SM Higgs Searches at CDF

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Abstract. We present the latest CDF searches for the Standard Model Higgs boson with 1.96 TeV center-of-mass energy collisions produced at the Fermilab Tevatron. The data was collected with the CDF II detector at the Tevatron collider and correspond to an integrated luminosity from 2 to 4.8 fb$^{-1}$. To achieve maximal sensitivity, many channels are analyzed including final states from gluon fusion, vector boson fusion, and associated production with W and Z bosons.

1. Introduction

One of the most fundamental problems in particle physics is understanding the mechanism that breaks electroweak symmetry and generates the mass of all known elementary particles. The Higgs boson is the only Standard Model (SM) particle that has not been observed yet and is introduced into the SM theory to explain the origin of the electroweak symmetry breaking [1]. Its mass is a free parameter of the SM, but from direct searches for the Higgs boson at the LEP collider the mass of the Higgs boson is excluded below 114.4 GeV/c$^2$ at 95% confidence level (C.L.). Indirectly, precision electroweak measurements, performed at LEP and by SLD, CDF, and D0, show a preferred low mass Higgs and lead to the 95% C.L. m$_H < 157$ GeV/c$^2$. The 95% C.L. lower limit obtained from LEP is not used in the determination of this limit.

At the Tevatron, a $p\bar{p}$ collider at Fermilab, the most important SM Higgs boson production processes are gluon fusion ($gg \rightarrow H$) and Higgs boson production in association with a vector boson ($WH$ or $ZH$) [2], summarized in Figure 1 as a function of the Higgs mass ($m_H$).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{SM Higgs production cross sections for $p\bar{p}$ collisions at 1.96 TeV [3] (on the left) and branching ratios for the main decays of the SM Higgs boson [4] (on the right).}
\end{figure}
The branching ratios for the most relevant decay modes of the SM Higgs boson are shown in Figure 1 as functions of $m_H$. The search strategy for the Higgs boson at the Tevatron is driven by the decay modes. For masses below 135 GeV/c², decays to fermion pairs dominate, of which the decay $H \to b\bar{b}$ has the largest branching ratio. Decays to $\tau^+\tau^-$, $c\bar{c}$ and gluon pairs together contribute less than 15%. In this case, the most promising discovery channels are $WH$ and $ZH$ with $H \to b\bar{b}$. For Higgs boson masses above 135 GeV/c², the $WW$ decay dominates with an important contribution from $H \to ZZ$. Both the direct ($gg \to H$) and the associated production ($p\bar{p} \to WH$ or $ZH$) channels are explored.

2. SM Higgs Boson Searches at CDF
An overview of the SM Higgs analyses done at CDF is presented in this section. The analyses are exploited in two regions: low and high mass region. At masses below about 135 GeV/c², low mass region, the searches for associated production, $p\bar{p} \to WH, ZH$ are performed in different channels: $p\bar{p} \to WH \to l\nu b\bar{b}$, $p\bar{p} \to ZH \to \nu\bar{\nu} b\bar{b}$, and $p\bar{p} \to ZH \to l^+l^- b\bar{b}$. At the high mass region, the dominant $H \to WW$ decay mode is best exploited in direct $gg \to H$ production, however the vector boson fusion, and the associated production with $W$ and $Z$ bosons modes are also used.

2.1. $p\bar{p} \to WH \to l\nu b\bar{b}$
The $W$ decays leptonically, to a lepton (electron or muon) and a neutrino, and $H \to b\bar{b}$; such searches have been published by the CDF collaboration on 2.7 fb⁻¹ [5]. These analyses use very advanced analysis techniques such as neural networks (NNs) or a matrix element method to separate a potential signal from the background processes, and also a NN is used to separate correctly identified $b$-jets from jets originating from gluons or from light or $c$ quarks. The latest results using 4.8 fb⁻¹ of the CDF integrated luminosity, are public but have not been published yet [6]. The Higgs boson production cross section limits obtained are about three times higher than the SM expectation in this channel. The expected and observed limits for a Higgs boson mass of 115 GeV/c² for this channel and for the other two low mass Higgs channels are shown in Table 1 with the corresponding integrated luminosity.

| Channel | Int. Luminosity (fb⁻¹) | Expected/SM | Observed/SM |
|---------|-------------------------|-------------|-------------|
| $p\bar{p} \to WH \to l\nu b\bar{b}$ | 4.8 | 3.8 | 3.3 |
| $p\bar{p} \to ZH \to \nu\bar{\nu} b\bar{b}$ | 3.6 | 4.2 | 6.1 |
| $p\bar{p} \to ZH \to l^+l^- b\bar{b}$ | 4.1 | 6.8 | 5.9 |

Table 1. Expected and observed upper limits in Standard Model units for a Higgs boson mass of 115 GeV/c² for the three low mass Higgs channels with their corresponding integrated luminosities.

