Searches for Higgs at Tevatron

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Abstract. A summary of the latest results of Standard Model Higgs boson searches from CDF and DØ analyses using up to 3.0 fb$^{-1}$ of Tevatron data are reviewed. 95% C.L. upper limits on Higgs boson production are shown for Higgs masses ranging from 100 to 200 GeV.

1. Introduction

In the Standard Model (SM), the Higgs mechanism breaks the electroweak symmetry by introducing a scalar field to generate particle masses. It predicts the existence of a neutral spin 0 boson, the Higgs boson, but not its mass. Direct searches at LEP 2 have excluded a SM Higgs boson with mass below 114.4 GeV at 95% confidence level (C.L.). Indirect measurements from SLD, LEP and the Tevatron, favor a light Higgs boson with mass of 84$^{+34}_{-26}$ GeV at 68% C.L. and constrain its mass to be below 185 GeV at 95% C.L. when including the LEP 2 exclusion [1].

At the Tevatron, SM Higgs production is dominated by gluon fusion, with smaller contributions from W or Z bosons associated productions. Cross sections range from 0.1 to 1 pb. Below 135 GeV (low-mass), the SM Higgs boson decays predominantly to $b\bar{b}$. In order to avoid the huge SM QCD multijets background, searches use the associated productions: $WH$ and $ZH$. Above 135 GeV (high-mass), SM Higgs decays predominantly to $WW^*$, thus making it possible to use the gluon fusion production.

This document describes the searches for a SM Higgs boson by the CDF and DØ collaborations using up to 3.0 fb$^{-1}$ of Run II data. The majority of those results are preliminary, and more information can be found on the public pages of CDF [2] and DØ [3].

2. Search for $WH \rightarrow \ell \nu b\bar{b}$

Searches for Higgs production in associated production with a $W$ boson decaying leptonically provides the most stringent constraints on the low mass SM Higgs. The event selection consists on identifying one isolated high-$p_T$ electron or muon, $p_T > 20$ GeV (15 GeV for DØ), large missing transverse energy, $E_T > 20$ GeV, and two (two or three for DØ) jets with high transverse energy $E_T > 20$ GeV where at least one of them has been identify as a jet coming from a $b$-quark. Additionally, CDF used the $E_T$+jets trigger to identify events with one isolated track which failed the electron or muon identification, thus increasing the Higgs acceptance by 25%. DØ uses a Neural Network (NN) trained on several kinematic variables and a matrix element discriminant, and splits the data into sixteen exclusive sets based on the number of $b$-tagged jets, lepton flavor, jet multiplicity and the two data periods to optimize the sensitivity. As no excess is observed compared to the expectation, a limit is derived from the eight individual analysis and combined. DØ sets a limit of 6.4 (6.7 expected) at 95% C.L. above SM expectation for a...
Figure 1. DØ NN output (left) and CDF combined NN output for the double tagged sample.

Table 1. Summary of expected and observed 95% C.L. upper cross section limits in SM units for a Higgs mass of 115 GeV for the $WH \rightarrow \ell\nu b\bar{b}$ search.

| Analysis            | Luminosity (fb$^{-1}$) | Expected ($\sigma/SM$) | Observed ($\sigma/SM$) |
|---------------------|-------------------------|-------------------------|------------------------|
| DØ NN               | 2.7                     | 6.4                     | 6.7                    |
| CDF NN              | 2.7                     | 5.8                     | 5.2                    |
| CDF ME+BDT          | 2.7                     | 5.2                     | 6.2                    |
| CDF combo           | 2.7                     | 4.8                     | 5.6                    |

Higgs mass of 115 GeV. CDF has two different analyses that share the event selection but use different techniques to discriminate the Higgs signal from the different backgrounds. The first one is based in a NN trained on six discriminating kinematic variables. The second one is based on a Boosted Decision Tree (BDT) trained on several kinematic variables, event probability densities from matrix elements information, and the output of a neural network optimized to separate the jet flavor. Both analysis are split in six exclusive channels based on three different $b$-tagged categories (using two different $b$-tagging algorithms) and two lepton types (triggered or not triggered) and the discriminant outputs are then combined to construct a final discriminant trained using a genetic neural network technique. In the absence of signal, CDF sets a limit of 5.6 (4.8 expected) 95% C.L. above SM expectation for a Higgs mass of 115 GeV. Figure 1 shows the discriminant in the double tag sample for both DØ and CDF combination. In table 1 the results for the upper cross section limits for a Higgs mass of 115 GeV are summarized.

