Combination of searches for the Higgs boson using the full CDF data set
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We present a combination of searches for the standard model Higgs boson using the full CDF Run II data set, which corresponds to an integrated luminosity of 9.45–10.0 fb$^{-1}$ collected from $\sqrt{s} = 1.96$ TeV $pp$ collisions at the Fermilab Tevatron. The searches consider Higgs boson production from gluon-gluon fusion, vector-boson fusion, and associated production with either a $W$ or $Z$ boson or a $t\bar{t}$ pair. Depending on the production mode, Higgs boson decays to $W^+W^-$, $ZZ$, $bb$, $\tau^+\tau^-$, and $\gamma\gamma$ are examined. We search for a Higgs boson with masses ($m_H$) in the range 90–200 GeV/$c^2$. In the absence of a signal, we expect based on combined search sensitivity to exclude at the 95% credibility level the mass regions $90 < m_H < 94$ GeV/$c^2$, $96 < m_H < 106$ GeV/$c^2$, and $153 < m_H < 175$ GeV/$c^2$. The observed exclusion regions are $90 < m_H < 102$ GeV/$c^2$ and $149 < m_H < 172$ GeV/$c^2$. A moderate excess of signal-like events relative to the background expectation at the level of 2.0 standard deviations is present in the data for the $m_H = 125$ GeV/$c^2$ search hypothesis. We also present interpretations of the data within the context of a fermiophobic model and an alternative standard model incorporating a fourth generation of fermions. Finally, for the hypothesis of a new particle with mass 125 GeV/$c^2$, we constrain the coupling strengths of the new particle to $W^\pm$ bosons, $Z$ bosons, and fermions.

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I. INTRODUCTION

Within the standard model (SM) of particle physics, the mechanism of electroweak symmetry breaking implies the existence of a single observable particle referred to as the Higgs boson, $H$. The mass of this neutral scalar is not predicted by the theoretical framework of the SM and must be measured experimentally. Similarly, Yukawa couplings between fundamental fermions and the Higgs field, which are responsible for fermion masses, are not predicted by the SM.

Precision electroweak measurements from LEP, SLC, and the Tevatron have been interpreted within the context of the SM to constrain the mass of the potential SM Higgs boson. Recently, a new particle was observed in data collected from $\sqrt{s} = 7–8$ TeV $pp$ collisions at the CERN Large Hadron Collider (LHC) by the ATLAS and CMS collaborations. The reported measurements of the observed particle are consistent with a Higgs boson mass smaller than 152 GeV/$c^2$ at the 95% confidence level, within the framework of the SM. Direct searches at LEP exclude the SM Higgs boson for masses less than 114.4 GeV/$c^2$. Recently, a new particle was observed in data collected from $\sqrt{s} = 7–8$ TeV $pp$ collisions at the CERN Large Hadron Collider (LHC) by the ATLAS and CMS collaborations. The reported measurements of the observed particle are consistent with the expectations for the SM Higgs boson with a mass of roughly...
125 GeV/c^2. The specific final states contributing the greatest amount of significance to these observations are γγ and ZZ → ℓℓℓℓ \cite{3}. Complementary evidence was also reported recently in the b¯b final state based on a combination of searches from the CDF and D0 experiments \cite{4}. Precision measurements of the properties of the new particle such as its spin, parity, production rates via the different mechanisms, and decay branching ratios are necessary for identifying if the new particle is in fact the SM Higgs boson. Higgs boson searches at the Tevatron obtain most of their sensitivity from production and decay modes that are different from those of the LHC searches. Tevatron measurements therefore provide important contributions to the available constraints on several of these properties.

The SM Higgs boson production process with the largest cross section at the Tevatron is gluon fusion. Associated production with a W or Z boson (VH) is the second largest. The cross section for VH production is twice that of Zh and is about a factor of ten smaller than gluon fusion. The Higgs boson decay branching fraction is dominated by than gluon fusion. The Higgs boson decay branching fraction via the different mechanisms, and decay branching ratios are necessary for identifying if the new particle is in fact the SM Higgs boson. Higgs boson searches at the Tevatron obtain most of their sensitivity from production

and decay modes that are different from those of the LHC searches. Tevatron measurements therefore provide important contributions to the available constraints on several of these properties.

This article presents a combination of CDF searches for the SM Higgs boson. The combined searches incorporate potential contributions from Higgs boson production via gluon fusion, production in association with a W or Z boson, vector-boson fusion (VBF) production, and production in association with a top-quark pair. Higgs boson decay modes considered are H → W^+W^−, H → bb, H → τ^+τ^−, and H → γγ. The individual searches are performed for potential Higgs boson masses in the range from 90 to 200 GeV/c^2 using non-overlapping data sets defined by distinct final states. For each search sub-channel, SM backgrounds are estimated and validated using data events populating appropriately-defined control regions. Finally, a discriminant, which is typically the output of a multivariate algorithm constructed from kinematic event variables, is used to separate a potential signal from much larger background event contributions. The multivariate algorithms are separately optimized for each Higgs boson mass hypothesis and for each analysis sub-channel. Search results are combined by constructing a combined likelihood function based on the final discriminant distributions in each search sub-channel, taking into account the correlations among channels. After performing the combined search over the full Higgs boson mass range, we focus on the 125 GeV/c^2 mass hypothesis, motivated by the recent ATLAS and CMS observations \cite{3, 5}. Assuming the LHC signal is present in CDF data, we constrain fermion and boson couplings to this new particle.

We additionally interpret the search results within the context of a fermiophobic Higgs model (FHM) \cite{11, 13}, which assumes SM couplings to the Higgs boson except in the case of fermions, for which the couplings are assumed to vanish. In this model, gluon-fusion production is highly suppressed, while branching fractions for H → γγ, H → W^+W^−, and H → ZZ are enhanced. We also consider an extension of the SM incorporating a heavy fourth generation of fermions (SM4). Within this model, gluon-fusion production is significantly enhanced \cite{15, 16}.

This article is organized as follows: Section II briefly describes the CDF II detector and the data samples used for this combination; Section III describes the predictions for Higgs boson production and decay that are assumed throughout, as well as the Monte Carlo models used to predict the differential distributions; Section IV describes the search channels included in the combination; Section V describes the dominant sources of uncertainty in each channel and the correlations of these uncertainties between channels; Section VI describes the statistical methods used; Section VII presents results in the context of the SM; Section VIII presents results in the context of the fermiophobic model; Section IX presents results in the context of the SM4 model; Section X describes the measurement of fermion and boson couplings in the context of a new 125 GeV/c^2 boson; and Section XI summarizes the article.

II. THE CDF II DETECTOR AND THE FULL CDF DATA SET

The CDF II detector is described in detail elsewhere \cite{18, 19}. Silicon-strip tracking detectors \cite{20} surround the interaction region and provide precision measurements of charged-particle trajectories in the range |η| < 2.1. A cylindrical drift chamber provides full coverage over the range |η| < 1. The tracking detectors are located within a 1.4 T superconducting solenoidal magnet with field oriented along the beam direction. The energies of individual particles and particle jets are measured in segmented electromagnetic and hadronic calorimeter modules arranged in a projective tower geometry surrounding the solenoid. Ionization chambers are located outside of the calorimeters to help identify muon candidates \cite{22}. The Tevatron collider luminosity is mea-
sured with multi-cell gas Cherenkov detectors [28]. The total uncertainty on luminosity measurements is ±6.0%, of which 4.4% originates from detector acceptance uncertainties and 4.0% is due to the uncertainty on the inelastic \( p\bar{p} \) cross section [24].

All of the results combined in this article, with the exception of the \( H \rightarrow \tau^+\tau^- \) search, use the full CDF Run II data sample. Small variations in the luminosities reported for the different search channels reflect the application of channel-specific data-quality criteria designed to ensure proper data modeling. For example, the silicon detector is required to be operational for the \( H \rightarrow b\bar{b} \) searches, for which the identification of secondary track vertices from \( b \) hadrons plays an important role, but not in the case of the \( H \rightarrow \gamma\gamma \) search. The \( H \rightarrow \gamma\gamma \) search makes use of the largest data set, 10 fb\(^{-1}\), which is about 82% of the 12 fb\(^{-1}\) that was delivered by the Tevatron collider and about 99.5% of the luminosity in which the CDF detector was considered to be operational.

CDF uses a three-level online event selection system (trigger) to select beam collision events at a rate that can be written into permanent storage. The first trigger level relies on special-purpose hardware [24] to reduce the effective beam-crossing frequency of 1.7 MHz to an event rate of approximately 15 kHz. The second level uses a mixture of dedicated hardware and fast software algorithms to further reduce the event rate to roughly 1 kHz. Events satisfying level-two trigger requirements are read out of the detector and passed to an array of computers running fast versions of offline reconstruction algorithms, which allow for third-level trigger decisions based on quantities that are nearly the same as those used in offline analyses [26]. The final rate of events written into permanent storage is approximately 100 Hz.

The basic trigger criteria for events used in these searches are the presence of high-transverse momentum (pt) leptons, clustered calorimeter energy deposits associated with partons originating from the collision (jets) [27], and large imbalances in the transverse energies (\( E_T \)) [21] of measured depositions within the calorimeter, associated with evidence for undetected neutrinos within the event (\( E_T \)) [21].

### III. STANDARD MODEL HIGGS BOSON SIGNAL PREDICTIONS

In order to conduct the most sensitive Higgs boson search possible, we include contributions from all significant production modes that are expected to occur at the Tevatron. When conducting the search using multiple production modes, the predictions of the relative contributions of each mode and the uncertainties on those predictions are required. In addition, because we use multivariate analysis techniques, the predictions of the kinematic distributions for the signal model are also important. Here we provide a summary of the tools we use to make predictions for the Higgs boson signal. The theoretical uncertainties on the signal model play a significant role at higher masses where gluon fusion is the major production mode, but are less important for low-mass Higgs boson searches where associated production is most important.

To predict the kinematic distributions of Higgs boson signal events, we use the PYTHIA [29] Monte Carlo program, with CTEQ5L [28] leading-order (LO) parton distribution functions (PDFs). We scale these Monte Carlo predictions to the highest-order cross section calculations available. The PYTHIA differential distributions for some important variables, such as the Higgs boson \( p_T \) and the number of associated jets, are also corrected based on higher-order calculations as described below. The \( gg \rightarrow H \) production cross section is calculated at next-to-next-to leading order (NNLO) in quantum chromodynamics (QCD) with a next-to-next-to-leading log (NLL) resummation of soft gluons; the calculation also includes two-loop electroweak effects and handling of the running b-quark mass [30, 31]. The numerical values in Table I are updates [32] of the predictions in [31] with \( m_t \) set to 173.1 GeV/c\(^2\) [32], and with a treatment of the massive top and bottom loop corrections up to next-to-leading-order (NLO) and next-to-leading-log (NLL) accuracy.

For these calculations the factorization scale (\( \mu_F \)) and renormalization scale (\( \mu_R \)) are set to \( \mu_F = \mu_R = m_H \), and the MSTW 2008 NNLO PDF set 33, as recommended by the PDF4LHC working group [34], is used. The calculations are refinements of earlier NNLO calculations of the \( gg \rightarrow H \) production cross section [35, 37]. Electroweak corrections were computed in Refs. [38, 39]. Soft gluon resummation was introduced in the prediction of the \( gg \rightarrow H \) production cross section in Ref. [40]. The \( gg \rightarrow H \) production cross section depends strongly on the gluon PDF and the value of the strong interaction coupling constant corresponding to the value \( q \) of transferred momentum, \( \alpha_s(q^2) \).