2.2. $p\bar{p} \to ZH \to \nu\bar{\nu} b\bar{b}$
The $Z$ decays into $\nu\bar{\nu}$ and $H \to b\bar{b}$, is also a very sensitive channel, the sensitivity is comparable to that obtained in the $WH$ channel. Since the final state is characterized by missing transverse energy and two $b$-jets, the QCD multijet processes are the dominant background processes. In CDF, a data-driven model is implemented to remove 70% of the QCD background events. The sensitivity of this search is enhanced by $pp \to WH$ events in which the charged lepton from the $W$ decay escapes detection; these events have the same experimental signature as the $ZH \to \nu\bar{\nu}$ signal. The latest result has been updated using 3.6 fb⁻¹ of the CDF II data [7]. For a Higgs boson mass of 115 GeV/c² the expected and observed limits are given in Table 1.
2.3. $p\bar{p} \rightarrow ZH \rightarrow l^+l^-b\bar{b}$

The $Z$ decays into two charged leptons ($e^+e^-$ or $\mu^+\mu^-$), and the Higgs boson, as well as the other two channels, to a $b\bar{b}$ pair. This channel suffers from a smaller $Z$ branching fraction, but has lower background, so its sensitivity is not much lower than that of the previous two channels. The main background processes are $Z$+jets ($b\bar{b}$, and $c\bar{c}$), top pairs, and $ZZ$. Two neural networks were implemented, one to improve the energy resolution of the two final state jets and the other, a two dimensional NN, to discriminate between signal to background events. The latest result presented by the CDF collaboration is based on 4.1 fb$^{-1}$ of the CDF integrated luminosity [8]. The upper limits for a Higgs boson mass of 115 GeV/c$^2$ are shown in Table 1.

2.4. $H \rightarrow WW \rightarrow l^+l^-\nu\bar{\nu}$

It is the most sensitive channel for possible SM Higgs bosons with a mass above 135 GeV/c$^2$. The $WW$ pair issued from a Higgs boson decay has a spin correlation which is different from the dominant background process, electroweak $WW$ production. These spin correlations are transmitted to the distributions of observed leptons, providing a handle to separate the signal from the background. The invariant mass of the Higgs boson decay products cannot be reconstructed due to the undetected neutrinos, but the sensitivity is nevertheless significant. Other physics processes like Drell-Yan, $W$ boson production associated with a photon or jets and top quark pair production are also characterized as background processes for this channel.

In order to maximize sensitivity, seven dedicated channels are exploited: opposite-sign (OS) final states with either zero, one, or two or more jets, opposite-sign low dilepton invariant mass ($M_{ll}$), same-sign (SS) dileptons and trileptons outside and inside of the $Z$ peak in the final state. The results from the seven independent channels are combined together to obtain the final limits. Using an integrated luminosity of 4.8 fb$^{-1}$, an observed (expected) 95% C.L. upper cross section limit of 1.2 (1.2) times the SM prediction for a Higgs mass of 165 GeV/c$^2$ is obtained [9].

3. Conclusions

All the presented Standard Model Higgs bosons searches, with other channels that are not as sensitive like $H \rightarrow \tau^+\tau^-+jets$, are combined together to extract the maximum sensitivity. No evidence for a Higgs boson signal has been reported yet. The CDF Standard Model Higgs boson combination results an exclusion limit that is approaching the predicted cross sections. With 2 to 4.8 fb$^{-1}$ of data analyzed at CDF, the 95% C.L. upper limits observed (expected) are factors of 3.1 (2.4) and 1.2 (1.2) higher than the Standard Model production cross sections for Higgs boson masses of 115 and 165 GeV/c$^2$, respectively, shown in Figure 2 [10].

The results on direct searches for a SM Higgs boson of both Tevatron experiments, CDF and DØ are also combined to maximize the sensitivity to the Higgs boson [11].

4. References

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[10] http://www.cdf.fnal.gov/physics/new/hdg/Results_files/results/combcdf_nov09/ Combined Upper Limit on Standard Model Higgs Boson Production at CDF for HCP 2009.
Figure 2. Expected and observed 95% C.L. upper limits on different channels of Higgs production in CDF, expressed as a ratio to the SM cross section expectation times branching. The limits are obtained using integrated luminosities from 2 to 4.8 fb$^{-1}$. The dashed line indicates the expected limit and the solid line the observed limit. All the separate channel results are combined to obtain the CDF combination (maroon).

[11] http://tevnphwg.fnal.gov/results/SM_Higgs_Fall_09/. Combined CDF and D0 Upper Limits on Standard-Model Higgs-Boson Production, arXiv:0911.3930 [hep-ex].