3. Search for $ZH \rightarrow \ell^+\ell^- b\bar{b}$

For the low mass region (below 135 GeV) where the Higgs decays predominantly to $b\bar{b}$, the cleanest channel is the associated production with a $Z$ boson, where the $Z$ decays leptonically to $e^+e^-$ or $\mu^+\mu^-$. Although the cross section times branching ratio is lower that the associated production with a $W$ boson, this channel offers several tight constraints since $M_{\ell^+\ell^-} = M_Z$ and
the lack of direct missing transverse energy can be used to improve the jet energy resolution. Candidate events are selected by requiring two high $p_T$ (typically above 15 GeV) electrons or muons of opposite charge with invariant mass matching that of a Z boson. DØ requires two jets with $E_T > 15$ GeV, while CDF requires additionally that the highest energetic jet passes $E_T > 25$ GeV. After this pre-selection, the sample is dominated by $Z$+jets and therefore $b$-jets identification is crucial to reduce this background. DØ utilizes an artificial neural network (NN) tagger based on lifetime information, which performs with efficiencies ranging 50-70% for a mis-identification (also referred to as mistag) rate of 0.3-4.5%. CDF uses a secondary vertex reconstruction algorithm with efficiencies ranging 40-50% for a mistag rate of 0.3-0.5%. To further discriminate signal and background events, DØ uses a NN discriminant for the electron channels and a BDT discriminant for the muon channels separately trained for 1-tag and 2-tag events using ten kinematic variables. Since no excess of signal is observed, the output of the NN is fitted to extract a 95% C.L. limit corresponding to 11.0 (12.3 expected) above the theoretical SM expectation for $M_H = 115$ GeV. CDF uses a NN to improve the dijet mass distribution, which essentially is a correction function that reassigns the $E_T$ to the jets according to their $E_T$ corrections and relative $\phi$. Then, a 2-dimensional NN, trained to discriminate $ZH$ from the main $Z$+jets background and the kinematically different $t\bar{t}$ background, is used separately for single and double tags events. The NN output is fitted to extract a 95% C.L. limit corresponding to 7.1 (9.9 expected) above the theoretical SM expectation for $M_H = 115$ GeV. Figure 2 shows discriminants in the double tag samples for both DØ run IIb data and CDF data. In table 2 the results for the upper cross section limits for a Higgs mass of 115 GeV are summarized.

| Analysis         | Luminosity (fb$^{-1}$) | Expected ($\sigma/SM$) | Observed ($\sigma/SM$) |
|------------------|------------------------|-------------------------|------------------------|
| DØ NN, BDT       | 2.3                    | 12.3                    | 11.0                   |
| CDF NN           | 2.7                    | 9.9                     | 7.1                    |

Figure 2. DØ NN output for the electron channel using run IIb data (left) and CDF combined NN output projection along the $Z$+jets vs. $ZH$ axis cutting on the high scored bins of the $t\bar{t}$ vs. $ZH$ axis. Both figures in the double tagged sample.

Table 2. Summary of expected and observed 95% C.L. upper cross section limits in SM units for a Higgs mass of 115 GeV for the $ZH \rightarrow \ell^+\ell^-b\bar{b}$ search.
4. Search for $Z \bar{H} \rightarrow \nu \bar{\nu} b \bar{b}$

