1. Introduction

Direct searches for Standard Model Higgs boson have been performed at the LEP experiment through the past decade [1]. No signal has been observed in $e^+e^-$ collisions and a lower limit on Higgs mass has been set at 114 GeV/c$^2$ @95% of confidence level (CL). Indirect limits on the Higgs mass have also been derived by the radiative correction of this parameter to electroweak constants. Figure 1 shows the $\Delta\chi^2$ curve derived from high precision electroweak measurements, performed at LEP and by SLD, CDF, and D0, as a function of the Higgs boson mass, assuming the Standard Model to be the correct theory of nature [2]. The preferred value for its mass, corresponding to the minimum of the curve, is at $89^{+42}_{-30}$ GeV/c$^2$, with an upper limit at 175 GeV/c$^2$. This limit increases to 207 GeV/c$^2$ when including the LEP direct search limit of 114 GeV/c$^2$ (shown in yellow in the figure).

In this paper, we introduce the main channels and techniques for the Higgs boson search at the CDF experiment of the Tevatron collider in the mass range suggested by the results above. Successively, we present the most recent results obtained by the CDF collaboration. Finally, we discuss the perspective for a Higgs boson discovery at the Tevatron collider.

2. Higgs Boson at the CDF Experiment

The production cross section for a Standard Model Higgs boson in $p\bar{p}$ collisions at the center of mass energy of $\sqrt{s} = 1.96$ TeV reached by the Tevatron collider is shown in figure 2 as a function of the mass of the Higgs particle. The main production mechanism is the direct production via gluon fusion (see figure 3). The cross section for this process ranges from 1 to 0.1 pb for Higgs mass between 100 and 200 GeV/c$^2$. The associated production of the Higgs boson with a gauge boson $W$ or $Z$ (see figure 4) is about one order of magnitude smaller. The decay modes of the Higgs boson depend on its mass, as shown in figure 5. The most interesting mass range for Higgs boson searches at the Tevatron is $114 < M_H < 180$ GeV/c$^2$, the region below 114 GeV/c$^2$ having already been excluded by LEP searches. For light Higgs boson ($114 < M_H < 135$ GeV/c$^2$), the dominant decay mode is to a $b\bar{b}$ pair, while for higher masses the Higgs decays predominantly in two $W$ bosons. With these ingredients, we can classify the possible Higgs boson searches at
Figure 1. $\Delta \chi^2$ curve derived from high precision electroweak measurements as a function of the Standard Model Higgs boson mass.

Figure 2. Production cross sections for a Standard Model Higgs boson at the Tevatron collider as a function of the Higgs mass.

Figure 3. Feynman diagram for Higgs boson production via gluon fusion.

Figure 4. Feynman diagram for Higgs boson production in association with a vector boson.

the CDF experiment in two categories: for high Higgs boson mass, we can exploit the leptonic decays of the $W$ boson originating from Higgs decay to discriminate the signal from background processes. In this analysis, the Higgs direct production with high cross section can be therefore studied. For low Higgs boson mass, the only way to reconstruct the $b\bar{b}$ decays of the Higgs boson out of the predominant QCD jet production is to require a gauge boson to be produced
Figure 5. Branching ratios for a Standard Model Higgs boson decay as a function of the Higgs mass.

in association with the Higgs and to decay into leptons. In this mass range the Higgs boson searches will therefore suffer of a smaller production cross section.

3. Searches for a Low Mass Higgs
The searches for Higgs boson with mass below 135 GeV/c² are based on the reconstruction of the $b\bar{b}$ pair from Higgs decay. For these analyses, a high efficiency algorithm to tag the $b$ quarks and discriminate the signal events from QCD jet production is mandatory. Moreover, the invariant mass of the reconstructed $b\bar{b}$ dijet system is a powerful parameter for further discriminating Higgs production from background.

