Higgs Boson Searches at CDF

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Abstract. Results are presented on searches for standard model and non-standard model production of a Higgs boson in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with the CDF II detector at the Fermilab Tevatron. Using data corresponding to 2-3.6 1/fb of integrated luminosity, searches are performed in a number of different production and decay modes. No excess in data above that expected from backgrounds is observed; therefore, we set upper limits on the production cross section times branching fraction as a function of the Higgs boson mass.

1. Introduction
Although the Higgs mechanism [1] was proposed in the 1960’s, the fundamental particle it predicts, the Higgs boson ($h$), has yet to be discovered. Direct limits from the LEP experiments exclude Higgs boson masses below 114.4 GeV/$c^2$ [2] at 95% Confidence Level (CL), while electroweak precision measurements place an indirect upper limit on the mass of a SM Higgs boson of 154 GeV/$c^2$ [3] at 95% CL.

Here we will summarize the status of the search for the Higgs boson using the the CDF II detector [4] to analyze the $p\bar{p}$ collision data from the Fermilab Tevatron.

2. Summary of Standard Model Search Efforts
For Higgs boson masses below 135 GeV/$c^2$, $bb$ is the main decay mode [5]. For higher masses the Higgs boson decays primarily into a pair of $W$ bosons. Due to these different decay modes, it is natural to also split the discussion of the analysis effort at CDF into the low mass and high mass categories.

The search for a Higgs boson is quite challenging due to the large backgrounds and small signal expectation. In order to increase signal-background discrimination, analyses make maximal use of the information in each event by employing multivariate techniques to collect the discriminating power of multiple input variables into a single more powerful output variable. When using these techniques it is crucial to prove that all of the multivariate inputs and the discriminant outputs are described well by the background models. These checks are performed by comparing the background model with the data in various control regions carefully defined to test the modeling of major background components. Over the years CDF has built confidence in their detector modeling and has had success with the use of multivariate techniques in SM analyses such as the recent evidence and observation of single top quark production [6, 7].

The Higgs boson search strategy is to perform dedicated analyses for each distinct final state with a significant production rate and then combine these results to make a statement about the sensitivity of the CDF experiment to the SM Higgs boson.
2.1. Low mass Higgs boson searches

In the $h \to b\bar{b}$ decay, each $b$ quark fragments into a jet of hadrons and the Higgs boson signal appears as a peak in the invariant mass distribution of these two jets. The two-jet signature alone is not useful to reject the dijet QCD background which is produced at the Tevatron with a rate about ten orders of magnitude higher than the Higgs boson. To handle this problem the low mass Higgs boson searches focus on production processes where the Higgs boson is produced in association with a $W$ or $Z$ boson ($Vh$).

The requirements of a high $P_T$ charged lepton candidate, missing transverse energy ($\not{E}_T$), and at least one $b$-tagged jet reduce the background in the $W h \to \ell\nu b\bar{b}$ [8, 9] search channel. In the past CDF has used an analysis based on an artificial neural network (NN) which includes the dijet invariant mass, the total system $P_T$ and, the event $P_T$ imbalance to improve the discrimination between the Higgs signal and background. Recently, CDF has combined this analysis with a new analysis which incorporates matrix element (ME) calculations into a boosted decision tree. This combination was done using another NN optimized based on genetic algorithms [10]. The combined result is the most sensitive low mass analysis obtaining observed (expected) 95% C.L. limit of 5.6 (4.8) times the SM prediction of the production cross section for a Higgs boson mass of 115 GeV/$c^2$ using 2.7 fb$^{-1}$ of integrated luminosity.

The $Z h \to \ell\ell b\bar{b}$ [11] has a smaller background but also a smaller signal expectation due to the reduced cross section of $Zh$ production. The reach of this analysis has been improved by loosening the lepton identification requirements to increase signal acceptance. In addition, this final state is fully constrained by the reconstructed objects and the $\not{E}_T$ can be used to correct the jet energies to improve the dijet mass resolution. CDF has a two-dimensional NN analysis and an analysis based on ME probabilities. For a Higgs boson mass of 115 GeV/$c^2$ the NN analysis obtains an observed (expected) 95% C.L. limit of 7.7 (9.1) times the SM prediction of the production cross section using 2.7 fb$^{-1}$ of integrated luminosity.

The third major low mass Higgs analysis is based on a $\not{E}_T$ requirement and identifying $b$ jets but does not allow any reconstructed leptons in the events [12]. It is sensitive to $Zh \to \nu\nu b\bar{b}$ but also $Wh \to \ell\nu b\bar{b}$ when the lepton escapes detection. Without the charged lepton requirement the dominant background is QCD events where mismeasured jets fake the $\not{E}_T$ requirement. A NN selection tool is derived which uses information about the angular correlations between the jets and the $\not{E}_T$ as well as a “missing $P_T$” variable based on tracking information. By cutting on this NN the signal to background ratio is improved to the level of the lepton based analyses, making this channel competitive as one of the most sensitive low mass Higgs boson search channels. The $\not{E}_T+b\bar{b}$ analysis obtains observed (expected) 95% C.L. limit of 6.9 (5.6) times the SM prediction of the production cross section for a Higgs boson mass of 115 GeV/$c^2$ using 2.1 fb$^{-1}$ of integrated luminosity.

