Search for the Standard Model Higgs Boson in the $H \rightarrow WW \rightarrow l\nu q'\bar{q}$ Decay Channel

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We present a search for the standard model Higgs boson (H) in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV in events containing a charged lepton (ℓ), missing transverse energy, and at least two jets, using 5.4 fb^{-1} of integrated luminosity recorded with the D0 detector at the Fermilab Tevatron Collider. This analysis is sensitive primarily to Higgs bosons produced through the fusion of two gluons or two electroweak bosons, with subsequent decay $H \to WW \to \ell\nu q'\bar{q}$, where ℓ is an electron or muon. The search is also sensitive to contributions from other production channels, such as $WH \to \ell\nu b\bar{b}$. In the absence of a signal, we set limits at the 95% C.L. on the cross section for H production $\sigma(p\bar{p} \to H + X)$ in these final states. For a mass of $M_H = 160$ GeV, the limit is a factor of 3.9 larger than the cross section in the standard model and consistent with an *a priori* expected sensitivity of 5.0.

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The Higgs mechanism [1–4] accommodates the observed breaking of electroweak symmetry in the standard model (SM). In addition to generating masses for the electroweak W and Z bosons, as well as for fermions, the theory predicts a scalar Higgs boson (H) with well-determined couplings but unknown mass (M_H). Confirmation of the existence and properties of the H boson would be a key step in elucidating the origins of electroweak symmetry breaking. For a Higgs boson with mass $M_H \gtrsim 135$ GeV, the dominant decay mode is $H \to W^+W^-$, where at least one W boson must be virtual when $M_H < 2M_W$. Previous searches [5–7] for this process were based on events with two charged leptons (ℓ) and large missing transverse energy ($\not\!\!E_T$) from the decay $H \to W^+W^- \to \bar{\ell}\nu\ell'\bar{\nu}'$ ($\ell = e, \mu$). This Letter presents the first search for production of Higgs bosons with subsequent decay to WW having only one charged lepton in the final state. The data correspond to 5.4 fb^{-1} of integrated luminosity from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded with the D0 detector at the Fermilab Tevatron Collider. The largest SM contributions to the inclusive cross section for producing H bosons in $p\bar{p}$ collisions are from mechanisms involving the fusion of two gluons or two weak vector bosons into an H boson, and associated production of H and a weak vector boson ($V = W$ or Z). In the following we will not distinguish between particles and antiparticles. The most striking signatures from $H \to VV$ decays are the all-leptonic 4ℓ and $2\ell 2\nu$ final states, but these account for only $\approx 5\%$ of all decays. Final states containing a single charged lepton have larger backgrounds, but their branching fractions are a factor of ≈ 6 larger than for the all-leptonic modes.

A recent calculation of the differential width for $H \to WW \to \ell\nu q'q$ decays [8] supports the importance of these mixed modes for characterizing a potential SM Higgs-boson signal. Our analysis is most sensitive to final-state topologies with a single charged lepton, two or more jets, and $\not{E}_T$ arising from $H \to WW \to \ell\nu q'q$ decays. For $M_H \lesssim 140$ GeV, significant sensitivity is gained from the $WH \to \ell\nu bb$ channel, where we do not attempt to identify the b quark flavor. Smaller contributions from $H \to ZZ \to \ell\ell qq$, where ℓ represents an unidentified lepton and $H \to WW \to \tau\nu q'q$ with $\tau \to \ell\nu\nu$, are also included. For $M_H \geq 160$ GeV, by assuming that the observed $\not{E}_T$ is due to the neutrino from the decay of a W boson, it is possible to reconstruct the longitudinal momentum of the neutrino (p_z^ν) up to a twofold ambiguity and thereby extract M_H from the WW decay [9]. We choose the solution with smallest $|\mathrm{Re}(p_z^\nu)|$ to calculate M_H, resulting in the correct choice for $\approx 70\%$ of signal events. The primary backgrounds are from V + jets, top quark and diboson production, and multijet (MJ) events containing a lepton or leptonlike signature, with $\not{E}_T$ generally arising from the mismeasurement of jet energies.

The D0 detector [10] consists of tracking, calorimetric, and muon subsystems. Charged particle tracks are reconstructed by using silicon microstrip detectors and a scintillating fiber tracker, within a 2 T solenoid. Three uranium–liquid-argon calorimeters measure particle energies that are reconstructed into hadronic jets using an iterative midpoint cone algorithm with a cone radius of 0.5 [11]. Electrons and muons are identified through association of charged particle tracks with clusters in the electromagnetic sections of the calorimeters or with hits in the muon detector, respectively. We obtain the $\not{E}_T$ from a vector sum of transverse components of calorimeter energy depositions and correct it for identified muons. Jet energies are calibrated by using transverse momentum balance in photon + jet events [12], and the correction is propagated to the $\not{E}_T$. The data are recorded by using triggers designed to select single electrons or muons and combinations of an electron and jets. After imposing data quality requirements, the total integrated luminosity is 5.4 fb^{-1} [13], where the first 1.1 fb^{-1}, run IIa, precedes an upgrade to the silicon microstrip and trigger systems. The remaining 4.3 fb^{-1} is denoted as run IIb. The four data sets, e or μ for the two run epochs, are analyzed separately and combined in the final result.

Background contributions from most SM processes are simulated by using Monte Carlo (MC) generators, with normalizations constrained by the data, whereas the multijet background is fully estimated from the data. The dominant background is from V + jets processes, which are generated with ALPGEN [14]. The transverse momentum (p_T) spectrum of the Z boson in MC is reweighted to match that observed in the data [15]. The p_T spectrum of the W boson is reweighted by using the same dependence but corrected for differences between the p_T spectra of Z and W bosons predicted in next-to-next-to-leading order QCD [16]. Backgrounds from $t\bar{t}$ and electroweak single-top quark production are simulated by using the ALPGEN and COMPHEP [17] generators, respectively. Vector-boson pair production and H boson signals are generated with PYTHIA [18]. All these simulations use CTEQ6L1 parton distribution functions [19]. Both ALPGEN and COMPHEP samples are interfaced with PYTHIA to model parton evolution and hadronization.

Relative normalizations for the various V + jets processes are obtained from calculations of cross sections at next-to-leading order using MCFM [20], while the absolute normalization for the total V + jets background is constrained through a comparison to the data, following the subtraction of other background sources. This increases the normalization for V + jets background by about 2%, compared with the expectation from ALPGEN normalized by using total cross sections calculated at next-to-next-to-leading order [21] with the MRST2004 next-to-next-to-leading order parton distribution functions [22]. Cross sections for other SM backgrounds are taken from Ref. [23] or calculated with MCFM, and those for signal are taken from Ref. [24]. The p_T spectra for diboson events in background are corrected to match those of the MC@NLO generator [25]. The p_T spectra from the contribution of gluon fusion to the H boson signal, as generated in PYTHIA, are modified to match those obtained from SHERPA [26].

Signal and background events from MC are passed through a full GEANT3-based simulation [27] of detector response and then processed with the same reconstruction program as used for the data. Events from randomly selected beam crossings, corresponding to the same instantaneous luminosity profile as the data, are overlaid on the simulated events to model detector noise and contributions

TABLE I. Number of signal and background events expected after selection requirements. The signal sources include gluon-gluon and vector-boson fusion and associated production WH. The three numbers quoted for the signals correspond to $M_H = 130$, 160, and 190 GeV. For backgrounds, "Top" includes pair and single-top quark production and "VV" includes all nonsignal diboson processes. The overall background normalization is fixed to the data by adjusting the V + jets cross sections.

Channel	$gg \to H$	$qq \to qqH$	WH	V + jets	Multijet	Top	VV	Total background	Data
Electron	11.2|46.3|27.8	2.1|6.4|4.2	7.2|0|0	52 158	11 453	2433	1584	67 627	67 627
Muon	9.5|34.7|20.4	1.5|4.4|2.9	5.7|0|0	47 970	2720	1598	1273	53 562	53 562

from the presence of additional $p\bar{p}$ interactions. Parameterizations of trigger efficiency for leptons are determined by using $Z \to \ell\ell$ decays [28]. Any remaining differences between the data and simulation in the reconstruction of electrons, muons, and jets are adjusted in simulated events to match those observed in the data, and these corrections are also propagated to the $\not{E}_T$.

Events are selected to contain candidates for $W \to \ell\nu$ decay by requiring $\not{E}_T > 15$ GeV and the presence of a lepton with $p_T > 15$ GeV that is isolated relative to jets, namely, located outside jet cones, $\Delta R(\ell, j) > 0.5$, with $(\Delta R)^2 = (\phi^\ell - \phi^j)^2 + (\eta^\ell - \eta^j)^2$, where ϕ^x and η^x are, respectively, the azimuth and pseudorapidity [29] of object x. The position of the $p\bar{p}$ interaction vertex (PV) along the beam direction (z_{PV}) is required to be reconstructed within the longitudinal acceptance of the silicon microstrip, $|z_{PV}| < 60$ cm. The lepton is required to originate from the PV and to pass more restrictive isolation criteria based on tracking information and energy deposited near its trajectory in the calorimeter. Electrons must also satisfy criteria on the spatial distribution of the shower, and timing information is used to reject the cosmic ray background in events with muons. All lepton selections are described in Ref. [30], except that this analysis requires both the scalar sum of track p_T and calorimeter energy in the vicinity of the muon to be less than 2.5 GeV. Electrons and muons are required to be located within $|\eta_{det}| < 1.1$ and <1.6, respectively, where η_{det} is the pseudorapidity assuming the object originates from the center of the detector. To reduce background from $Z \to \ell\ell$, top quark, and diboson events, and to assure selected events do not overlap those used in $WW \to \ell\nu\ell'\nu'$ analysis channels, we veto any event containing an additional lepton satisfying less stringent identification criteria. We also require at least two jets with $|\eta^j| < 2.5$ and $p_T > 20$ GeV that contain associated tracks originating from the PV. The jet p_T requirement is 23 GeV when the second-leading jet (ordered in p_T) has $0.8 < |\eta_{det}| < 1.5$ [10]. The two leading jets are used to reconstruct the W boson decaying to $q'q$. To suppress background from MJ events [31], we require events to have $M_T^W(\text{GeV}) > (40 - 0.5)\not{E}_T$, where M_T^W is the transverse mass [32] of the W boson candidate.

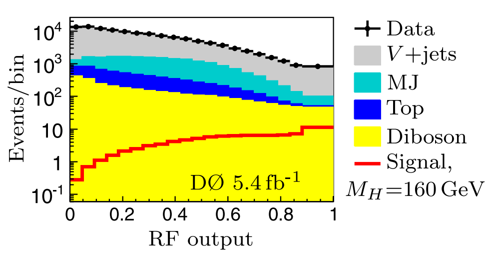

FIG. 1 (color online). The output of RF discriminants for the data, different backgrounds, and signal for $M_H = 160$ GeV for the combined data sets.

To estimate the MJ background, we use data samples orthogonal to our signal sample. For the electron channel, we form a "loose" category for which the selection on a likelihood discriminant used to select a "tight" electron, based on calorimeter and track variables [31], is reversed. Following the method of Ref. [33], the MJ background is evaluated from independently determined probabilities for loose electrons or jets to pass the tight signal selections. For the muon channel, we reverse requirements on muon isolation in both the tracking detectors and calorimeters and subtract contributions arising from SM processes containing a true muon from W or Z decay. The normalization is obtained from fits to both the V + jets and MJ contributions using observed distributions of p_T^μ and $\not{E}_T$. Event yields in the data and those expected for the signal and background are shown in Table I.

We use a random forest (RF) of 50 decision trees to separate the signal from the background [34,35]. Each decision tree is trained on a randomly selected collection of signal and background MC events and also MJ events from the data. The decision trees examine a random set of about 30 discriminating variables formed from particle four-vectors, angles between objects, and combinations of kinematic variables such as reconstructed masses and event shapes. An RF is trained separately for each data set, by using signal hypotheses $115 < M_H < 200$ GeV in steps of 5 GeV. The strongest discriminants in each RF vary with M_H. The dominant variables are, for $M_H < 2M_W$, the three-body mass (ℓjj); for $M_H \approx 2M_W$, variables involving relative angles between objects; and for $M_H > 2M_W$, variables related to the decay of a boosted W boson. The outputs of the final RF discriminants for the four data sets combined, background, and signal for $M_H = 160$ GeV are shown in Fig. 1. Agreement is observed with expectations from the SM background, and the RF-output distributions are therefore used to set upper limits on the cross section for SM Higgs production.

Systematic uncertainties affect the normalizations and distributions of the final discriminants and are therefore included in the determination of limits. These arise from a

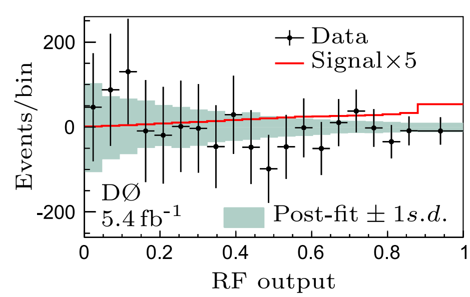

FIG. 2 (color online). The combined background-subtracted data and 1 standard deviation (s.d.) uncertainty on the total background after applying constraints on systematic uncertainties by fitting to the data. The expected SM Higgs signal for $M_H = 160$ GeV, shown by the line, is scaled up by a factor of 5.