The main tool developed by the CDF collaboration to identify a $b$ quark is the Secondary Vertex algorithm, that exploits the long time of life of B mesons produced in the hadronization of $b$ quarks which can travel for a detectable distance before decaying. The typical $b$ quark signature inside a jet will be therefore a set of tracks coming from a secondary vertex displaced from the primary interaction point, as displayed in figure 6. Two version of the algorithm with looser and tighter track selection have been studied. All the analyses presented in this paper use the tight version of the algorithm. Figure 7 shows the efficiency to tag a jet originating from the hadronization of a $b$ quark as a function of its transverse energy. The average efficiency for a central $b$ jet is about 42%, while the probability to tag a jet originating from a light quark is typically around 0.5%.

A second powerful tool to reject QCD background is the identification of the gauge boson produced in association with the Higgs particle. Typical signatures exploited at this purpose are the presence in the event of isolated charged leptons and large missing transverse energy due to neutrinos.

3.1. Search for Higgs production in association to a $W$ boson
In the search for a Standard Model Higgs produced in association to a $W$ boson, the event selection starts requiring an isolated lepton and large missing transverse energy to reconstruct the gauge boson:

- Isolated electron or muon with transverse energy $E_T > 20$ GeV,
Figure 6. B mesons produced in the hadronization of a b quark have a long time of life and can travel for a detectable distance before decaying, originating a set of tracks coming from a secondary vertex displaced from the primary interaction point.

Figure 7. Efficiency of the Secondary Vertex tagging algorithm as a function of the transverse energy of the jet. Two version of the algorithm with looser and tighter track selection have been studied. The bands show the systematic uncertainties on the tagging efficiency.

- Missing $E_T > 20$ GeV.

Exactly two jets with $E_T > 15$ GeV, of which at least one identified as a b jet, are further required to reconstruct the Higgs boson decay. Several vetoes are also applied to reject background from Z boson production, gluon conversions in $e^+e^-$ pairs and cosmic ray events. Figure 8 compares the number of observed events passing the selection as a function of the jet multiplicity to the estimate for several background sources. Data are in good agreement with the expectation. In particular, we observe 187 events with exactly two jets in 319 pb$^{-1}$ of data. The invariant mass of the two jet system in events passing the final selection is shown in figure 9. The overall dijet mass distribution results to be 18%. A fit to the dijet mass distribution is used to extract 95% CL limits on the $WH$ production cross section times the branching ratio of the $W$ boson to leptons. Final results are shown in figure 10. The obtained limits range from 10 to 4 pb for Higgs boson mass between 110 and 150 GeV and are in good agreement with the a priori expectations [3].

3.2. Searches for Higgs production in association to a Z boson

In the search for Higgs boson production in association to a Z boson decaying into a $\nu\bar{\nu}$ pair, the following criteria are used to identify the gauge boson decay:

- Missing $E_T > 70$ GeV
- Azimuthal separation between the missing transverse energy, and the second leading jet $\Delta(\vec{E}_T, 2^{nd} jet) > 0.4$.
- Veto on isolated leptons.

Two jets with $E_T > 25$ GeV, of which at least one identified as a b jet, are further required to reconstruct the Higgs boson decay.

Two control regions are defined in order to estimate the background, as shown in figure 11. The first control region consists of the events failing the cut on the azimuthal angle. This region is dominated by QCD production and it is used to normalize this background. The second region is defined by the events failing the isolated lepton veto and it is used to check the prediction for all the background sources. Figures 12 and 13 show the agreement between data and background predictions in the control regions for missing transverse energy and dijet mass distributions.
Figure 8. Number of observed events passing the selection as a function of the jet multiplicity. Points represent the data while the histograms represent several background sources.

Figure 9. Invariant mass of the two jet system in events passing the final selection for data (the points) and expected background and signal (histograms).

Figure 10. Limits on $WH$ production cross section as a function of the Higgs mass. Red points are the limit derived from data. The blue band represents the a priori expectations, while the black line shows the Standard Model predictions.

Figure 11. Control regions for background estimate in the $Z^0H^0 \rightarrow \nu\bar{\nu}b\bar{b}$ channel. The control region 1 is defined by the events failing the cut on the azimuthal angle, while the control region 2 consists of events failing the isolated lepton veto.
Figure 12. Comparison between missing transverse energy distributions for data (points) and background expectation (histograms) in the control region 1.

Having the background under control, further cuts are applied to increase the signal to background ratio on the following variables:

- Leading jet and $\not{E}_T$ azimuthal separation: $\Delta(\not{E}_T, 1^{nd}jet) > 0.8$,
- $H_T$ significance: $H_T/H_T > 0.6$,
- $E_T$ of the leading jet: $E_T^{lead,jet} > 60$ GeV,
- Invariant mass of the dijet system (cut depending on the Higgs mass hypothesis).

Final upper limits on the $ZH$ production cross section from 289 pb$^{-1}$ of data range from 6 to 3 pb for Higgs boson mass between 90 and 130 GeV/c$^2$, as shown in figure 14.

Figure 14. Limits on $ZH$ production cross section as a function of the Higgs mass. Red points are the limit derived from data. The green band represents the a priori expectations, while the black line shows the Standard Model predictions.
Figure 15. Higgs boson decay into W bosons in the Higgs rest frame. Since the Higgs is a scalar particle, the W bosons are produced with opposite spin. The charged leptons from W bosons decays are expected to be preferentially aligned due to their opposite helicity.

The last search channel for a Standard Model Higgs boson in the low mass range is the Higgs production in association to a Z boson decaying to charged leptons. This analysis is still blind, id est data have not been looked yet. The selection is based on a full reconstruction of the Z decay and on the identification of two or three jets with at least one tag. Missing transverse energy smaller than 50 GeV is also required to clean up the sample. A Neural Network approach has been found to improve the signal to background ratio from about 0.01 to about 0.1. By extrapolating the result from RunI, we expect to set a limit on the cross section at 3.1 pb for a Higgs boson mass of 120 GeV with 1 fb$^{-1}$ of data.

4. Searches for a High Mass Higgs

The searches for a high mass Higgs are based on the reconstruction of the Higgs decay to two W bosons, the successive W boson decays to leptons providing a strong experimental signature. The search for Higgs direct production via gluon fusion benefits of a high production cross section (see figure 2). The signature is provided by two leptons with opposite charge and large missing transverse energy. The search for Higgs boson production in association to a W boson suffers for a smaller cross section (see figure 2), but at large Higgs mass we expect three W bosons in the final states, so we can require two leptons with the same charge as a signature with very low background contamination.

4.1. Search for Higgs Direct Production

The search for Higgs direct production starts by selecting events with two leptons with opposite charge, large missing transverse energy ($\not{E}_T > 25$ GeV) and no jets to remove background from top pair production.

The background can be further reduced by exploiting the fact that the Higgs boson is a scalar particle with spin zero, as displayed in figure 15. The W bosons from Higgs decay are therefore
produced with opposite spin, and the charged leptons from successive $W$ boson decays will result preferentially aligned due to their opposite helicity. This suggests to require a small value for the invariant mass $M_{ll}$ of the dilepton system: chosen cuts range from $M_{ll} < 55$ to $M_{ll} < 80$ GeV/$c^2$ for Higgs mass between 140 and 180 GeV/$c^2$. Figure 16 exemplifies the requirement for a particular value of the Higgs mass.

Eight events are observed in 200 pb$^{-1}$ of data when a cut on the dilepton mass at 80 GeV/$c^2$ is used, while we expect 8.9 events from different background sources. Figure 17 compares the distribution of azimuthal angle between the two charged leptons for these events to the expected distributions for backgrounds and signal. Upper limits on the Higgs direct production cross section can be set by fitting similar distributions for different Higgs mass value hypothesis. Results are shown in Figure 18. Observed limits range from 17.8 to 6.4 pb for Higgs mass between 140 and 180 GeV/$c^2$.

4.2. Search for Higgs associated production

In the search for Higgs associated production at high Higgs mass values, a data sample is defined by requiring two leptons with the same charge, with transverse momentum greater than 20 and 6 GeV respectively. Background from diboson production and QCD processes with false lepton identification are carefully studied, leading to a good understanding of the sample composition, as shown for different kinematic variables in figure 19. Having the background under control, a signal region is defined in the plane defined by the second lepton transverse momentum ($P_{T2} > 18$ GeV/$c$) and the vector sum of the transverse momenta of the two leptons ($P_{T12} > 35$ GeV/$c$), as shown in figure 20. No events are observed in this region, while we expect 0.95 events from background. Upper limits on the Higgs associated production cross section from 193 pb$^{-1}$ of data range from 12 to 8 pb for Higgs mass between 110 and 120 GeV/$c^2$. Comparison between
obtained limits and theoretical predictions is provided in figure 21.

5. Summary and Perspective

Figure 22 summarizes the upper limits on the Higgs boson production cross sections we described in this paper. Standard Model expectations and results from the D0 experiment are also shown for comparison. The experimental sensitivity at the Tevatron is not yet good enough to observe or exclude a Standard Model Higgs boson production in the mass range between 110 and 180 GeV/c². However, lot of improvement have being studied and implemented in the Higgs searches at CDF:

- New data have being collected: analyses on 1 pb⁻¹ of collected data have already started.
- Different and larger control samples allow also to improve background estimates.
- Results for the analyses that are still using counting experiment can be improved by using likelihood fit.
- Signal acceptances can be increased. For instance, algorithms for τ reconstruction are already available but not exploited so far.
- Different b tagging algorithm or tagging of b jets in the forward region of the detector are available and allow to further improve the signal acceptance.

An other important parameter that can be improved for future Higgs boson searches at CDF is the dijet mass resolution. So far, RunI algorithms to reconstruct the jets are still used. Work
Figure 20. Definition of the signal region in the $HW \rightarrow WWW$ search. The plan is defined by the second transverse momentum vector sum of the transverse momenta of the two same-sign leptons required as a experimental signature. Also shown are the distributions for the data.

Figure 21. Upper limits on the Higgs associated production cross section. The black line shows the limits derived from data. The blue line represents the Standard Model predictions, while the red line shows the predictions expected assuming no coupling of Higgs boson to fermions.

is in progress to implement new algorithms that use track information to correct the energy measured by the calorimeter towers, and to develop b specific corrections and more advanced multivariate techniques to correct the dijet mass. Preliminary results show that an improvement from 18 to 10% resolution on the dijet mass is achievable.

Finally, figure 23 shows the integrated luminosity required for a 5 $\sigma$ discovery or a 3 $\sigma$ evidence or a 95% CL exclusion as a function of the Higgs boson mass [4]. These curves have been obtained by extrapolating the CDF and D0 detector and reconstruction performances, and indicate that a 3 $\sigma$ evidence over a significant range of Higgs mass values can be reached at the Tevatron collider.

6. References
[1] Heister A 2003 Phys. Lett. B 565 61-75
[2] The LEP Electroweak Working Group 2006 http://lepewwg.web.cern.ch/LEPEWWG/
[3] Abulencia A et al 2006 Phys. Rev. Lett. 96 081803
[4] CDF and D0 Collaborations 2003 Results of the Tevatron Higgs Sensitivity Study FERMILAB-PUB-03/320-E
Figure 22. Summary of the upper limits on the Standard Model Higgs boson production cross sections at CDF. Also indicated are the results from D0 experiment and the theoretical predictions. Results for Higgs production in association to a $W$ or a $Z$ boson in the low mass range are indicated by red and blue lines respectively. Limits on Higgs direct or associated production in the high mass range are represented by black and green lines respectively.

Figure 23. The three bands show the integrated luminosity per experiment needed for a 95% exclusion (purple), a 3 $\sigma$ evidence (green), or a 5 $\sigma$ discovery (blue of the Higgs boson as a function of the particle mass.)