Analyses consider \( gg \rightarrow H \) production are either treated inclusively, or are divided into categories based on the number of reconstructed jets. This division is described in Table II. For analyses that consider inclusive \( gg \rightarrow H \) production we use uncertainties calculated from simultaneous variation of the factorization and renormalization scales by factors of two. We use the prescription of the PDF4LHC working group [34] for evaluating PDF uncertainties on the inclusive production cross section. QCD scale uncertainties that affect the cross section through their impacts on the PDFs are included as a correlated part of the total scale uncertainty. The remainder of the PDF uncertainty is treated as uncorrelated with the QCD scale uncertainty.

For analyses seeking \( gg \rightarrow H \) production that divide events into categories based on the number of reconstructed jets (see Table II), we follow Refs. [41, 42] for evaluating the impacts of the scale uncertainties. We treat the QCD scale uncertainties obtained from the NNLL inclusive [30, 31], NLO one or more jets [43], and NLO two or more jets [44] cross section calculations as
uncorrelated with one another. We then obtain QCD scale uncertainties for the exclusive $gg \rightarrow H + 0$ jet, 1 jet, and 2 or more jet categories by propagating the uncertainties on the inclusive cross section predictions through the subtractions needed to predict the exclusive rates. For example, the $H + 0$ jet cross section is obtained by subtracting the cross section for production of Higgs bosons with one or more jets at NLO from the inclusive NNLL+NNLO cross section. We assign three separate, uncorrelated scale uncertainties with correlated and anti-correlated contributions among exclusive jet categories. The procedure in Ref. 43 is used to determine PDF model uncertainties. These are obtained separately for each bin of jet multiplicity and treated as 100% correlated among jet bins.

The scale choice affects the $p_T$ spectrum of the Higgs boson when produced in gluon-gluon fusion, thus biasing the acceptance of the selection requirements and also the shapes of the distributions of the final discriminants. The effect of the acceptance change is included in the calculations of Ref. 16 and Ref. 17, as the experimental requirements are simulated in these calculations. The effects on the final discriminant shapes are obtained by reweighting the $p_T$ spectrum of the Higgs boson production in the Monte Carlo simulations to higher-order calculations. The Monte Carlo signal simulation used is provided by the LO generator PYTHIA 28, which includes a parton shower and fragmentation and hadronization models. We reweight the Higgs boson $p_T$ spectra in the PYTHIA Monte Carlo samples to that predicted by HQT 18 when making predictions of differential distributions of $gg \rightarrow H$ signal events. To evaluate the impact of the scale uncertainty on the differential spectra, we use the RESBOS 19 generator, apply the scale-dependent differences in the Higgs boson $p_T$ spectrum to the HQT prediction, and propagate these to the final discriminants as a systematic uncertainty on the shape, which is included in the calculation of the limits.

We include all significant Higgs boson production modes in the $H \rightarrow W^+W^-$, $H \rightarrow ZZ$, and $H \rightarrow \gamma\gamma$ searches. Besides gluon-gluon fusion through virtual quark loops ($ggH$), we include Higgs boson production in association with a $W$ or $Z$ vector boson ($VH$) or with a top-antitop quark pair ($ttH$), and vector boson fusion (VBF). For the $H \rightarrow bb$ searches, we target the $WH$, $ZH$, VBF, and $ttH$ production modes with specific searches. In addition to the leading signal production mode in each final state, we include contributions of sub-leading signal production mode, which lead to increased signal acceptance. The predictions for the $WH$ and $ZH$ cross sections are taken from Ref. 17. This calculation starts with the NLO calculation of v2hv 18 and includes NNLO QCD contributions 41, as well as one-loop electroweak corrections 50. A similar calculation of the $WH$ cross section is available in Ref. 51. The VBF cross section is computed at NNLO in QCD in Ref. 52. Electroweak corrections to the VBF production cross section are computed with the HAWK program 53, and are small and negative (2-3%) in the Higgs boson mass range considered here. We include these corrections in the VBF cross sections used for this result. The $tH$ production cross sections we use are from Ref. 54.

We use the predictions for the branching ratios of the Higgs boson decay from Refs. 12, 55. In this calculation, the partial decay widths for all Higgs boson decays except to pairs of $W$ and $Z$ bosons are computed with HDECAY 56, and the $W$ and $Z$ pair decay widths are computed with PROPHECY-4F 57. The relevant decay branching ratios are listed in Table I. The uncertainties on the predicted branching ratios from uncertainties in the charm- and bottom-quark masses, $\alpha_s$, and missing higher-order effects are presented in Refs. 58, 59.

IV. SEARCH CHANNELS

Individual searches typically consist of an event selection based on the topology and kinematic properties of the final state for the specific Higgs boson production and decay mode under consideration. Separation of a potential signal from the remaining background contributions is obtained in most cases by performing a fit, using the signal and background models, for a single discriminant variable that is the output of a multivariate algorithm, which considers many kinematic event variables as its inputs. The quality of the background model prediction for the distribution of each input variable and the final discriminant is studied using orthogonal data samples carefully selected to validate the modeling of the major background components of each analysis channel. The search samples of each analysis are divided into various sub-channels based on event information such as types of reconstructed leptons, jet multiplicity, and $b$-quark-tagging characterization criteria. A summary of the individual searches and the sub-channels included within each is given in Table I. We attempt to group events with similar signal-to-background ratios within individual sub-channels to optimize search sensitivities. This approach allows the inclusion of information from less sensitive event topologies without degrading the overall sensitivity (for example, events containing higher-impurity lepton types). In addition, the isolation of specific signal and background components within individual sub-channels allows for further optimization of the multivariate discriminants trained for each, leading to additional gains in search sensitivity. The final multivariate discriminants are separately optimized for each Higgs boson mass hypothesis in 5 GeV/$c^2$ steps within the mass range under consideration.

A. $H \rightarrow bb$ searches

For searches focusing on the $H \rightarrow bb$ decay, the efficiency for identifying reconstructed jets originating from $b$ quarks and the resolution of the invariant-mass mea-
| $m_H$ (GeV/$c^2$) | $\sigma_{gg\rightarrow H}$ (fb) | $\sigma_{WH}$ (fb) | $\sigma_{ZH}$ (fb) | $\sigma_{VBF}$ (fb) | $\sigma_{t\bar{t}H}$ (fb) | $Br(H \rightarrow bb)$ (%) | $Br(H \rightarrow \tau^+\tau^-)$ (%) | $Br(H \rightarrow W^+W^-)$ (%) | $Br(H \rightarrow ZZ)$ (%) | $Br(H \rightarrow \gamma\gamma)$ (%) |
|-----------------|-------------------------------|-------------------|-------------------|-------------------|-------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 90              | 2442.3                        | 394.7             | 224.0             | 114.8             | 81.2              | 8.41            | 0.21            | 0.04            | 0.12            |
| 95              | 2101.1                        | 322.1             | 190.3             | 105.6             | 80.4              | 8.41            | 0.47            | 0.07            | 0.14            |
| 100             | 1821.8                        | 281.1             | 162.7             | 97.3              | 79.1              | 8.36            | 1.11            | 0.11            | 0.15            |
| 105             | 1584.7                        | 238.7             | 139.5             | 89.8              | 77.3              | 8.25            | 2.43            | 0.22            | 0.17            |
| 110             | 1385.0                        | 203.7             | 120.2             | 82.8              | 74.5              | 8.03            | 4.82            | 0.44            | 0.19            |
| 115             | 1215.9                        | 174.5             | 103.9             | 76.5              | 70.5              | 7.65            | 8.67            | 0.87            | 0.21            |
| 120             | 1072.3                        | 150.1             | 90.2              | 70.7              | 64.9              | 7.11            | 14.3            | 1.60            | 0.22            |
| 125             | 949.3                         | 129.5             | 78.5              | 65.3              | 57.8              | 6.37            | 21.6            | 2.67            | 0.23            |
| 130             | 842.9                         | 112.0             | 68.5              | 60.5              | 49.4              | 5.49            | 30.5            | 4.02            | 0.22            |
| 135             | 750.8                         | 97.2              | 60.0              | 56.0              | 40.4              | 4.52            | 40.3            | 5.51            | 0.21            |
| 140             | 670.6                         | 84.6              | 52.7              | 51.9              | 31.4              | 3.54            | 50.4            | 6.92            | 0.19            |
| 145             | 600.6                         | 73.7              | 46.3              | 48.0              | 23.1              | 2.62            | 60.3            | 7.96            | 0.16            |
| 150             | 539.1                         | 64.4              | 40.8              | 44.5              | 15.7              | 1.79            | 69.9            | 8.28            | 0.13            |
| 155             | 484.0                         | 56.2              | 35.9              | 41.3              | 9.18              | 1.06            | 79.6            | 7.36            | 0.10            |
| 160             | 432.3                         | 48.5              | 31.4              | 38.2              | 3.44              | 0.40            | 90.9            | 4.16            | 0.05            |
| 165             | 383.7                         | 43.6              | 28.4              | 36.0              | 1.6               | 0.19            | 96.0            | 2.22            | 0.02            |
| 170             | 344.0                         | 38.5              | 25.3              | 33.4              | 0.79              | 0.09            | 96.5            | 2.36            | 0.01            |
| 175             | 309.7                         | 34.0              | 22.5              | 31.0              | 0.61              | 0.07            | 95.8            | 3.23            | 0.01            |
| 180             | 279.2                         | 30.1              | 20.0              | 28.7              | 0.50              | 0.06            | 93.2            | 6.02            | 0.01            |
| 185             | 252.1                         | 26.9              | 17.9              | 26.9              | 0.39              | 0.05            | 84.4            | 15.0            | 0.00            |
| 190             | 228.0                         | 24.0              | 16.1              | 25.1              | 0.32              | 0.04            | 78.6            | 20.9            | 0.00            |
| 195             | 207.2                         | 21.4              | 14.4              | 23.3              | 0.27              | 0.03            | 75.7            | 23.9            | 0.00            |
| 200             | 189.1                         | 19.1              | 13.0              | 21.7              | 0.24              | 0.03            | 74.1            | 25.6            | 0.00            |
TABLE II: Luminosities, explored mass ranges, and references for the various processes and final states ($\ell$ represents $e$ or $\mu$ and $\tau_{\text{had}}$ denotes a hadronic tau-lepton decay) for combined analyses. The generic labels “1×”, “2×”, “3×”, and “4×” refer to separations based on lepton or photon categories.

