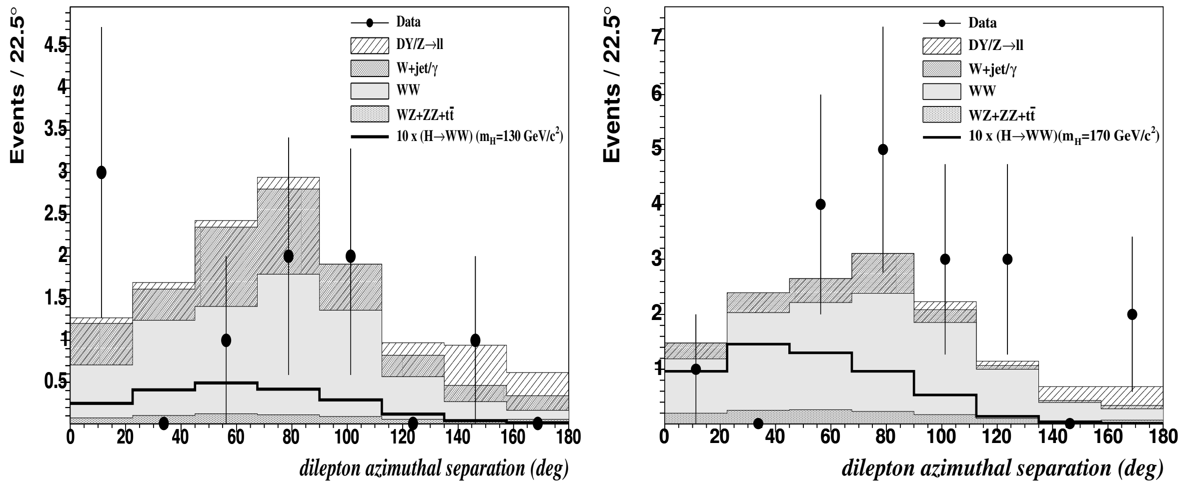

FIG. 1: Dilepton azimuthal distributions for SM backgrounds, HWW signal and data are shown for two Higgs masses: 130 GeV/c^2 and 170 GeV/c^2.

The expected and observed upper limits on the cross section times branching ratio $\sigma(p\bar{p} \to H)\times$ BR$(H \to WW^*)$ for different Higgs masses are shown in Table III. The expected limits are calculated using 1000 pseudo-experiments, assuming no signal, for each Higgs mass. The median is chosen as the *a priori* upper limit.

TABLE III: The expected and observed 95% CL limits on $\sigma(gg \to H)\times$ BR$(H \to WW^*)$.

M_H (GeV/c^2)	120	140	160	180	200
Expected Limits (pb)	7.1	4.8	3.5	3.4	3.6
Observed Limits (pb)	4.5	4.6	3.2	4.3	4.6

In conclusion, we have searched for SM Higgs boson production using the decay $H \to WW^*$ with the subsequent decay of the W bosons to leptons. We observe good agreement between the data and the SM expectation in both event yield and kinematic distributions. Given that no excess is observed, we set mass dependent limits at 95% CL on $\sigma\times$ BR($H \to$WW).

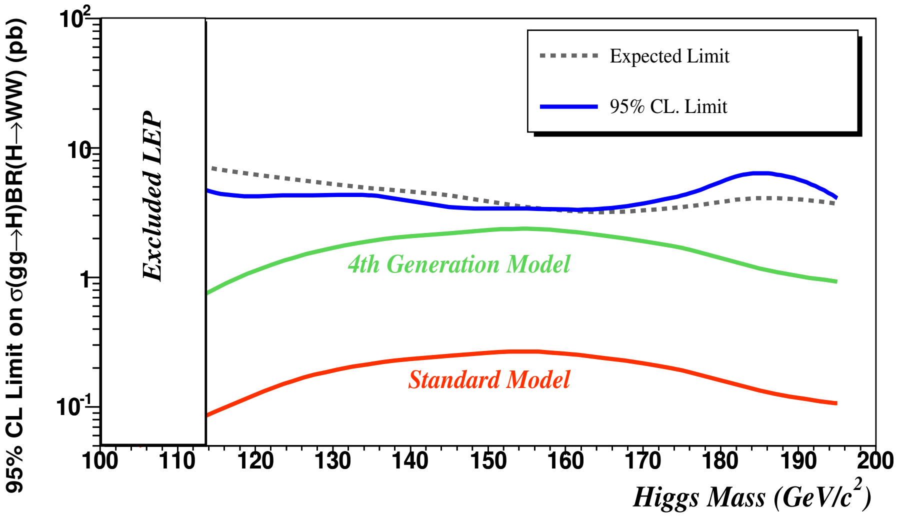

FIG. 2: Summary of the Run II CDF 95% credibility level upper limits on $\sigma(p\bar{p} \to H)\times\mathrm{BR}(H \to WW^*)$. Shown for comparison is the standard model prediction, and the region excluded by the LEP experiments.

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[14] The calorimeter isolation I_{cal} is defined as the extra energy deposited in the calorimeter cone of radius $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$ around the lepton cluster. The I_{cal} is required to be less than 10 % of the lepton E_T.

[15] The track isolation I_{trk} is defined as the sum p_T of all the tracks in a cone of radius $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$ around the lepton candidate track, but excluding it. The I_{trk} is required to be less than 10% of the lepton track P_T.

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