2.2. High mass Higgs boson searches

At high mass the $h \to WW \to \ell\nu\ell\nu$ channel dominates the sensitivity to the Higgs boson. The leptonic decay mode of the $W$ bosons is chosen to reduce background and improve signal purity. The CDF analysis [13] includes all significant production modes (gluon fusion, $Vh$, and vector boson fusion (VBF)), and splits the analysis up based on the number of jets observed in the final state. This is useful since the background and signal composition change considerably depending on the number of jets. The $h \to WW$ analysis is the most sensitive single analysis at CDF.

2.3. Results

The observed (expected) limits on the Higgs boson cross section in units of the SM prediction for all of the CDF analyses are shown in Fig. 1(a). These results are combined into a single limit on the Higgs boson production rate for each Higgs boson mass hypothesis. In addition to
the most sensitive low mass analyses, CDF also has analyses that focus on the all hadronic final state ($Vh$ where the vector boson decays into two jets), and an inclusive $h \to \tau \tau$ analysis that are included in the combination. The result of the combination of CDF results is shown as the garnet line in Fig. 1(a). The limits range from 1.4 to about 5 times the prediction of the SM rate.

The CDF results have also been combined with the results of the DØ experiment. This is shown in Fig. 1(b). The combined result excludes Higgs bosons with masses between 160 and 170 GeV/$c^2$ at the 95% C.L. This is the first new exclusion of a standard model Higgs boson based on a direct search using Tevatron data.

Figure 1. Limits at 95% C.L. on the Higgs boson production cross section in factors away from the standard model prediction for the individual analysis channels and the CDF combined result (a). The full Tevatron result from the combination of the CDF and DØ experiment (b).

3. Beyond the Standard Model Example: Fermiophobic Higgs Boson Search
The CDF experiment also searches for Higgs bosons produced in many extensions to the SM. One example which has been recently updated [14] is a search in the diphoton final state. The SM prediction for the $h \to \gamma \gamma$ branching fraction is extremely small (reaching a maximal value of only about 0.2% at a Higgs boson mass ($m_h$) $\sim$ 120 GeV/$c^2$) [5]; however, in “fermiophobic” models, where the coupling of the Higgs boson to fermions is suppressed, the diphoton decay can be greatly enhanced. This phenomenon has been shown to arise in a variety of extensions to the SM [15, 16, 17, 18, 19], and the resulting collider phenomenology has been described [20, 21, 22]. For this fermiophobic case, the decay into the diphoton final state dominates at low Higgs boson masses and is therefore the preferred search channel.

A benchmark fermiophobic model is considered in which the Higgs boson does not couple to fermions, yet retains its SM couplings to bosons. In this model, the fermiophobic Higgs boson production is dominated by two processes: $Vh$, and VBF. Two identified photon candidates are required in the analysis. In addition, a cut is applied on the transverse momentum of the diphoton pair ($P_{\gamma\gamma}$) designed to optimize sensitivity ($VBF$ and $Vh$ have more $P_{\gamma\gamma}$ on average than the SM diphoton production and QCD backgrounds).

The decay of a Higgs boson into a diphoton pair appears as a very narrow peak in the invariant mass distribution of these two photons ($\sigma_{m/m < 3 \%}$). The search can therfore be performed by looking for a narrow bump on an otherwise smooth background distribution. No narrow resonance is observed. In order to set limits on the Higgs boson production rate, a sideband fit excluding the hypothetical mass window is performed to estimate the background in the search window (see Fig. 2(a)). The analysis results in 95 % C.L. limits on the production cross section.
$(\sigma \times \text{Br}(h \rightarrow \gamma\gamma))$ and on the branching fraction $(\text{Br}(h \rightarrow \gamma\gamma))$ as shown in Fig. 2(b). The result excludes the benchmark model predictions for $m_h$ of less than 106 GeV/$c^2$.

**Figure 2.** An example of the sideband fits (a) and the 95% C.L. limits (b) obtained on the $\text{Br}(h \rightarrow \gamma\gamma)$ from the search for a fermiophobic Higgs boson in the $h \rightarrow \gamma\gamma$ channel.

4. Conclusions, and Outlook
The CDF experiment is carefully searching for SM and BSM Higgs bosons. A combination of results with DØ excludes Higgs boson masses between 160 and 170 GeV/$c^2$, and this is the first exclusion of SM Higgs bosons based on Tevatron data. At low mass, sensitivity is better than three times the standard model prediction. With more data on tape to analyze, and improvements still being added to analysis techniques, the Higgs boson search results will be an exciting topic until the end of the Tevatron run. With the full dataset expected to be on the order of $10 \text{ fb}^{-1}$, there is a significant chance that the Tevatron will see some evidence of the elusive Higgs boson.

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