Although the $Z \bar{H}$ associated production has a larger branching ratio to neutrinos, it is very challenging to trigger on and background wise. Events are triggered on jets plus $E_T$ and tight cuts are applied to reject background. DØ requires two or three jets with $E_T > 20$ GeV, where the two leading ones are not back-to-back and with at least 50 GeV of $E_T$ in the event. CDF asks for two or three jets, where the $E_T$ of the leading jet is above 35 GeV, 25 GeV for the second jet and at least 50 GeV of $E_T$ not aligned with the jets. Both experiments require that there be no identified electrons or muons so that the data sample is orthogonal to the $WH \rightarrow \ell \nu b \bar{b}$ searches, however, significant event yield from $WH$ channel remains due to leptonic decay of the $W$ where the lepton escapes identification. Additionally, angular cuts between the jets and the $E_T$ are used to reject further the background, and identify a QCD multijets control sample, and $b$-tagging requirements are applied to the jets. DØ uses a decision tree (DT) technique trained on 25 input variables as the final discriminant (figure 3). CDF uses two separate NN. The first one uses track-based quantities to discriminate $Z \bar{H}$ from the dominant QCD multijets background. The second one, used to extract the limit, takes as input the first NN and combines other kinematic variables to discriminate $Z \bar{H}$ and $WH$ from QCD multijet and $t \bar{t}$ backgrounds (figure 3). In the absence of any signal, DØ sets a limit of 7.5 (8.4 expected) at 95% C.L. above SM expectation, while CDF obtains a limit of 6.9 (5.6 expected) at 95% C.L. The results for the upper cross section limits for a Higgs mass of 115 GeV are summarized in table 3.

**Figure 3.** DØ NN output for the electron channel using run IIb data (left) and CDF combined NN output projection along the $Z$+jets vs. $Z \bar{H}$ axis cutting on the high scored bins of the $t \bar{t}$ vs. $Z \bar{H}$ axis. Both figures in the double tagged sample.

**Table 3.** Summary of expected and observed 95% C.L. upper cross section limits in SM units for a Higgs mass of 115 GeV for the $Z \bar{H} \rightarrow \nu \bar{\nu} b \bar{b}$ search.

| Analysis | Luminosity (fb$^{-1}$) | Expected ($\sigma/SM$) | Observed ($\sigma/SM$) |
|----------|------------------------|------------------------|------------------------|
| DØ DT    | 2.1                    | 8.4                    | 7.5                    |
| CDF NN   | 2.1                    | 5.6                    | 6.9                    |
5. Search for $H \rightarrow W^+W^-$

In the high mass region (above 135 GeV), SM Higgs decays predominantly to $W^+W^-$. This channel benefits from a very clean signature with low SM backgrounds thus providing the largest sensitivity for a SM Higgs boson search at the Tevatron. The event selection consists in identifying two opposite charged isolated high $p_T$ leptons ($ee$, $\mu\mu$ and $e\mu$), $E_T > 20, 25$ GeV (DØ, CDF) and little jet activities to reduce background from top pair production. The QCD multijet background is further reduced by requiring the di-lepton mass to be above 15 GeV. The remaining background is SM $WW$ production, and the opening angle between the two leptons, $\Delta \phi_{\ell\ell}$ can be used as a discriminating variable since the leptons from a spin-0 Higgs tend to be more co-linear. DØ tunes the various pre-selection criteria thresholds for each di-lepton class and the various SM Higgs masses. To improve the separation between signal and backgrounds, DØ uses a NN for each of the di-lepton channel. The input variables consist of various event and object kinematics, angular variables and a discriminant constructed using the Matrix Element method in the $ee$ and $\mu\mu$ channels (figure 4). DØ obtains a 95% C.L. of 2.0 (1.9 expected) above SM expectation for $M_H = 165$ GeV. In order to maximize sensitivity, CDF optimize a multivariate technique based on neural networks and matrix element information separately for final states with either zero, one, or two or more identified jets. To gain extra acceptance, we also include associated production with a W or Z and vector boson fusion production mechanisms for events with one or more jets. In figure 4 the output of the neural network discriminant combining the different jet multiplicities and lepton types is shown. In absence of signal, the NN output is fitted to extract a 95% C.L. of 1.6 (1.6 expected) above SM expectation for $M_H = 165$ GeV. The results for the upper cross section limits for a Higgs mass of 165 GeV are summarized in table 4.