| Channel | Luminosity ($fb^{-1}$) | $m_H$ range (GeV/$c^2$) | Reference |
|---------|-------------------------|-------------------------|-----------|
| $WH \to \ell\nu\bar{b}\bar{b}$ 2-jet channels | 4×(5 b-tag categories) | 9.45 | 90–150 | [60] |
| $WH \to \ell\nu\bar{b}\bar{b}$ 3-jet channels | 3×(2 b-tag categories) | 9.45 | 90–150 | [60] |
| $ZH \to \nu\bar{b}\bar{b}$ (3 b-tag categories) | | 9.45 | 90–150 | [61] |
| $ZH \to \ell^+\ell^-\bar{b}\bar{b}$ 2-jet channels | 2×(4 b-tag categories) | 9.45 | 90–150 | [62] |
| $ZH \to \ell^+\ell^-\bar{b}\bar{b}$ 3-jet channels | 2×(4 b-tag categories) | 9.45 | 90–150 | [62] |
| $H \to W^+W^-$ | 2×(0 jets)+2×(1 jet)+1×(2 or more jets)+1×(low-$m_{\ell\ell}$) | 9.7 | 110–200 | [63] |
| $H \to W^+W^- (e-\tau_{\text{had}})+(\mu-\tau_{\text{had}})$ | | 9.7 | 130–200 | [63] |
| $WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons) | | 9.7 | 110–200 | [63] |
| $WH \to WW^+W^-$ (tri-leptons with 1 $\tau_{\text{had}}$) | | 9.7 | 110–200 | [63] |
| $ZH \to ZW^+W^-$ (tri-leptons with 1 jet)+(tri-leptons with 2 or more jets) | | 9.7 | 110–200 | [63] |
| $H \to ZZ (4 leptons)$ | | 9.7 | 120–200 | [64] |
| $H \to \tau^+\tau^- (1 jet)+(2 or more jets)$ | | 6.0 | 100–150 | [65] |
| $WH + ZH \to jj\bar{b}\bar{b}$ (2 b-tag categories) | | 9.45 | 100–150 | [66] |
| $H \to \gamma\gamma 1\times(0 \text{ jet})+1\times(1 \text{ or more jets})+3\times(\text{all jets})$ | | 10.0 | 100–150 | [67] |
| $t\bar{t}H \to WWb\bar{b}\bar{b}$ (4 jet, 5 jet, \geq 6 jet)×(5 b-tag categories) | | 9.45 | 100–150 | [68] |
measurement from the two $b$-quark jets are of primary importance. The three most sensitive searches in this decay mode utilize a recently-developed multivariate $b$-quark-tagging algorithm (HOBIT) \cite{ref69} which is based on the kinematic properties of tracks associated with displaced decay vertices and other characteristics of reconstructed jets sensitive to the flavor of the initiating parton. Tight and loose operating points are defined for this algorithm. For example, the loose operating point is found to have a $b$-quark tagging efficiency of approximately 70\% and an associated misidentification rate for light quarks and gluons of approximately 5\%. Compared to the SECVTX \cite{ref18} algorithm, the most commonly used $b$-quark tagging algorithm at CDF, the new algorithm improves $b$-tag efficiency by roughly 20\%, for operating points with equivalent misidentification (mistag) rates. The secondary channels that require $b$-jet identification (the all-hadronic and $t\bar{t}H \rightarrow t\bar{t}bb$ searches) were not updated to use the HOBIT tagger and instead rely on the the SECVTX and JETPROB \cite{ref70} algorithms. The decay width of the Higgs boson is expected to be much smaller than the experimental dijet mass resolution, which is typically 15\% of the mean reconstructed mass. The $H \rightarrow b\bar{b}$ searches are most sensitive in final states that include two jets. However, sometimes initial-state or final-state radiation can produce a third jet in the event. Including three-jet events increases signal acceptance and adds sensitivity, motivating the inclusion of these events in the $H \rightarrow b\bar{b}$ searches. Since a SM Higgs boson signal would appear as a broad enhancement in the reconstructed mass distribution of candidate $b$-quark-jet pairs, dedicated efforts to improve the mass resolution have been performed in each sub-channel \cite{ref71}. Along with improved $b$-jet identification and jet-energy resolution, the primary $H \rightarrow b\bar{b}$ analyses have all benefited from increased trigger acceptance by including events from many different trigger paths. In many cases, the complicated correlations between kinematic variables used in the trigger decision are modeled with a neural network using linear regression based on event kinematic properties and geometric acceptance \cite{ref72}.

1. $WH \rightarrow \ell\nu b\bar{b}$ search

The search focusing on the $WH \rightarrow \ell\nu b\bar{b}$ production and decay mode \cite{ref60} has separate analysis channels for events with two and three reconstructed jets. Events are further separated into sub-channels based on the type of reconstructed lepton and the quality of the tagging information associated with the candidate $b$-quark jets. In particular, separate sub-channels are used for events containing a high-quality central muon or central electron candidate, a forward muon candidate, a forward electron candidate, and a looser central electron or muon candidate based on the presence of an isolated track \cite{ref72, ref73}. The final two-lepton categories, which provide some acceptance for lower-quality electrons and single prong tau decays, are considered only in the case of two-jet events. For two-jet events, five sub-channels are used associated with each lepton category based on the quality of the $b$-tagging information associated with each jet: two tight tags (TT), one tight and one loose tag (TL), a single tight tag (Tx), two loose tags (LL), and a single loose tag (Lx). In the case of three-jet events, only two $b$-tag sub-channels, TT and TL, are considered since the other categories contribute negligibly to the overall search sensitivity. A Bayesian neural network is used to distinguish potential Higgs boson signal events from other background contributions.

2. $ZH \rightarrow \ell^+\ell^- b\bar{b}$ search

The search for $ZH \rightarrow \ell^+\ell^- b\bar{b}$ production and decay \cite{ref62} is based on events with two isolated leptons and a minimum of two jets. A combination of triggers based on electromagnetic energy clusters and signals in the muon chambers matched to reconstructed tracks are used to select events containing $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ candidates. Some triggers based on missing transverse energy requirements are also used to select $Z \rightarrow \mu\mu$ candidates, taking advantage of the apparent imbalance in transverse energies that results from the muons depositing only a small fraction of their energies in the calorimeter. Neural networks are used to select di-electron and di-muon candidates \cite{ref72}. The absence of missing energy from neutrinos allows for improved dijet mass resolution through event-wide transverse momentum constraints. These are incorporated through corrections to the measured jet energies based on the observed $E_T$ using a neural-network approach. The search maintains separate analysis channels for events with two and three jets, as well as for events with di-electron and di-muon candidates. Each of the resulting four channels is further split into four sub-channels (TT, TL, Tx, and LL) based on the quality of the tagging information available from the multivariate algorithm. Signal is separated from background in multiple phases. First, three networks are used to distinguish the $ZH$ signal from each of the $t\bar{t}b$, $Z+\text{jets}$, and diboson backgrounds. Then, a final network further separates the signal from all backgrounds simultaneously.

3. $WH, ZH \rightarrow \not{E}_T b\bar{b}$ search

The search for $WH, ZH \rightarrow \not{E}_T b\bar{b}$ production and decay \cite{ref61, ref71} is based on events with large $E_T$ and no isolated-lepton candidates. Additional background suppression techniques are applied to reduce large background contributions from multi-jet production processes. In particular, prior to construction of the final discriminant, a requirement on a multivariate discriminant trained specifically for separating potential signal from the multi-jet background is applied to the event sample. Events that do not satisfy this requirement are
used to normalize the remaining multi-jet background contribution, which is modeled using a mistag rate function for gluon and light-quark jets measured in data and applied to the untagged jets in data events that otherwise satisfy the kinematic selection criteria. One of the inputs to this multivariate discriminant is a track-based missing-transverse-momentum calculation that discriminates against false $E_T$ [76]. A second, final multivariate discriminant is used to separate the potential Higgs boson signal from the remaining backgrounds, such as $W^+ +$ heavy flavor jets (where heavy flavor refers to jets originating from $b$ or $c$ quarks) and $t\bar{t}$ production. Events with two and three jets are treated as a single search channel that is subdivided into three sub-channels (TT, TL, and Tx) based on the quality of tagging information from the multivariate algorithm.

4. All-hadronic search

The all-hadronic search [69] focuses on $WH, ZH$ and VBF production contributing to the $jjbb$ final state. We use events containing four or five reconstructed jets, at least two of which have been tagged as $b$-quark candidates based on information from the previously developed SECVTX [18] and JETPROB [70] algorithms. The use of these two algorithms results in two search sub-channels containing events with either two SECVTX tagged jets (SS) or one SECVTX tagged jet and one JETPROB tagged jet (SJ). Large multi-jet background contributions are modeled from the data by applying a measured mistag probability to the non-$b$-tagged jets within data events that contain a single $b$-tagged jet but otherwise satisfy event selection requirements. The multivariate discriminants used to separate potential signal from the large background contributions are based on kinematic variable inputs including some variables developed to distinguish the reconstructed jets originating of $b$ quarks from those of light quarks and gluons.

5. $t\bar{t}H \rightarrow t\bar{t}bb$ search

The search for $t\bar{t}H \rightarrow t\bar{t}bb$ production and decay [63] is based on events with one reconstructed lepton, large $E_T$, and four or more reconstructed jets in which at least two jets are identified as $b$-quark candidates based on the SECVTX [18] or JETPROB [70] algorithms. Events containing four, five, and six or more jets are analyzed as separate channels, and the events within each channel are further separated into five sub-channels (SSS, SSJ, SJJ, SS, and SJ), based on the number of tagged jets and the algorithms contributing to each tag. Multivariate discriminant variables are used to separate potential signal from the dominant $t\bar{t}$ background contributions.

B. $H \rightarrow \tau^+\tau^-$ search

The search for Higgs bosons decaying to tau lepton pairs [63] incorporates potential contributions from all four production modes. The search is based on events containing one electron or muon candidate and one hadronically-decaying tau-lepton candidate. To help reduce $Z/\gamma^* \rightarrow \tau^+\tau^-$ background contributions, events are also required to contain at least one reconstructed jet. Events that contain one jet and two or more jets are treated as independent search sub-channels. Boosted decision trees are trained for both sub-channels to separate potential signal events from those associated with each significantly contributing background production mechanism. Significant numbers of background events are removed from the samples by placing lower cuts on the outputs of each boosted decision tree. The output of the boosted decision tree trained to separate potential signal from $Z/\gamma^* \rightarrow \tau^+\tau^-$ background contributions is used as the final discriminating variable for events surviving all of the selection criteria.

C. $H \rightarrow W^+W^-$ search

In the search for Higgs bosons decaying to $W$ boson pairs [63] the greatest sensitivity originates from Higgs bosons produced through gluon fusion; however, the signal contributions from all four production modes are included. The primary search is based on events with two oppositely-charged isolated leptons and large $E_T$, focusing on the $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\nu$ decay mode. The presence of neutrinos in the final state prevents an accurate reconstruction of the candidate Higgs boson mass, and separation of a potential signal from background contributions is based on other kinematic variables. In particular, the distribution of angular separations between the final-state leptons produced in the decays of $W^+W^-$ pairs is significantly different for pairs originating from a spin-zero particle, such as the Higgs boson signal, and the major backgrounds.

Events in the primary search are separated into eight sub-channels based on the types of reconstructed leptons, the number of reconstructed jets, and the invariant mass of the dilepton pair. In the case of events with two electron or muon candidates, separate analysis channels are used for those events with zero, one, and two or more reconstructed jets. This separation helps to isolate potential signal contributions associated with the four signal production mechanisms as well as specific background contributions such as $t\bar{t}$ production, which is dominant for events containing two or more jets. Based on this separation, the final multivariate discriminant used for each channel is optimized, leading to a significant improvement in the overall search sensitivity.

In the case of events with zero or one reconstructed jet, separate search sub-channels are used for events containing low-purity and high-purity lepton types. Events con-
taining forward electron candidates, for example, have much higher background contributions from $W+\text{jets}$ and $W+\gamma$ production processes where a jet or photon mimics the signature of an isolated-lepton candidate.

A separate search sub-channel is used for events in which the dilepton mass is smaller than 16 GeV/$c^2$. The main background event contribution in this kinematic region originates from $W+\gamma$ production, and additional search sensitivity is obtained from the use of a separately-trained multivariate discriminant focused on separating the potential signal from this particular background. Two additional search sub-channels are used for events with one electron or muon candidate and a second, oppositely-charged hadronically-decaying tau-lepton candidate. These event samples contain significant background contributions from $W+\text{jets}$ and multijet production processes, necessitating the use of independent search channels. No further separation of events based on the number of reconstructed jets is performed within these additional sub-channels.

Higgs boson production in association with a $W$ or $Z$ boson in conjunction with the decay $H \rightarrow W^+W^-$ leads to additional potential signal events in other, more exotic final states. The signal contributions are expected to be small, but these final states contain much smaller contributions from SM background processes. Hence, the inclusion of these additional sub-channels improves the overall search sensitivity. A search for $W^+H \rightarrow W^+W^+W^-\rightarrow \ell^+\nu\ell^+\nu jj$ production and decay is included through a sub-channel focused on events containing two same-sign, isolated lepton candidates and one or more reconstructed jets. Two additional sub-channels are used to search for even smaller potential signal contributions from $W^+H \rightarrow W^+W^+W^-\rightarrow \ell^+\nu\ell^+\nu\ell^-\nu$ production and decay. These sub-channels, one based entirely on electron and muon candidates and the other requiring exactly one hadronically-decaying tau-lepton candidate, focus on events with a total of three isolated lepton candidates. In all three sub-channels, the final multivariate discriminants for separating potential signal from other background contributions incorporate multiple kinematic event variables including the observed $E_T$. The $E_T$ provides good separation against dominant background contributions with misidentified lepton candidates because of the presence of multiple neutrinos within each signal final state.

Finally, we use events with three isolated lepton candidates to search for $ZH \rightarrow ZW^+W^-\rightarrow \ell^+\ell^-\ell^+\nu jj$ production and decay. Three-lepton events that are found to contain a same-flavor, opposite-sign lepton pair with a reconstructed mass within 10 GeV/$c^2$ of the $Z$ boson mass are classified into one of two separate sub-channels based on the presence of one reconstructed jet or two or more reconstructed jets. Within the second sub-channel, all final-state particles from the Higgs boson production and decay are reconstructed (the transverse momentum components of the neutrino are obtained from the observed $E_T$) and a reconstructed Higgs boson mass is used as one of the kinematic input variables to the final multivariate discriminant.

D. $H \rightarrow ZZ$ search

The search for Higgs bosons decaying to $Z$ boson pairs [64] is based on events with four reconstructed lepton candidates (electrons or muons). The selected events consist primarily of the background from non-resonant diboson production of $Z'/Z$-boson pairs. A four-lepton invariant mass discriminant is used for separating the potential Higgs boson signal from the non-resonant $ZZ$ background. The event $E_T$ is used as an additional discriminating variable to improve sensitivity to potential four-lepton event signal contributions from $ZH \rightarrow ZW^+W^-\rightarrow \ell^+\ell^-\ell^+\ell^-\nu$ and $ZH \rightarrow \ell^+\ell^-\tau^+\tau^-\nu$ production and decay.

E. $H \rightarrow \gamma\gamma$ search

The search for Higgs bosons decaying to photon pairs [65] incorporates potential signal contributions from all four Higgs production mechanisms. Photon candidates are reconstructed in both the central and forward calorimeters. Conversion ($\gamma \rightarrow e^+e^-$) candidates are also reconstructed in the central calorimeter. Four search channels based on these candidate types (central-central, central-forward, central-conversion, and forward-conversion) are formed from the inclusive diphoton event sample. In order to better optimize the most sensitive search category, central-central events are further separated into two sub-channels consisting of events with zero reconstructed jets (where the majority of ggH events are expected) and one or more reconstructed jets (where the majority of VH and VBF events are expected). For these sub-channels, multivariate discriminants using the reconstructed diphoton mass and other kinematic event variables as inputs are used to separate the potential signal from the non-resonant backgrounds. In the other analysis channels, the diphoton invariant mass is used as the sole kinematic discriminant. For each Higgs boson mass hypothesis, the signal region is defined to be at least $\pm 2$ standard deviations of the expected Higgs boson diphoton mass resolution. The width of signal windows were taken to be 12 GeV/$c^2$, 16 GeV/$c^2$, and 20 GeV/$c^2$ for mass hypotheses of 100–115 GeV/$c^2$, 120–135 GeV/$c^2$, and 140–150 GeV/$c^2$, respectively. The sideband regions around each signal search window are used to normalize background contributions within the signal region for all sub-channels, and to validate the background modeling of the multivariate discriminants for central-central events.
V. SYSTEMATIC UNCERTAINTIES

The Higgs boson signal production rate is expected to be small compared with the copious backgrounds produced in $pp$ collisions at Tevatron energies. Systematic uncertainties associated with background predictions can be significant relative to expected signal rates in the highest $s/b$ bins of the discriminant distributions. Therefore, it is expected that systematic uncertainties can have a large impact on search sensitivity. As an example, in the case of the search for a 125 GeV/$c^2$ Higgs boson the inclusion of systematic uncertainties weakens the sensitivity of the combined analysis by roughly 20%. We consider uncertainties that affect the normalizations as well as those that affect the shapes of the multivariate discriminants used in the searches. We refer to these respectively as rate and shape uncertainties. Some systematic uncertainties are correlated between analyses, between sub-channels within an analysis, and between signal and background predictions within a sub-channel. The nature of the fits that are performed requires careful evaluation of the common and independent sources of systematic uncertainty. The details of the statistical treatment of the uncertainties are described in Sec. VI.

The most important rate uncertainties in the backgrounds to the $WH \rightarrow Wbb$ and $ZH \rightarrow Zbb$ searches come from the $W+$jets and $Z+$jets backgrounds. These uncertainties are separated into heavy-flavor components and mistags. The mistags are calibrated using data control samples. Because these backgrounds are corrected $in situ$ in events with different selection requirements from the analysis search region, and because the differences between the predictions and the true rates may not be the same between the $W+$jets and $Z+$jets samples, the $W+$heavy flavor and $Z+$heavy flavor uncertainties are not correlated between analyses, but are correlated between sub-channels of a single analysis. This treatment ensures that we do not use the $Z+$jets searches to cross-calibrate the backgrounds in the $W+$jets searches and vice versa.

The uncertainties on the $b$-tag efficiencies for each $b$-jet selection requirement are evaluated both for true $b$ jets and for mistagged jets. These uncertainties are propagated to each $b$-tag category. The resulting uncertainties are treated as correlated between the signal predictions and the background predictions. The uncertainties related to the $b$-tag efficiencies are treated as correlated between analyses that use the same $b$-tag algorithm. Similarly, the uncertainty on the total integrated luminosity as measured by the luminosity monitor is considered correlated among all signal and background MC-based predictions in all analyses.

We ensure that each analysis uses the same cross section assumptions and theoretical uncertainties on the prediction for the production of diboson ($W^+W^−$, $W^±Z$, and $ZZ$), $tt$, $W/Z$ with $s$-channel and $t$-channel single-top quark events. The three diboson processes share common dependencies on factorization and renormalization scales and PDFs, so we correlate the uncertainties on all three production modes, and correlate these uncertainties across all channels.

The jet energy scale is calibrated with experimental data using events in which a photon recoils from a jet, and events in which a leptonically-decaying $Z$ boson recoils from a jet [27]. The associated uncertainties are applied to each analysis. They change the predicted rates of events passing the respective selections, largely due to $E_T$ requirements, but also distort the predicted shapes of the distributions of the final discriminant variables. Hence, the systematic uncertainty from the jet energy scale can be further constrained $in situ$. We do not, however, correlate the jet energy scale uncertainty from one analysis to another, because the analyses handle jet energies differently, and accept different fractions of quark and gluon jets in their respective backgrounds. For example, the neural-network jet energy correction technique used in the $ZH \rightarrow ℓ^+ℓ^−bb$ channels may have a different response to the jet energy mismodeling from the response in the other $H \rightarrow bb$ channels. Uncertainties due to initial-state and final-state gluon radiation are considered correlated with each other and across channels.

VI. STATISTICAL METHODS

The results of the searches in each sub-channel are represented as distributions of data event counts in intervals (bins) of a final discriminant variable, which is separately optimized for each sub-channel at each value of the Higgs boson mass $m_H$. Along with the observed data are predictions for each relevant source of background, each source of signal, and the associated uncertainties. These uncertainties affect the predicted yields of each component of signal and background, as well as the differential distributions of the components in each of the histograms. We also consider uncertainties that are uncorrelated from one bin to the next of each component of the predictions, usually coming from the limited size of Monte Carlo simulated samples. The signal-to-background ratios in most of the channels are of the order of a few percent or less. The final discriminant histograms classify events into categories with different signal-to-background ratios. Events with higher discriminant output values populate bins with larger signal-to-background ratios.

This representation of the search results allows for the extraction of constraints on both the signal production rates in the decay modes selected and the background rates and shapes. Indeed, a major component of the sensitivity of the search stems from the ability of the data to constrain the rates and shapes of the major background sources. The multivariate discriminants sort the events based on signal purity. Typically, the low signal-to-background portions of the histograms have higher statistics and serve to constrain the background rates.
The shapes of the predictions for each background provide the basis by which the background prediction is extrapolated into the signal-rich region, and the shape uncertainties parametrize the extrapolation uncertainties.

We use the search results to compute upper limits on the signal rate for SM Higgs boson production, to determine the best-fit value of the signal strength and couplings, and to compute p-values for purposes of conducting a hypothesis test where the null hypothesis is that a Higgs boson signal is absent and the test hypothesis is that a SM Higgs boson is present with mass $m_H$. We employ both frequentist and Bayesian techniques. The upper limits on Higgs boson production and the cross section fits are based on a Bayesian calculation assuming a uniform prior probability density of the signal event rate, truncated to be non negative. The p-values are computed with a frequentist method, although the handling of the systematic uncertainties is Bayesian. The approach is the same as in Refs. [80, 81]. The likelihood function is a product over all channels of the Poisson probability of observing the data given the predictions, which depend on the values of the nuisance parameters that parametrize the systematic uncertainties. The likelihood $L$ is shown below multiplied by the prior probability density $\pi$.

\[ L(R, \vec{s}, \vec{b}, \vec{n}, \vec{\nu}, \vec{\nu}) \times \pi(\vec{\nu}) = \prod_{i=1}^{N_C} \prod_{j=1}^{N_{\text{bins}}} (RS_{ij} + b_{ij})^{n_{ij}} e^{-RS_{ij} - b_{ij}} \frac{n_{ij}!}{\prod_{k=1}^{n_{\text{sys}}} e^{-\nu_k^2/2}}, \tag{1} \]

where the first product is over the number of channels ($N_C$), and the second product is over histogram bins, each containing $n_{ij}$ events. The observed number of events in bin $j$ of channel $i$ is $n_{ij}$. The SM signal prediction in bin $ij$ is $s_{ij}$, summed over all production and decay modes contributing to channel $i$, and $b_{ij}$ is the corresponding background prediction in that bin. The predictions $s_{ij}$ and $b_{ij}$ are functions of the nuisance parameters $\vec{\nu}$. A nuisance parameter $\nu_k$ may affect many signal and background predictions in a correlated way, such as the uncertainty on the luminosity; it may distort the distributions of signal and background predictions, as is the case with jet energy scales, or it may affect only one bin’s prediction of one source of signal or background, as is the case with Monte Carlo statistical uncertainties. The prior probability distributions of the nuisance parameters are assumed to be independent Gaussians, and the units in which the nuisance parameters are expressed are in standard deviations (s.d.) with respect to their nominal values. The prior distributions for the nuisance parameters are truncated so that no prediction for the signal or background in any channel is negative. The factor $R$ is a simultaneous scaling of all signal components. Thus, each combination presented here assumes that the relative ratios of the contributing Higgs boson production and decay modes are as predicted by the model under test, within their theoretical uncertainties. We therefore present separate combinations assuming the SM, and several choices of models allowing nonstandard couplings. We also present separate measurements of $R$ for channels that are sensitive to one Higgs boson decay mode at a time.

To calculate the best-fit value of $R$, we assume a uniform prior probability density $\pi(R)$ for positive values of $R$ and zero for negative values of $R$, and integrate the likelihood function $L$ multiplied by the prior probabilities for the nuisance parameters over the values of the nuisance parameters

\[ L'(R, \vec{s}, \vec{b}, \vec{n}, \vec{\nu}) = \int L(R, \vec{s}, \vec{b}, \vec{n}, \vec{\nu})\pi(\vec{\nu})d\vec{\nu}. \tag{2} \]

The best-fit value of $R$, $R_{\text{fit}}$, is the value that maximizes the posterior probability density $L'(R)\pi(R)$. The 68% credibility interval on $R$ is the shortest interval that contains 68% of the integral of the posterior density. We then define the 95% credibility upper limit on $R$, $R_{95}$ with the following relation:

\[ 0.95 = \int_0^{R_{95}} L'(R)\pi(R)dR. \tag{3} \]

We compute the distribution of limits that are expected in the hypothesis that no signal is present by simulating experimental outcomes and computing $R_{95}$ in each of them. The experimental outcomes are simulated by varying the values of the nuisance parameters within their uncertainties, propagating these to the predictions of $b_{ij}$, and then drawing simulated data counts from Poisson distributions with the means of the predicted backgrounds. The sensitivity is expressed by the median expected limit $R_{95}^\text{med}$. A value of $R_{95} < 1$ indicates that the specific signal hypothesis under test is excluded at the 95% credibility level.

To evaluate the significance of excess data events compared with the background prediction, we compute a p-value, which is the probability to observe a result that is as signal-like or more than the observed result, assuming that no signal is truly present. A p-value less than $1.35 \times 10^{-3}$ is customarily identified as corresponding to a three s.d. excess, where the correspondence between the $p$-value and the number of s.d. is computed using the integral of one tail of a Gaussian distribution. We rank outcomes as more or less signal- or background-like based on their $R_{\text{fit}}$ values. We quote the local significance in the
Normalizations of the subtracted background contributions, with uncertainties indicated by the unfilled histograms, are obtained using the background model and analysis framework of the SM processes have been successfully extracted in the same final states as those used for the primary Higgs boson searches. For example, the production cross section for electroweak single top quark production was measured both in the $t\bar{t}b\bar{b}$ [81] and $\ell\nu\ell\nu$ [82] final states which provided important validation for the $WH\rightarrow t\bar{t}b\bar{b}$ and $WH, ZH\rightarrow \ell\nu\ell\nu$ searches. Similarly, the background model and analysis framework of the $H\rightarrow W^+W^-$ search have been validated through successful measurement of diboson cross sections have been published in three final states: $p\bar{p}\rightarrow W^+W^-$ cross section based on the $\ell^+\nu\ell^−\nu$ decay mode [83], $p\bar{p}\rightarrow ZZ$ cross section based on the $\ell^+\ell^−\nu\bar{\nu}$ decay mode [84], and a measurement of the $p\bar{p}\rightarrow W^\pm Z$ cross section based on the $\ell^\pm\ell^\mp\nu\bar{\nu}$ decay mode [85]. All three measurements were found to be in agreement with NLO predictions.

The searches for $WH\rightarrow Wb\bar{b}$ and $ZH\rightarrow Zb\bar{b}$ production and decay require careful modeling of large background event contributions from $W$+jets and $Z$+jets production. We gauge the sensitivity of these searches, and evaluate the background modeling and analysis techniques applied within them, by extracting from these search channels a combined cross section measurement for $WZ$ and $ZZ$ production. The NLO SM cross section for $VZ$ production times the branching fraction for $Z\rightarrow b\bar{b}$ is $0.68 \pm 0.05$ pb, about six times larger than the expected $0.12 \pm 0.01$ pb cross section times branching fraction of $VH\rightarrow Vb\bar{b}$ for a Higgs boson mass of 125 GeV/c^2.

This measurement is performed through a combination of the same set of search channels used for the $WH\rightarrow t\bar{t}b\bar{b}$, $ZH\rightarrow \ell^+\ell^−b\bar{b}$, and $WH, ZH\rightarrow \ell\nu\ell\nu$ boson searches. The data sample, event reconstruction, modeling of signal and background processes, uncertainties, and sub-channels are the same as in the Higgs boson search. However, dedicated multivariate discriminants are trained to separate event contributions of $VZ$ production from those of the other backgrounds and any potential contributions from Higgs boson production are not considered. Figure 1 shows the background-subtracted, reconstructed dijet mass distribution obtained from the combination of all search channels. A fit to the data is used to determine the absolute normalizations for $VZ$ signal and background contributions.

Separation of the $VZ$ signal component within these search channels is obtained from a multivariate discriminant that incorporates the dijet invariant mass as one of its most powerful kinematic inputs. For improved visualization of the result of the $VZ$ cross section measurement, we group event counts from all bins of the final discriminant distributions from each of the search channels with similar signal purity, $s/b$, and display the background-subtracted data contained within each grouping as a function of increasing $s/b$ (Fig. 1). A fit to the data is used to determine the absolute normalization of the $VZ$ signal contribution, indicated by the filled histogram, as well as the normalization for background
B. Expected sensitivity to Higgs boson production

The median expected limit in the absence of signal, $R_{95}^{med}$, is shown in Fig. 2 for combinations of the search channels within each Higgs boson decay mode, and for the full combination of all channels. For Higgs boson masses below about 130 GeV/c², searches based on the $H \rightarrow b\overline{b}$ final state provide the greatest sensitivity. Searches based on $H \rightarrow W^+W^-$ are the most sensitive for higher Higgs boson masses. Based on the combined result we expect to exclude the regions $90 < m_H < 94$ GeV/c², $96 < m_H < 106$ GeV/c², and $153 < m_H < 175$ GeV/c² in the absence of signal. For the case of a Higgs boson with a mass of 125 GeV/c², the signal event yields, approximate mass resolutions, and median expected limits are shown in Table III for combinations of the channels associated with each Higgs boson decay mode. At this mass, $H \rightarrow b\overline{b}$ has the best sensitivity, but the $H \rightarrow W^+W^-$ searches make an important contribution to the combination.

The final sensitivities of CDF Higgs boson searches are a direct result of a substantial effort made over the last decade to significantly improve the analysis techniques used. The evolution of CDF search sensitivity over time is illustrated in Fig. 3. The points show the median expected 95% C.L. upper limits on Higgs boson production relative to SM expectations assuming the background-only hypothesis from the combination of available CDF search results performed at various stages over the past decade. The integrated luminosities associated with each point are the sensitivity-weighted averages of analyzed luminosities corresponding to the analyzed samples at that time. The curves show how the sensitivity of each combination would be expected to improve in the absence of further analysis improvements assuming that sensitivity scales inversely with the square root of integrated luminosity. With respect to early versions of the CDF Higgs boson search sensitivity has been improved by more than a factor of two over what would be expected simply by incorporating more data. The illustrated gains
TABLE III: Expected number of signal events, Higgs boson mass resolution, and median expected 95% C.L. upper limits on Higgs boson production relative to the SM expectation assuming the background-only hypothesis for combinations of search channels within each Higgs boson decay mode at $m_H = 125$ GeV/$c^2$. \(^1\)Mass resolution is limited in the $H \to W^+W^-$ decay mode due to the presence of two neutrinos in the final state, which leads to an under-constrained system. \(^2\)Mass resolution is limited in the $t\bar{t}H \to WWb\bar{b}$ production and decay mode due to the presence of four $b$ quarks in the final state, which leads to an ambiguity in jet assignments for reconstructing the Higgs boson mass.

| Channel | Expected # of signal events | $m_H$ resolution | Expected limit relative to SM |
|---------|----------------------------|------------------|-------------------------------|
| $H \to bb$ | 87.0 | $\approx 15\%$ | 1.77 |
| $H \to W^+W^-$ | 24.2 | Limited\(^1\) | 3.25 |
| $H \to \gamma\gamma$ | 7.4 | $\approx 2.5\%$ | 9.9 |
| $t\bar{t}H \to WWb\bar{b}$ | 3.6 | Limited\(^2\) | 11.9 |
| $H \to \tau^+\tau^-$ | 2.3 | $\approx 25\%$ | 16.9 |
| $H \to ZZ$ | 0.2 | $\approx 3\%$ | 29 |

FIG. 3: Achieved and projected median expected 95% C.L. upper limits on Higgs boson production relative to the SM expectation as a function of integrated luminosity, assuming the background-only hypothesis. Each point represents a combination of CDF searches performed on the date indicated in the legend. The integrated luminosity associated with each point is the sensitivity-weighted average of the analyzed luminosities associated with each contributing channel. The solid lines show sensitivity projections, where a scaling inversely proportional to the square root of the integrated luminosity is assumed. The information is provided for combined searches performed at $m_H = 115$ GeV/$c^2$ (left) and $m_H = 160$ GeV/$c^2$ (right).

in search sensitivity have originated from a wide array of analysis improvements including the inclusion of additional triggered events, improved $b$-jet identification algorithms, implementation of algorithms for improved jet energy resolution, inclusion of new search channels such as those considering events with additional jets, and improved multivariate techniques for separating signal and background contributions.

C. Full combination

The data are categorized into 81 sub-channels for the $m_H = 125$ GeV/$c^2$ hypothesis. In order to better visualize the results and identify data events causing fluctuations in the observed limits and $p$-values with respect to expectations for the background-only scenario, we perform a joint fit of the background predictions for all channels to the observed data where nuisance parameters are allowed to float within their uncertainties. We then collect bins from the final discriminant distribution by merging bins with similar $s/b$. The result is shown in Fig. 4 for the combined channels contributing to the searches focusing on the $m_H = 125$ GeV/$c^2$ and 165 GeV/$c^2$ mass hypotheses. The predicted Higgs boson contributions based on SM expectations summed over the bins with similar $s/b$ are shown with the fitted background contributions overlaid. A subset of the same data is shown in Fig. 5 where the data are grouped into wider $s/b$ bins and the backgrounds determined from the fit have been
FIG. 4: Collected discriminant histograms, summed for bins with similar signal-to-background ratio \((s/b)\), for the combined SM Higgs boson searches focusing on the \(m_H = 125 \text{ GeV}/c^2\) (left) and \(m_H = 165 \text{ GeV}/c^2\) (right) hypotheses. Normalizations of the background contributions are obtained from fits to the data. Predicted signal contributions, scaled to SM expectations, are overlaid on the backgrounds.

FIG. 5: Background-subtracted collected discriminant histograms, summed for bins with similar signal-to-background ratio \((s/b)\), for the combined SM Higgs boson searches focusing on the \(m_H = 125 \text{ GeV}/c^2\) (left) and \(m_H = 165 \text{ GeV}/c^2\) (right) hypotheses. Background normalizations are obtained from fits to the data, and fit uncertainties are indicated by the unfilled histograms. Predicted signal contributions, scaled to SM expectations, are shown with the filled histograms. Uncertainties on the data points correspond to the square root of the sum of expected signal and background yields within each bin.

subtracted. A mild excess of data events is observed in the bins with the highest \(s/b\) for the \(m_H = 125 \text{ GeV}/c^2\) hypothesis. No such excess is seen for the case of the \(m_H = 165 \text{ GeV}/c^2\) hypothesis.

The likelihood from Equation 1 is used to combine the Higgs boson searches from all CDF sub-channels as described in Sec. VII. Figure 8 shows the resulting observed upper bound on the signal scale factor \(R_{95}\) for potential \(m_H\) values between 90 GeV/c\(^2\) and 200 GeV/c\(^2\). The median expected limit in the presence of no signal, \(R_{95}^{med}\), is shown by the dark dashed line, while the shaded regions indicate the limit fluctuation ranges at the level of one and two standard deviations. The lighter dashed line shows the broad excess in the limits that would be expected if a SM Higgs boson with \(m_H = 125 \text{ GeV}/c^2\) were present in the data. Values of the observed and expected limits are listed in Table IV. We exclude at the 95% credibility level (C.L.) the SM Higgs boson within the mass ranges 90 < \(m_H\) < 102 GeV/c\(^2\) and 149 < \(m_H\) < 172 GeV/c\(^2\). In the absence of a signal,
we expect to exclude the regions $90 < m_H < 94 \text{ GeV}/c^2$, $96 < m_H < 106 \text{ GeV}/c^2$, and $153 < m_H < 175 \text{ GeV}/c^2$.

![Graph](image_url)

FIG. 6: Observed and expected (median, for the background-only hypothesis) 95% C.L. upper limits on SM Higgs boson production as a function of the Higgs boson mass for the combination of CDF searches. The limits are expressed as multiples of the SM prediction for test masses in $5 \text{ GeV}/c^2$ steps from 90 to 200 $\text{ GeV}/c^2$. The points are connected with straight lines for improved readability. The bands indicate the 68% and 95% probability regions where the limits can fluctuate, in the absence of signal. The lighter dashed line indicates mean expected limits in the presence of a SM Higgs boson with $m_H = 125 \text{ GeV}/c^2$.

Mild excesses in the data compared with fitted background predictions are observed, in particular within the high $s/b$ bins of the discriminants associated with the $WH \rightarrow t\ell\bar{b}$ and $ZH \rightarrow \ell^+\ell^-bb$ searches [61,62]. However, in the low mass search region where there is overlap with the $H \rightarrow bb$ searches, the $H \rightarrow W^+W^-$ search, which contributes similar search sensitivity at $m_H = 125 \text{ GeV}/c^2$, does not contain data excesses in the high $s/b$ bins of its discriminants [63]. By combining channels, the location of the data excess within the range of potential $m_H$ values can be partially constrained based on knowledge of the available mass resolution and expected signal rates from each search channel. The constraints are observable in the measured values for $R_{\text{fit}}$, which are shown as a function of $m_H$ along with their associated 68% and 95% C.L. intervals in Fig. 7. The moderate excess is localized within the region $110 < m_H < 140 \text{ GeV}/c^2$, where the measured signal rate is found to be consistent with that expected from SM Higgs boson production. The best-fit value measured for the Higgs boson production cross section at $m_H = 125 \text{ GeV}/c^2$ is $1.54^{+0.77}_{-0.73}$ (stat.+syst.) relative to the SM prediction.

The $p$-value is shown as a function of $m_H$ in Fig. 8. The broad excess observed in the cross section measurement is also visible in the $p$-value. The $p$-value for the $m_H = 125 \text{ GeV}/c^2$ hypothesis is 0.0212 corresponding to a 2.0 standard deviation excess. A lower $p$-value (0.0060) is observed for the $m_H = 120 \text{ GeV}/c^2$ mass hypothesis, which is not expected to be distinguishable from the $m_H = 125 \text{ GeV}/c^2$ hypothesis based on the mass resolution of the most sensitive search channels. There is also approximately a two sigma excess in our data for Higgs boson mass hypotheses above $\approx 195 \text{ GeV}/c^2$. Recent results from the LHC experiments strongly exclude the SM Higgs boson in this mass range [86,87]. Taking this into consideration, the mild excess near 200 $\text{ GeV}/c^2$ is likely the result of a statistical fluctuation.

We study the couplings of a potential SM Higgs boson by also extracting best-fit signal cross sections for different combinations of channels corresponding to specific Higgs boson production and decay modes. In particular, we perform cross section fits for the subsets of CDF search channels corresponding to $VH \rightarrow Vbb$, $H \rightarrow W^+W^-$, $H \rightarrow \gamma\gamma$, $H \rightarrow \tau^+\tau^-$, and $t\bar{t}H \rightarrow t\bar{t}bb$ production and decay. Best-fit cross sections relative to SM expectations are provided as a function of $m_H$ for each of these modes in Table V. A comparison of the individual mode fitted cross sections versus the fitted SM cross section obtained from all search channels is shown in Fig. 9 for the $m_H = 125 \text{ GeV}/c^2$ hypothesis. The fitted signal contribution from the $H \rightarrow W^+W^-$ and $H \rightarrow \tau^+\tau^-$ channels is zero and for the $VH \rightarrow bb$, $H \rightarrow \gamma\gamma$, and $t\bar{t}H \rightarrow t\bar{t}bb$ channels it exceeds the SM expectation. However, all best-fit cross sections are found to be consistent within 1.5 standard deviations of SM Higgs boson expectations.
TABLE IV: Median expected (for the background-only hypothesis) and observed 95% C.L. upper limits on Higgs boson production relative to SM expectations as a function of Higgs boson mass in GeV/c² for the combination of CDF searches.

| Mass | Expected | Observed |
|------|----------|----------|
| 90   | 0.91     | 0.45     |
| 95   | 1.01     | 0.70     |
| 100  | 0.98     | 0.90     |
| 105  | 0.99     | 1.12     |
| 110  | 1.06     | 1.42     |
| 115  | 1.21     | 2.03     |
| 120  | 1.31     | 2.82     |
| 125  | 1.46     | 2.89     |
| 130  | 1.48     | 2.68     |
| 135  | 1.45     | 2.22     |
| 140  | 1.35     | 2.19     |
| 145  | 1.25     | 2.17     |
| 150  | 1.08     | 0.91     |
| 155  | 0.71     | 0.59     |
| 160  | 0.75     | 0.50     |
| 165  | 0.68     | 0.82     |
| 170  | 0.99     | 1.28     |
| 175  | 1.16     | 1.45     |
| 180  | 1.49     | 2.31     |
| 185  | 1.82     | 3.16     |
| 190  | 2.11     | 4.12     |
| 195  | 2.37     | 4.79     |
| 200  |          |          |

TABLE V: Best-fit signal cross sections, \( R_{SM} \), as a function of \( m_H \) for the combination of all SM search channels and for combinations of subsets of search channels corresponding to \( V H \rightarrow V f b, H \rightarrow W^+W^-, H \rightarrow \gamma \gamma, H \rightarrow \tau^+\tau^-, \) and \( t\bar{t}H \rightarrow t\bar{t}bb \) production and decay. The quoted uncertainties bound the smallest interval containing 68% of an integral over the posterior probability densities, which include both statistical and systematic effects.

| \( m_H \) (GeV/c²) | \( R_{SM} \) | \( R_{H \rightarrow W^+W^-} \) | \( R_{H \rightarrow \gamma \gamma} \) | \( R_{H \rightarrow \tau^+\tau^-} \) | \( R_{t\bar{t}H \rightarrow t\bar{t}bb} \) |
|-------------------|---------------|-----------------|-----------------|-----------------|-----------------|
| 90                | 0.06 ± 0.21   | 0.00 ± 0.00     | 0.00 ± 0.00     | 0.69 ± 1.02     | 7.40 ± 4.65     |
| 95                | 0.06 ± 0.34   | 0.00 ± 0.00     | 0.00 ± 0.00     | 0.81 ± 0.81     | 8.56 ± 4.10     |
| 100               | 0.06 ± 0.47   | 0.00 ± 0.00     | 2.97 ± 3.35     | 0.81 ± 0.81     | 8.56 ± 4.10     |
| 105               | 0.17 ± 0.17   | 0.00 ± 0.00     | 0.00 ± 0.00     | 0.81 ± 0.81     | 8.56 ± 4.10     |
| 110               | 0.44 ± 0.43   | 0.00 ± 0.00     | 1.99 ± 1.99     | 0.81 ± 0.81     | 8.56 ± 4.10     |
| 115               | 0.96 ± 0.55   | 0.00 ± 0.00     | 0.00 ± 0.00     | 0.81 ± 0.81     | 8.56 ± 4.10     |
| 120               | 1.60 ± 0.70   | 0.72 ± 2.24     | 1.30 ± 0.72     | 11.85 ± 4.53    | 8.51 ± 6.03     |
| 125               | 1.54 ± 0.73   | 0.72 ± 2.24     | 1.79 ± 0.92     | 7.81 ± 4.42     | 9.49 ± 6.28     |
| 130               | 1.29 ± 0.74   | 0.72 ± 2.24     | 1.94 ± 1.07     | 8.71 ± 4.42     | 9.49 ± 6.28     |
| 135               | 0.77 ± 0.66   | 0.00 ± 0.00     | 2.24 ± 1.45     | 5.15 ± 2.54     | 10.57 ± 7.15    |
| 140               | 0.83 ± 0.64   | 0.00 ± 0.00     | 2.49 ± 1.76     | 5.15 ± 2.54     | 10.57 ± 7.15    |
| 145               | 0.06 ± 0.67   | 0.00 ± 0.00     | 2.66 ± 2.72     | 5.15 ± 2.54     | 10.57 ± 7.15    |
| 150               | 0.06 ± 0.67   | 0.00 ± 0.00     | 2.66 ± 2.72     | 5.15 ± 2.54     | 10.57 ± 7.15    |
| 155               | 0.06 ± 0.67   | 0.00 ± 0.00     | 2.66 ± 2.72     | 5.15 ± 2.54     | 10.57 ± 7.15    |
| 160               | 0.06 ± 0.67   | 0.00 ± 0.00     | 2.66 ± 2.72     | 5.15 ± 2.54     | 10.57 ± 7.15    |
| 165               | 0.06 ± 0.67   | 0.00 ± 0.00     | 2.66 ± 2.72     | 5.15 ± 2.54     | 10.57 ± 7.15    |
| 170               | 0.06 ± 0.67   | 0.00 ± 0.00     | 2.66 ± 2.72     | 5.15 ± 2.54     | 10.57 ± 7.15    |
| 175               | 0.29 ± 0.44   | 0.30 ± 0.30     | 2.89 ± 0.80     | 5.15 ± 2.54     | 10.57 ± 7.15    |
| 180               | 0.28 ± 0.52   | 0.30 ± 0.30     | 2.89 ± 0.80     | 5.15 ± 2.54     | 10.57 ± 7.15    |
| 185               | 0.86 ± 0.70   | 0.99 ± 0.76     | 5.89 ± 10.57    | 5.89 ± 10.57    | 15.81 ± 10.70   |
| 190               | 1.31 ± 1.00   | 1.55 ± 1.55     | 5.89 ± 10.57    | 5.89 ± 10.57    | 15.81 ± 10.70   |
| 195               | 1.91 ± 1.14   | 2.32 ± 1.28     | 5.89 ± 10.57    | 5.89 ± 10.57    | 15.81 ± 10.70   |
| 200               | 2.30 ± 1.19   | 3.02 ± 1.38     | 5.89 ± 10.57    | 5.89 ± 10.57    | 15.81 ± 10.70   |

VIII. FERMIOPHOBIC MODEL INTERPRETATION

A number of theoretical models incorporate a Higgs boson with couplings to massive bosons as predicted by the SM, but negligible or zero couplings to fermions [11–14]. We denote these as fermiophobic Higgs models (FHM). Within these models \( gg \rightarrow H \) production is negligible, as this mechanism is mediated at lowest order by quark loops and only higher-order weak interactions involving \( W \) and \( Z \) bosons contribute for FHM [30]. Within the FHM interpretation, production rates for \( WH, ZH, \) and VBF are assumed to be as predicted by the SM, while the production rate for \( t\bar{t}H \) is assumed to be negligible. Higgs boson decay branching ratios to pairs of fermions and pairs of gluons are also set to zero. In addition, the decay width \( \Gamma(H \rightarrow \gamma \gamma) \) is enhanced since quark-loop contributions, which subtract from the larger \( W \)-loop contribution, are absent. The complete set of decay branching ratios assumed within the FHM
bosons, or recoiling from jets in the case of VBF. As a
Higgs bosons are produced in association with vector
the dominant Higgs boson production mechanisms. FHM
the different event kinematic properties associated with
the FHM interpretation to optimize the sensitivity for
values for the FHM than the SM, where the dominant
WH
tributions from
m
f
< 122 GeV/c²

FIG. 8: The significance of the observed data excess with re-
spect to the background-only expectation for the combina-
tion of all CDF search channels as a function of SM Higgs boson
mass. The probabilities for the background model to result in
a best-fit cross section as large or larger than that observed
in data, p-values, are shown with the solid line. The dashed
line indicates the mean expected p-values in the presence of
a SM Higgs boson evaluated separately for each test mass,
where the associated shaded regions show the ranges of one
and two standard deviation fluctuations in observed p-values
for these scenarios. The dot-dashed line indicates mean ex-
pected p-values for each mass hypothesis in the case of the
SM Higgs boson with \( m_H = 125 \text{ GeV/c}^2 \).

interpretation are listed in Table VI.

Previous searches for a fermiophobic Higgs boson at
the Tevatron excluded signals with masses smaller than
119 GeV/c² [88, 90]; the expected exclusion was also
\( m_H < 119 \text{ GeV/c}^2 \). The ATLAS and CMS Collabo-
rations excluded \( m_H \) in the ranges 110.0–118.0 GeV/c²
and 119.5–121.0 GeV/c² using diphoton final states [91]
and in the range 110–194 GeV/c² by combining multiple
final states [92].

Dedicated searches are conducted for \( H \rightarrow \gamma \gamma \) within
the FHM interpretation to optimize the sensitivity for
the different event kinematic properties associated with
the dominant Higgs boson production mechanisms. FHM
Higgs bosons are produced in association with vector
bosons, or recoiling from jets in the case of VBF. As a
result, the Higgs boson \( p_T \) spectrum is shifted to higher
values for the FHM than the SM, where the dominant
production mechanism is \( gg \rightarrow H \). Potential signal con-
tributions from \( WH, ZH \), and VBF production included
in the SM \( H \rightarrow W^+W^- \) and \( H \rightarrow ZZ \) search
channels are also incorporated. In the \( H \rightarrow W^+W^- \) search
sub-channel focusing on events with opposite-charge lep-
tons and two or more reconstructed jets, where potential
signal contributions from these production mechanisms
are significant, the final discriminant used for the FHM
interpretation has been re-optimized to focus on the ex-
pected event kinematic properties of the relevant signal
processes. The FHM search is performed over the range
\( 100 \leq m_H \leq 200 \text{ GeV/c}^2 \).

No evidence for a fermiophobic Higgs boson is found
in the data, and upper limits are set on the produc-
tion rate relative to the FHM expectation. These lim-
its are shown in Fig. 10 and listed in Table VI. We
exclude a fermiophobic Higgs boson in the mass range
\( 100 < m_H < 113 \text{ GeV/c}^2 \), and expect to exclude \( 100 < m_H < 122 \text{ GeV/c}^2 \) in the absence of a Higgs boson signal.

FIG. 9: Summary of best-fit signal cross sections relative
to SM expectations for the \( m_H = 125 \text{ GeV/c}^2 \) hypothesis.
Square dots with horizontal uncertainty bars show the fitted
cross sections obtained from the subsets of CDF search chan-
nels corresponding to \( VH \rightarrow Vbb, H \rightarrow W^+W^-, H \rightarrow \gamma \gamma, H \rightarrow \tau^+\tau^- \), and \( t\bar{t}H \rightarrow t\bar{b}b \) production and decay. The solid
vertical line and associated shaded region illustrate the fitted
SM cross section obtained from all search channels.

IX. FOURTH-GENERATION MODEL
INTERPRETATION AND
MODEL-INDEPENDENT LIMIT ON \( gg \rightarrow H \)
PRODUCTION

The lowest-order process mediating the \( ggH \) coupling
in the SM is a quark triangle-loop, with the dominant
contribution coming from the top quark, and a smaller
contribution from the bottom quark. The model tested
here is the standard model with a fourth sequential gen-
eration of fermions (SM4). The masses of the com-
ponents of the fourth generation are assumed to be larger
than the mass bounds from collider experiments. In the
SM4, the up-type \( (u_4) \) and down-type \( (d_4) \) quarks would
contribute approximately with the same magnitude as
the top quark to the \( ggH \) coupling, resulting in approxi-
mately a factor of nine increase in the \( gg \rightarrow H \) produc-
tion cross section and the \( H \rightarrow gg \) decay width [15, 17].

The enhancement is modified by resonant structure in
TABLE VI: Decay branching fractions of the Higgs boson in FHM computed with HDECAY [56]. Also listed are the observed 95% credibility level upper limits on the signal rate relative to FHM expectations, and the median expected limits assuming no signal is present.

| $m_H$ (GeV/c^2) | $Br(\gamma\gamma)$ | $Br(W^+W^-)$ | $Br(ZZ)$ | $R_{FHM}^{exp}$ | $R_{FHM}^{exp}$ |
|----------------|------------------|-------------|---------|----------------|----------------|
| 100            | 0.185            | 0.735       | 0.0762  | 0.25           | 0.19           |
| 105            | 0.104            | 0.816       | 0.0733  | 0.49           | 0.35           |
| 110            | 0.0603           | 0.853       | 0.0788  | 0.53           | 0.54           |
| 115            | 0.0366           | 0.866       | 0.0887  | 1.27           | 0.78           |
| 120            | 0.0233           | 0.869       | 0.0993  | 1.56           | 0.91           |
| 125            | 0.0156           | 0.868       | 0.109   | 1.57           | 1.11           |
| 130            | 0.0107           | 0.867       | 0.116   | 1.32           | 1.22           |
| 135            | $7.59 \times 10^{-3}$ | 0.866    | 0.120   | 1.74           | 1.34           |
| 140            | $5.44 \times 10^{-3}$ | 0.868    | 0.121   | 2.17           | 1.43           |
| 145            | $3.90 \times 10^{-3}$ | 0.874    | 0.118   | 1.89           | 1.51           |
| 150            | $2.73 \times 10^{-3}$ | 0.886    | 0.108   | 2.33           | 1.57           |
| 155            | $1.76 \times 10^{-3}$ | 0.909    | 0.0871  | 1.52           | 1.62           |
| 160            | $8.35 \times 10^{-4}$ | 0.951    | 0.0466  | 1.53           | 1.51           |
| 165            | $3.34 \times 10^{-4}$ | 0.975    | 0.0236  | 1.26           | 1.48           |
| 170            | $2.26 \times 10^{-4}$ | 0.975    | 0.0246  | 1.95           | 1.73           |
| 175            | $1.79 \times 10^{-4}$ | 0.966    | 0.0332  | 2.36           | 1.92           |
| 180            | $1.48 \times 10^{-4}$ | 0.939    | 0.0609  | 2.92           | 2.23           |
| 185            | $1.18 \times 10^{-4}$ | 0.848    | 0.152   | 3.66           | 2.63           |
| 190            | $9.79 \times 10^{-5}$ | 0.788    | 0.212   | 4.13           | 3.17           |
| 195            | $8.52 \times 10^{-5}$ | 0.759    | 0.241   | 5.11           | 3.47           |
| 200            | $7.59 \times 10^{-5}$ | 0.742    | 0.258   | 6.02           | 3.86           |

The quark loop (the top quark contributes most strongly when $m_H \approx 2m_t$), electroweak contributions [16], and QCD radiative corrections [17]. The decay branching fractions of the Higgs boson may further be modified by the presence of a fourth neutrino ($\nu_4$), which may have been too heavy to be discovered at LEP, or due to decays to a heavy fourth-generation charged lepton $\ell_4$. We do not include acceptance for these decays in our predicted signal yields. The precision electroweak constraints that place an upper bound on the SM Higgs boson mass [15] are significantly relaxed in the SM4, allowing Higgs boson masses up to 750 GeV/c^2.

The production cross section for $gg \rightarrow H$ is computed in Ref. [17] for two scenarios of $m_{u_4}$ and $m_{d_4}$, but the production rates do not depend significantly on these masses, once they are large enough to evade experimental bounds. If $2m_{u_4} < m_H$ and $2m_{d_4} < m_H$, the decay branching ratios have a large impact on our ability to test the model. In both scenarios we assume $m_{u_4} = 450$ GeV/c^2 and $m_{d_4} = 400$ GeV/c^2. In the first scenario, called the high-mass scenario, we assume $m_{u_4} = m_{u_4} = 1000$ GeV/c^2, and in the second scenario, the low-mass scenario, $m_{u_4} = 100$ GeV c^2 and $m_{d_4} = 80$ GeV/c^2.

We search for $gg \rightarrow H$ production primarily in the $H \rightarrow W^+W^-$ decay mode, but the $H \rightarrow ZZ$ decay mode also contributes, particularly for $m_H > 200$ GeV/c^2. The $H \rightarrow \gamma\gamma$ channels contribute in the SM mainly through the $gg \rightarrow H$ production, but this decay mode is suppressed due to negative contributions of the quark loops relative to the $W$-mediated loop in $H \rightarrow \gamma\gamma$ decay. We therefore include only the $H \rightarrow W^+W^-$ and $H \rightarrow ZZ \rightarrow ℓ^+ℓ^-ℓ^+ℓ^-$ searches in this interpretation.

Previous interpretations of SM Higgs boson searches within the context of a fourth generation of fermions at Tevatron excluded $131 < m_H < 207$ GeV/c^2 [92]. Searches with similar sensitivity were performed by the ATLAS [94] and CMS [95] Collaborations, excluding $140 < m_H < 185$ GeV/c^2 and $144 < m_H < 207$ GeV/c^2, respectively. A more recent search by the CMS Collaboration excluded the mass range $110 < m_H < 600$ GeV/c^2 [96].

The first step is to set a limit on $\sigma(gg \rightarrow H) \times Br(H \rightarrow W^+W^-)$, which can be interpreted in a variety of models. We assume the SM value for the ratio of $Br(H \rightarrow ZZ)/Br(H \rightarrow W^+W^-)$ when combining the ZZ results, an assumption which is accurate in the SM4. The $H \rightarrow W^+W^-$ channels are re-optimized for this search by training the discriminants to separate only the $gg \rightarrow H$ mode from the background, ignoring the $WH, ZH$, and VBF production modes. In setting upper limits on the $gg \rightarrow H$ production cross section, we also
ignore the acceptance for $WH$, $ZH$, and VBF production, which yields conservative limits. In setting limits on $\sigma(gg \to H) \times Br(H \to W^+W^-)$, we do not include uncertainties in theoretical predictions of the production cross section or the decay branching ratio, but we include the theoretical uncertainties on the relative signal expectations in the 0-jet, 1-jet, and 2+jet event selections in the $H \to W^+W^-$ searches. We search for Higgs bosons in the mass range $110 < m_H < 300$ GeV/c$^2$, in which the analysis is expected to be sensitive to the SM4. Limits on $\sigma(gg \to H) \times Br(H \to W^+W^-)$ are listed in Table VII and are shown in Fig. 11.

The second step in the SM4 interpretation is to consider specific model scenarios. In this step we reintroduce the theoretical uncertainties on the predicted cross sections due to QCD factorization and renormalization scale and PDF uncertainties. The limits obtained are shown in Fig. 12 as multiples of the predictions in the two scenarios. In the low-mass scenario, we exclude the range $124 < m_H < 203$ GeV/c$^2$ at the 95% C.L., and expect to exclude $123 < m_H < 231$ GeV/c$^2$. In the high-mass scenario, the lack of fourth-generation leptonic and neutrino decays provides more expected signal in the remaining visible decays. We exclude the range $124 < m_H < 206$ GeV/c$^2$ at the 95% C.L., and expect to exclude the range $123 < m_H < 245$ GeV/c$^2$.

X. CONSTRAINTS ON FERMIONIC AND BOSONIC COUPLINGS

Following the recent LHC observations of a new Higgs-like particle with a mass of approximately 125 GeV/c$^2$, we focus on this mass hypothesis and test the couplings of the new particle, assuming that the mild observed excesses in CDF’s Higgs boson searches originate from this source. Similar studies of the couplings have been performed by CMS \cite{07} and ATLAS \cite{08}.

We assume that the production and decay of the Higgs-like particle follows the predictions of the SM Higgs boson, but with modified coupling strengths to fermions, the $W$ boson, and the $Z$ boson. We follow the procedures and notation of Ref. \cite{99}, and scale all Higgs boson couplings to fermions, regardless of flavor, by the factor $\kappa_f$; we scale the $HW$ coupling by the factor $\kappa_W$, and the $HZZ$ coupling by the factor $\kappa_Z$. The predicted signal rates in each production and decay mode are functions of the SM predictions and the factors $\kappa_f$, $\kappa_W$, and $\kappa_Z$. The SM predictions are obtained by setting $\kappa_f = \kappa_W = \kappa_Z = 1$. Because the $\kappa$ factors scale the couplings, the production rates and decay widths are quadratic functions of the coupling scale factors. The decay branching ratios are computed from the decay widths and thus are ratios of quadratic functions of the coupling scale factors.

For each of the studies described below, we assume a uniform prior probability density in one or more of the coupling scale factors and compute the posterior probability density using all of CDF SM Higgs boson search results, integrating over systematic uncertainties. One-dimensional intervals are quoted as the shortest set of intervals containing 68% of the integral of the posterior density, and the two-dimensional contours are those with the smallest areas containing 68% and 95% of the integral of the posterior density. The values that maximize the posterior probability are quoted as best-fit values.

We study both positive and negative values of the coupling scale factors, although little information on the relative signs of the couplings remains after squaring the amplitudes. The posterior probability densities have multiple maxima, possibly asymmetric due to interference terms in the production and decay in some modes. The $H\gamma\gamma$ coupling has a destructive interference term arising from the contributions from fermion loops and the $W$-boson loop that introduces a term linear in $\kappa_f$ and $\kappa_W$. This term breaks the ambiguity of the relative sign between $\kappa_W$ and $\kappa_f$, although the contribution from the $H \to \gamma\gamma$ channel is weak in the analyses presented here. A smaller interference term exists in the $ggH$ coupling, in which the dominant fermion-loop contributions interfere constructively with two-loop electroweak contributions \cite{22,23,24}. A global sign on all Higgs boson couplings is unobservable in the current analysis.

We study each coupling scale factor independently, holding the others fixed to their SM values, and then to study the fits by relaxing the assumptions one at a time. We focus on this mass hypothesis and test the couplings of the new particle, assuming that the mild observed excesses in CDF’s Higgs boson searches originate from this source. Similar studies of the couplings have been performed by CMS \cite{07} and ATLAS \cite{08}.

We assume that the production and decay of the Higgs-like particle follows the predictions of the SM Higgs boson, but with modified coupling strengths to fermions, the $W$ boson, and the $Z$ boson. We follow the procedures and notation of Ref. \cite{99}, and scale all Higgs boson couplings to fermions, regardless of flavor, by the factor $\kappa_f$; we scale the $HW$ coupling by the factor $\kappa_W$, and the $HZZ$ coupling by the factor $\kappa_Z$. The predicted signal rates in each production and decay mode are functions of the SM predictions and the factors $\kappa_f$, $\kappa_W$, and $\kappa_Z$. The SM predictions are obtained by setting $\kappa_f = \kappa_W = \kappa_Z = 1$. Because the $\kappa$ factors scale the couplings, the production rates and decay widths are quadratic functions of the coupling scale factors. The decay branching ratios are computed from the decay widths and thus are ratios of quadratic functions of the coupling scale factors.

For each of the studies described below, we assume a uniform prior probability density in one or more of the coupling scale factors and compute the posterior probability density using all of CDF SM Higgs boson search results, integrating over systematic uncertainties. One-dimensional intervals are quoted as the shortest set of intervals containing 68% of the integral of the posterior density, and the two-dimensional contours are those with the smallest areas containing 68% and 95% of the integral of the posterior density. The values that maximize the posterior probability are quoted as best-fit values.

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We study each coupling scale factor independently, holding the others fixed to their SM values, and then to study the fits by relaxing the assumptions one at a time.
in Fig. 15. In this case the 68% C.L. to the intervals \( \kappa_0 \leq \kappa < \kappa_0 \) is shown in Fig. 15. The factor \( \kappa_W \) is constrained to the intervals \(-1.8 < \kappa_W < -0.8\) and \(1.0 < \kappa_W < 1.7\) at the 68% C.L. The best fit value for \( \kappa_W \) is \(-1.4\). We perform a similar fit for \( \kappa_Z \), setting \( \kappa_f = \kappa_W = 1 \). From the posterior probability distribution shown in Fig. 13, \( \kappa_Z \) is constrained at the 68% C.L. to the intervals \(-1.5 < \kappa_Z < -0.4\) and \(0.4 < \kappa_Z < 1.5\). The best fit value for \( \kappa_Z \) is 1.05. We also perform a one-dimensional fit for the Higgs boson coupling to fermions, \( \kappa_f \), setting \( \kappa_W = \kappa_Z = 1 \). The posterior probability distribution obtained from the fit is shown in Fig. 13. In this case \( \kappa_f \) is restricted at the 68% C.L. to the intervals \(-3.8 < \kappa_f < -1.2\) and \(2.0 < \kappa_f < 3.0\) and has a best fit value of \(-2.75\).

We also constrain the allowed parameter space in the two-dimensional (\( \kappa_W, \kappa_Z \)) plane. A fit to the observed data is performed allowing all three coupling parameters to float. Two-dimensional constraints on (\( \kappa_W, \kappa_Z \)) are obtained from the resulting three-dimensional posterior probability distribution by integrating over \( \kappa_f \). The smallest regions containing 68% and 95% of the integral of the posterior probability density are shown in Fig. 16. As a result of the global sign ambiguity in the couplings, the value of the posterior probability at \((-\kappa_W, \kappa_Z)\) is equal to the value at \((\kappa_W, -\kappa_Z)\). Similarly, the value of the posterior probability at \((-\kappa_W, -\kappa_Z)\) is equal to the value at \((\kappa_W, \kappa_Z)\). The posterior probability distribution in Fig. 16 is displayed only for positive values of \( \kappa_W \). The local maxima within the regions of positive and negative \( \kappa_Z \) are \((\kappa_W = 1.3, \kappa_Z = 0.9)\) and \((\kappa_W = 1.3, \kappa_Z = -0.9)\).

Finally, we constrain the allowed parameter space
with the two-dimensional \((\kappa_V, \kappa_f)\) plane. Here, \(\kappa_V\) refers to a generic coupling of the Higgs boson to both W and Z bosons where the ratio \(\lambda_{WZ} = \kappa_W/\kappa_Z\) is fixed to unity. We compute a two-dimensional posterior probability distribution in the \((\kappa_V, \kappa_f)\) plane assuming a uniform prior probability density. The smallest regions containing 68% and 95% of the integral of the posterior probability density are shown in Fig. 17. Accounting for the symmetries \((-\kappa_V, -\kappa_f) = (\kappa_V, -\kappa_f)\) and \((-\kappa_V, \kappa_f) = (-\kappa_V, -\kappa_f)\) the posterior probability distribution is only displayed for positive values of \(\kappa_V\). The local maxima within the regions of positive and negative \(\kappa_f\) are \((\kappa_V = 1.05, \kappa_f = 2.6)\) and \((\kappa_V = 1.05, \kappa_f = -2.7)\).
FIG. 16: Two-dimensional constraints in the \((\kappa_W, \kappa_Z)\) plane. The 68% and 95% credibility regions are shown. A three-dimensional posterior probability distribution is obtained from a fit to the observed data in all CDF search channels by floating all three coupling parameters \((\kappa_W, \kappa_Z, \text{and} \kappa_f)\). The two-dimensional constraints are obtained by integrating the three-dimensional posterior probability density over \(\kappa_f\).

The results in the \((\kappa_V, \kappa_f)\) plane shown here are more constraining than those previously extracted in Ref. [101]. This is due to the inclusion of more channels and the use of separate scalings for each signal component, itemized by production and decay mode, contributing to individual search channels. The search channels with the most sensitivity to SM Higgs boson production measure the product of vector boson and fermion couplings. For example, search modes focusing on decays to fermion pairs \((b\bar{b} \text{ and } \tau^+\tau^-)\) require production in association with a vector boson. Conversely, searches focusing on Higgs boson decays to \(W^+W^-\) and \(ZZ\) pairs obtain a majority of their sensitivity from \(gg \rightarrow H\) production, which proceeds mostly via fermionic couplings to the Higgs boson.

Our searches for \(t\bar{t}H \rightarrow t\bar{t}bb\), on the other hand, are sensitive primarily to \(\kappa_f\) in both the production and decay modes. Hence, this search channel contributes significantly to the observed constraints on the coupling parameters, although it provides only a small contribution to combined CDF SM search result.

FIG. 17: Two-dimensional constraints in the \((\kappa_V, \kappa_f)\) plane. The 68% and 95% credibility regions are shown. A two-dimensional posterior probability distribution is obtained from a fit to the observed data in all CDF search channels where \(\kappa_V\) is the generic Higgs boson coupling to \(W\) and \(Z\) bosons assuming the SM value of one for \(\lambda_{WZ} = \kappa_W/\kappa_Z\).

Similarly, search channels focusing on events with same-charge di-leptons and tri-leptons are sensitive to \(\kappa_V\) in both the production \((VH)\) and decay \((H \rightarrow W^+W^-)\) modes. These channels provide a loose constraint on \(\kappa_V\) independent of \(\kappa_f\) and in the process help eliminate tails in the posterior probability distributions.

XI. SUMMARY

In summary, we present a final combination of the CDF Higgs boson searches. In the context of the standard model, we exclude at the 95% C.L. Higgs bosons with masses in the ranges \(90 < m_H < 102 \text{ GeV}/c^2\) and \(149 < m_H < 172 \text{ GeV}/c^2\). In the absence of a signal, we expect to exclude the ranges \(90 < m_H < 94 \text{ GeV}/c^2\), \(96 < m_H < 106 \text{ GeV}/c^2\), and \(153 < m_H < 175 \text{ GeV}/c^2\). An excess of data with respect to background predictions is observed, which has a local significance of 2.0 standard deviations at \(m_H = 125 \text{ GeV}/c^2\). We exclude fermiophobic Higgs boson bosons with mass in the range \(100 < m_H < 113 \text{ GeV}/c^2\), and expect to exclude...
100 < m_H < 122 GeV/c^2 in the absence of a Higgs boson signal. In the fourth-generation scenario incorporating the lowest possible fourth generation lepton and neutrino masses, we exclude the range 124 < m_H < 203 GeV/c^2 at the 95% C.L., and expect to exclude 123 < m_H < 231 GeV/c^2. The constraints placed on the fermionic and bosonic couplings are consistent with standard model expectations.

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FIG. 1: Median expected (assuming the background-only hypothesis) and observed 95% C.L. upper limits on Higgs boson production relative to the SM expectation for combinations of search channels within each Higgs boson decay mode and the combination of all search channels as a function of Higgs boson mass in the range between 90 and 200 GeV/c^2.
FIG. 2: Background-subtracted dijet invariant mass distribution from the combination of all search channels contributing to the $VZ$ cross section measurement. Expected signal contributions from $VZ$ production (red) and a $m_H = 125$ GeV$/c^2$ SM Higgs boson (green) are indicated with the filled histograms. The normalization of the subtracted background contribution, with uncertainties indicated by the unfilled histogram, is obtained from a fit to the data.