TABLE II. Ratios of the observed and expected exclusion limits relative to the SM production cross section for $\sigma(p\bar{p} \to H + X)$ multiplied by the branching fraction for $H + X \to \ell + \ell/\nu + qq$ at the 95% C.L. as a function of M_H.

M_H (GeV)	115	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200
Observed	28.5	20.4	32.8	36.6	33.0	33.7	23.1	17.1	8.3	3.9	5.2	5.6	8.2	7.1	12.0	10.6	10.0	10.4
Expected	19.5	23.4	26.4	28.4	25.7	19.7	13.7	10.4	8.0	5.0	5.1	5.9	6.7	8.0	9.6	10.7	11.2	12.1

variety of sources, and their impact is assessed by changing each input discriminant to the RF by ±1 standard deviation. The most significant uncertainties affecting the normalizations are from calibration of jet energies (0.7–6)%, jet resolution (0.5–3)%, jet reconstruction efficiency (0.5–4)%, lepton identification and modeling of the trigger (4%), estimation of multijet background (6.5–26)%, and integrated luminosity (6.1%). Theoretical uncertainties on cross sections for backgrounds are taken from Refs. [20,23]. The uncertainties on cross sections for the signal are taken from Ref. [24]. Because the overall cross section for V + jets production is constrained by the data, the uncertainty on its normalization is anticorrelated with the MJ background. The impact of theoretical uncertainties on distributions of the final discriminants is assessed by varying a common renormalization and factorization scale, by comparing ALPGEN interfaced with HERWIG [36] to ALPGEN interfaced with PYTHIA for V + jets samples, and by varying the parton distribution function parameters using the prescription of Ref. [19] for all MC samples.

Upper limits on the production cross section multiplied by branching fractions are determined by using the modified frequentist CL_S approach [37]. A test statistic based on the logarithm of the ratio of likelihoods (LLR) [37] for the data to represent signal + background and background-only hypotheses is summed over all bins of the final discriminant in each data set. To minimize degradation in sensitivity, scaling factors for the systematic uncertainties are fitted to the data by maximizing a likelihood function

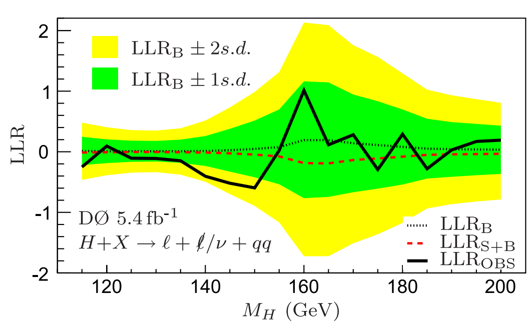

FIG. 3 (color online). The observed LLRs for the combined data are given by the solid line. Expected LLRs for the background-only and signal + background hypotheses are shown as dots and dashes, respectively, and the dark and light-shaded areas correspond to 1 and 2 s.d. around the expected LLR for the background-only hypothesis. Negative values of $\mathrm{LLR_{OBS}}$ represent signal-like fluctuations in the data.

for both the signal + background and background-only hypotheses, with the systematic uncertainties constrained through Gaussian priors on their probabilities [38]. Correlations among systematic uncertainties in the signal and background are taken into account in extracting the final results. Figure 2 shows the combined background-subtracted data and the uncertainties on the RF discriminant after they are fitted to the data.

The resulting limits on standard model Higgs-boson production are given in Table II. The $\mathrm{LLR_{OBS}}$ values shown in Fig. 3 as functions of M_H are within ~1.5 standard deviations of the expected median for $\mathrm{LLR_B}$, the background-only hypothesis, as calculated from statistical fluctuations and systematic uncertainties.

In conclusion, we have determined the first limits on standard model Higgs-boson production by examining decays of the Higgs boson to two vector bosons, one of which decays leptonically and the other into a pair of quarks. For $M_H = 160$ GeV, the observed and expected 95% C.L. upper limits on the combined cross section for Higgs production, multiplied by the branching fraction for $H + X \to \ell + \ell/\nu + qq$, are factors of 3.9 and 5.0 larger than the SM cross section, respectively.

Supplemental material, including a list of variables used in the RF, samples of input distributions, and a table of systematic uncertainties, is available [39].

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