![Figure 4](image-url)  

**Figure 4.** DØ NN output distribution for the $\mu\mu$ channel (left) and CDF combined NN output.

**Table 4.** Summary of expected and observed 95% C.L. upper cross section limits in SM units for a Higgs mass of 165 GeV for the $H \rightarrow W^+W^-$ search.

| Analysis     | Luminosity (fb$^{-1}$) | Expected $(\sigma/SM)$ | Observed $(\sigma/SM)$ |
|--------------|------------------------|------------------------|------------------------|
| DØ NN        | 3.0                    | 1.9                    | 2.0                    |
| CDF ME+NN    | 3.0                    | 1.6                    | 1.6                    |
6. Combined upper limits on Standard Model Higgs boson production

Since no single decay channel and neither experiment has sufficient statistical power to reach the SM prediction over the full mass range, results from all searches for both experiments are combined for each single experiment and also together in a Tevatron combination.

The DØ combination includes all searches mentioned in the previous chapters plus other searches such as the associated production \( WH \rightarrow WW^+W^- \), the gluon fusion \( H \rightarrow \gamma\gamma \) and the vector boson fusion \( qq' \rightarrow qq'W^+W^- \), taking into account all the systematic uncertainties between the different channels using a Modified Frequentist approach. The observed (expected) 95% confidence level upper limits are found to be a factor of 5.3 (4.6) and 2.0 (1.9) higher than the predicted standard model cross section at \( m_H = 115 \text{ GeV} \) and \( m_H = 165 \text{ GeV} \), respectively (figure 5).

CDF combines all searches explained in the previous chapters together with the associated production \( WH \rightarrow WWW \) search in the like-sign di-lepton final state, and the combined search of vector boson fusion, gluon fusion and associated production \( H \rightarrow \tau^+\tau^-+2\text{jets} \). All systematic uncertainties within the different channels are taken into account using a Bayesian approach. The 95% CL upper limits observed (expected) are factors of 3.76 (3.17) and 1.56 (1.75) higher than the Standard Model production cross sections for Higgs boson masses of 115 and 160 GeV, respectively (figure 5).

Finally both experiments results at high mass are combined in a Tevatron result where all systematic uncertainties and their correlations between channels and across the experiments are taken into account. To verify that the final result does not depend on the details of the statistical formulation, we performed several types of combinations, using the Bayesian and Modified Frequentist approaches, which are found to be in good agreement within 10%. The observed (expected) 95% C.L. upper limits on Higgs boson production are a factor of 1.2, 1.0 and 1.3 (1.2, 1.4 and 1.7) higher than the SM cross section for a Higgs boson mass of \( m_H = 165 \), 170 and 175 GeV, respectively (figure 5). We exclude at 95% C.L. a standard model Higgs boson of \( m_H = 170 \) GeV.

7. Conclusions and prospects

CDF and DØ have performed searches for the SM Higgs boson over a wide range of masses (100-200 GeV) with an integrated luminosity up to 3.0 fb\(^{-1}\). Since no excess of signal above the

![Figure 5](image-url)  
*Figure 5.* The combined upper limit as a function of the Higgs boson mass between 100 and 200 GeV for DØ (left) and CDF (right). The solid (dashed) line is the observed (median expected) limit/SM. Colored bands indicates the ±1 and ±2 sigma distributions around the median expected limit.
expected backgrounds were observed, limits were set. At low mass upper cross sections limits from both experiments are about 3-5 times above the standard model prediction. At high mass the limits from the Tevatron combination are reaching sensitivity to a standard model Higgs, being able to exclude at 95% C.L. a standard model Higgs boson of $m_H = 170$ GeV.

Both experiments have brought a variety of improvements to the analyses: trigger and lepton identification optimization, dijet mass resolution, b-tagging algorithms, splitting classes of events, advance analysis techniques (NN, BDT, ME), all of which permitted to improve on the limit faster than the gain from increasing luminosity. With the expected integrated luminosity of 6-8 fb$^{-1}$ by the end of 2009 we expect to reach the sensitivity to a standard model Higgs over the full mass range and set wider exclusion zones if no evidence is found.

References
[1] http://lepewwg.web.cern.ch/LEPEWWG/
[2] http://www-cdf.fnal.gov/physics/new/hdg/hdg.html
[3] http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm