Fermilab FERMILAB-Conf-01/100-E CDF & D0 June 2001

Prospect for Discovering a Light Higgs at the Tevatron in RUN II

Gueorgui V. Velev

e-mail: velev@fnal.gov

Fermi National Accelerator Laboratory, Batavia, IL 60510

For the CDF and DØ Collaborations

Abstract

The present upgrades of the CDF and DØ detectors as well as of the Fermilab Tevatron have dramatically improved their sensitivity for Standard Model and minimal suppersymmetry Higgs bosons searches in Run II. This paper reviews the recent estimates of this sensitivity in terms of Higgs discovery and exclusion reach based on a total expected Run II Tevatron luminosity of 15 fb^{-1} delivered to each experiment.

Published Proceedings of the *15th Les Rencontres de Physique de la Vallée d'Aoste: Results and Perspectives in Particle Physics*, La Thuile, Aosta Valley, Italy, March 4-10, 2001.

1 Introduction

In the past three decades the Standard Model (SM) has achieved remarkable success as a theory of elementary particles and their interactions. Its predictions have been confirmed by experiment with spectacular precision. However, one of its most fundamental mechanism, which provides the electro-week symmetry breaking and as a consequence the origin of masses, has not yet been discovered. The Higgs formalism that was introduced in the SM to provide a mechanism to generate fermion and electro-week boson masses, implies the existence of a neutral scalar boson. The mass of this Higgs boson is not predictable from the theory. The most recent fit of the electroweek observables indicates that SM Higgs, if exists, should be light $m_H < 198$ GeV/c^2 at 95% CL (Figure 1) [1] .

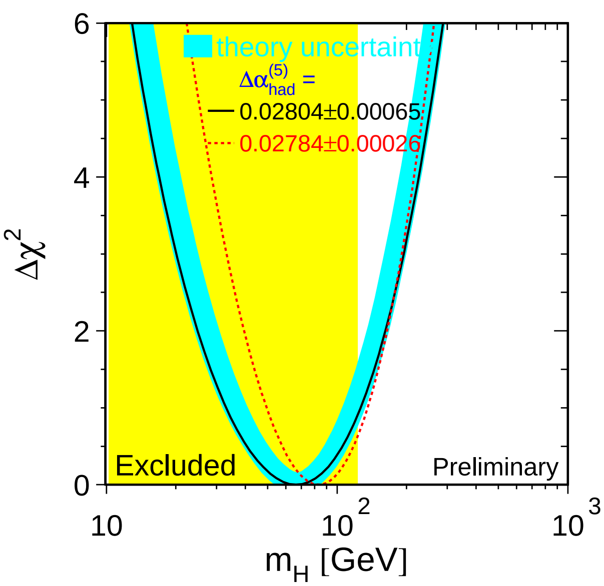

Figure 1: Result of a global fit to the measured electroweek observables (from LEP Electroweek Working Group web page [1]). The shaded area indicates the excluded region from LEP 2 (direct searches) $m_H > 113.5$ GeV/c^2 at 95% CL.

After LEP 2 was shutdown [2] the Tevatron is the only place where Higgs discovery could occur in the near future. Discovery could be possible within about 3-4 years from now if m_H <120 GeV/c^2.

In the past few years a major upgrade of the machine was done. The center of mass energy is increased to $\sqrt{s}$=1.98 TeV. The initial Run IIa goal is to achieve a peak luminosity of 2×10^{32} cm^{-2} sec^{-1} which will be increased to 5×10^{32} cm^{-2} sec^{-1} in Run IIb.

The total integrated luminosity goal for Run IIa+Run IIb delivered to each experiment is 15 fb^{-1}, a factor of 150 more then in Run I. The integrated luminosity accumulated in the years is summarized in Table 1.

Year	Luminosity (fb^{-1})
2001 Run IIa	0.6
2002 Run IIa	1.2
2003 Run IIb	0.8
2004 Run IIb	2.0
2005 Run IIb	3.5
2006 Run IIb	2.3
2007 Run IIb	3.8
Total Run II	15.0

Table 1: Expected accumulation of the Tevatron luminosity before the LHC era.

Both CDF and DØ finished their upgrades for Run II. Both detectors include: new silicon vertex detectors, new central trackers, better muon coverage, new front-end and trigger electronics and better triggering. The estimate is that sensitivity for the Higgs searches will improve roughly by at least a factor of 50 comparing to Run I [3]. More details about CDF and DØ upgrades can be found [4] and [5].

In the past six months the Fermilab Higgs Working Group finalized a report [6] describing the recent estimates for the Higgs discovery or exclusion, combining all observable channels and both CDF and DØ detectors. The report includes several SM Higgs decay modes in the mass region, explored by the Tevatron as well Higgs production in the higher mass region. A detailed interpretation of the future results in the frame of the minimal supersymetric extension of the SM (MSSM) is added. The results are based on a simulated "average" detector with parametrized calorimeter resolution and particle identification efficiencies. The final result is presented in terms of integrated luminosity required to either exclude the Higgs boson at the 95% CL, or to establish a 3σ "evidence" or a 5σ discovery signal over the predicted backgrounds. In this paper we summarize the content of this report.

2 Standard Model Higgs Production Cross Sections at the Tevatron and Higgs Decay Modes

The SM Higgs production cross section at the center of mass energy of $\sqrt{s}$=2.0 TeV [7] is shown in Figure 2a. The dominant production is due to gluon fusion $p\bar{p} \rightarrow gg \rightarrow H$. An order of magnitude below is associated Vector Bosons-Higgs production $p\bar{p} \rightarrow V(W,Z)H$. Despite the lower cross-section, these associated production processes provide greater sensitivity, because of the much smaller background than QCD di-jet events in inclusive production.

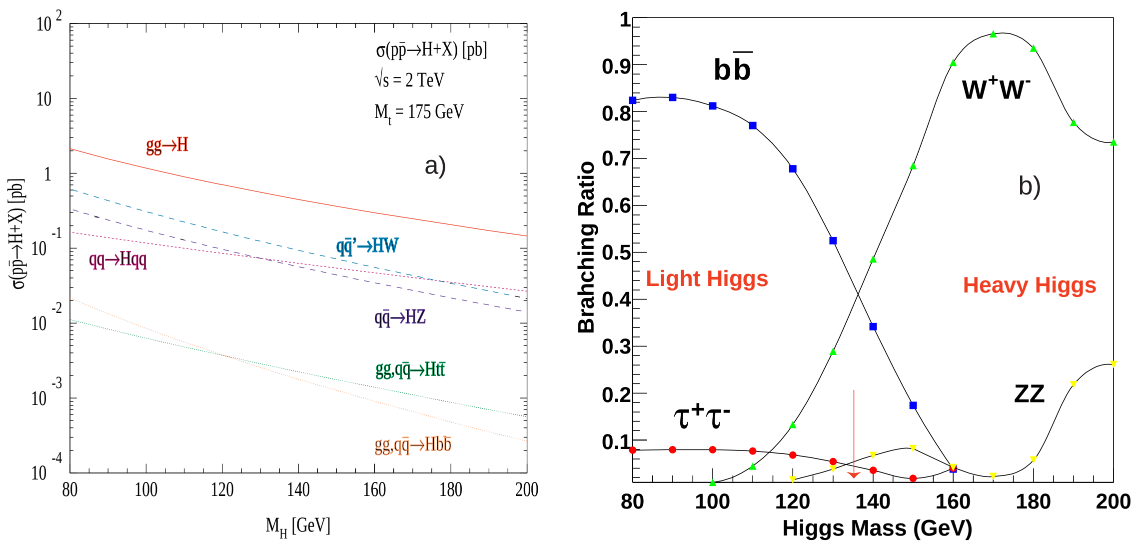

Figure 2: SM Higgs production cross sections (a) decay branching ratios (b) as a function of m_H. At low m_H, about 8% of the decays are shared between the $c\bar{c}$ and gg channels.

Figure 2b [7] shows the SM Higgs decay branching ratios as a function of m_H. The crossing of $b\bar{b}$ and W^+W^- branching fractions at m_H =135 GeV/c^2 somehow naturally separates the low mass region, where $H \rightarrow b\bar{b}$ dominates, from the high mass region, where $H \rightarrow WW^*, ZZ^*$ dominates [1].

[1] W^* (Z^*) denotes a W(Z) off-mass-shell boson.

3 Standard Model Higgs Searches

The planned Run II SM Higgs searches for the regions below and above 135 GeV/c^2 are discussed here. The results from Run I are summarized in [8].

3.1 Low Mass Searches: m_H <135 GeV/c^2

As one can see from Figure 2b at low masses the Higgs decay mode $H \to \mathrm{b\bar{b}}$ largely dominates. In addition, the decay mode of the satellite W or Z bosons determines the final state. The largest value of $\sigma \times BR$ is for $W/Z \to \mathrm{q\bar{q}}$, giving a four jet $\mathrm{q\bar{q}b\bar{b}}$ final state. The next to largest is when $W \to \ell\nu$, generating a $\ell\nu\mathrm{b\bar{b}}$ final state, and finally the lowest rate is when $Z \to \ell^+\ell^-$ or $\nu\bar{\nu}$. Primary backgrounds are coming from $W\mathrm{b\bar{b}}$ and $Z\mathrm{b\bar{b}}$, where $\mathrm{b\bar{b}}$ pair is from gluon radiation, and from top quark production (including single top).

In all decay channels at least two b-tagged central jets with $\mathrm{E_T}$ at greater then 15 GeV are required.

The four quark final state, where W and Z decay to $\mathrm{q\bar{q}}$ pairs, is over dominated by the huge QCD background with heavy flavor production. The discriminating power comes from the $\mathrm{b\bar{b}}$ di-jet mass resolution, and the different kinematics of QCD $\mathrm{b\bar{b}}$ production (QCD $\mathrm{b\bar{b}}$ pairs have lower average $\mathrm{p_T}$ then from Higgs). However, discovery in this channel looks very hard.

The main selection criteria for the W,Z leptonic decay modes are a combination of the lepton transverse momentum $\mathrm{p_T^{\ell,\mu}}$ and/or missing transverse energy $\not{E}_\mathrm{T}$. Typical cuts for the $WH \to \ell\nu\mathrm{b\bar{b}}$ channel are $\mathrm{p_T^{\ell}}$ and $\not{E}_\mathrm{T}$ greater than 20 GeV. In case of $ZH \to \nu\bar{\nu}\mathrm{b\bar{b}}$ a $\not{E}_\mathrm{T}$ greater than 35 GeV is requested. Additional cleaning from $\mathrm{t\bar{t}}$ background events is done by requesting $H_T < 175$ GeV (H_T is the scalar sum of the transverse hadronic energy). For the channel $ZH \to \ell^+\ell^-\mathrm{b\bar{b}}$ two opposite sign leptons (e^+e^- or $\mu^+\mu^-$ with $\mathrm{E_T(p_T)}$ >10 GeV are required.

An example of Monte Carlo simulated mass plot in the case of $\ell^+\ell^-\mathrm{b\bar{b}}$ and $\nu\bar{\nu}\mathrm{b\bar{b}}$ final states at m_H=120 GeV/c^2 is shown on Figure 3. A small Higgs signal is observed over the background.

The finding of the Higgs signal over a large background, which is sometimes signal like, critically depends on the resolution in the Higgs mass, reconstructed from the two

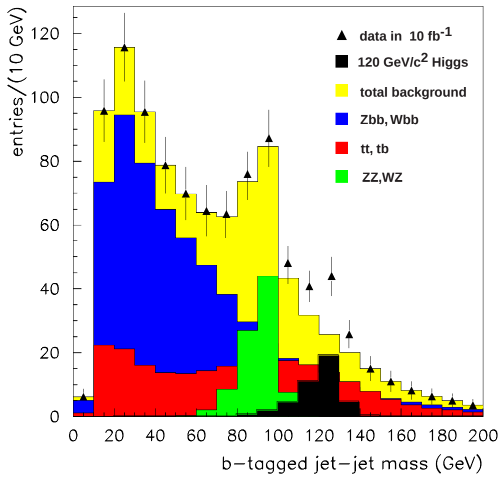

Figure 3: The invariant $b\bar{b}$ di-jet invariant mass for the processes $ZH \rightarrow \ell^+\ell^- b\bar{b}, \nu\bar{\nu}b\bar{b}$. The signal (SM Higgs at 120 GeV/c^2 mass) and background are represented for a single experiment in 10 fb^{-1} luminosity. A 10% di-jet mass resolution is assumed.

measured b-jets. Both CDF and DØ invested a lot of work to improve the mass resolution. It was shown that a gain of 30% in jet energy resolution is achievable (reducing the resolution on Higgs mass of m_H = 120 GeV/c^2 from 16% to 10%). After 10 fb^{-1} this propagates in increasing the significance of the Higgs signal by almost 25% [6, 9].

Table 2 summarizes the sensitivities for 1 fb^{-1} luminosity in various search channel. The numbers are obtained with a standard "cut-type" analyses. One can see that the 4-jet final state has very low sensitivity comparing to the other ones. In average using a multidimensional analyses [10] we can obtain a 15% to 25% gain in the signal to background ratio.

The second largest Higgs decay mode in the low mass region is $H \rightarrow \tau^+\tau^-$. However the ratio $BR(H \rightarrow \tau^+\tau^-)/BR(H \rightarrow b\bar{b})$ is about 10%, and this channel was not jet shown to play a significant role in the Higgs search at the Tevatron.

3.2 High Mass Searches: $m_H \geq 135\ GeV/c^2$

The decay mode $H \rightarrow WW^*$ starts to dominate for the SM Higgs with the mass above 135 GeV/c^2 (fig.2b). The similar mode where $H \rightarrow ZZ^*$ is suppressed by an order of magnitude. The most promising final states are:

Channel	Signal Background $S/\sqrt{B}$	Higgs mass (GeV/c^2) 100	110	120	130
$\ell\nu b\bar{b}$	S	8	5	4	3
	B	68	57	58	52
	$S/\sqrt{B}$	0.9	0.7	0.6	0.4
$\nu\bar{\nu}b\bar{b}$	S	6.7	4.6	3.2	2.1
	B	34.6	27.9	19.4	15.0
	$S/\sqrt{B}$	1.1	0.9	0.7	0.5
$\ell^+\ell^- b\bar{b}$	S	1.2	0.9	0.6	0.4
	B	4.3	3.2	2.3	1.9
	$S/\sqrt{B}$	0.6	0.5	0.4	0.3
$q\bar{q}b\bar{b}$	S	5.6	3.5	2.5	1.3
	B	3600	2800	2300	2000
	$S/\sqrt{B}$	0.09	0.07	0.05	0.03

Table 2: Summary of the sensitivities for the low mass SM Higgs search. 10% mass resolution of two the b-jets is assumed. The values of S and B are quoted as the number of events expected per detector in 1 fb^{-1}.

- $p\bar{p} \to gg \to H \to WW^* \to \ell^+\ell^-\nu\bar{\nu}$
- $p\bar{p} \to VH \to \ell^\pm\ell^\pm jj + X$
- $p\bar{p} \to VH \to \ell^\pm\ell^\pm\ell^\mp + X$

The main backgrounds come from vector boson pair production VV as well as V+jets which are 10-100 times larger than SM Higgs production. Some fraction of background (∼20%) is due to $t\bar{t}$ and and single top productions.

To increase the signal to background ratio additional kinematical requirements are employed, for example cuts on cluster transverse mass defined as $M_C = \sqrt{p_T^2(\ell\ell) + m^2(\ell\ell)} + \not{E}_T$. Sensitivity is maximized with precise tuning of these requirements. The detailed procedure is described in [11].

Table 3 summarizes the sensitivities per experiment for 1 fb^{-1} luminosity in a number of search channels.

Finding Higgs in the high mass region looks very hard, if the Tevatron does not exceed its present goal of delivering 15 fb^{-1}.

Channel	Signal Background $S/\sqrt{B}$	Higgs mass (GeV/c^2) 140	150	160	170	180
$\ell^+\ell^-\nu\bar{\nu}$	S	2.6	2.8	1.5	1.1	1.0
	B	44.0	30.0	4.4	2.4	3.8
	$S/\sqrt{B}$	0.39	0.51	0.71	0.71	0.51
$\ell^\pm\ell^\pm jj$	S	0.29	0.36	0.41	0.38	0.26
	B	0.58	0.58	0.58	0.58	0.58
	$S/\sqrt{B}$	0.38	0.47	0.54	0.5	0.34

Table 3: Summary of the sensitivities for the high mass SM Higgs search. The values of S and B are quoted as the number of events expected per detector in 1 fb^{-1}. The tri-lepton channel is not visible at the expected Tevatron luminosity.

3.3 Combined Standard Model Higgs Searches

Figure 4 [6] shows the combined CDF/DØ thresholds for the Higgs search in the mass range from 90 to 190 GeV/c^2. The bands indicate the required luminosities versus SM Higgs mass for 95% exclusion, 3σ evidence and 5σ discovery. For combining the different search channels a Bayesian approach based on the joint likelihood is employed. The systematic uncertainties of the background estimate for each channel are incorporate into the likelihood. For each channel which is smaller of 10% of the expected background or $1/\sqrt{\mathcal{L}B}$, where $\mathcal{L}$ is the integrated luminosity and B is the expected number of background events in 1 fb^{-1}, is taken. In the low-mass channels a 10% resolution in $m_{b\bar{b}}$ is assumed. Uncertainties in the b-tagging efficiency is incorporated in the likelihood. This generates the bands which expand upward from the nominal thresholds by about 30% [2].

[2] The uncertainties in the detector simulation are taken or scaled from Run I values. The first indications from Run II show that probably they were overestimated. Thus we believe that the lower edge of the bands is the best estimate.

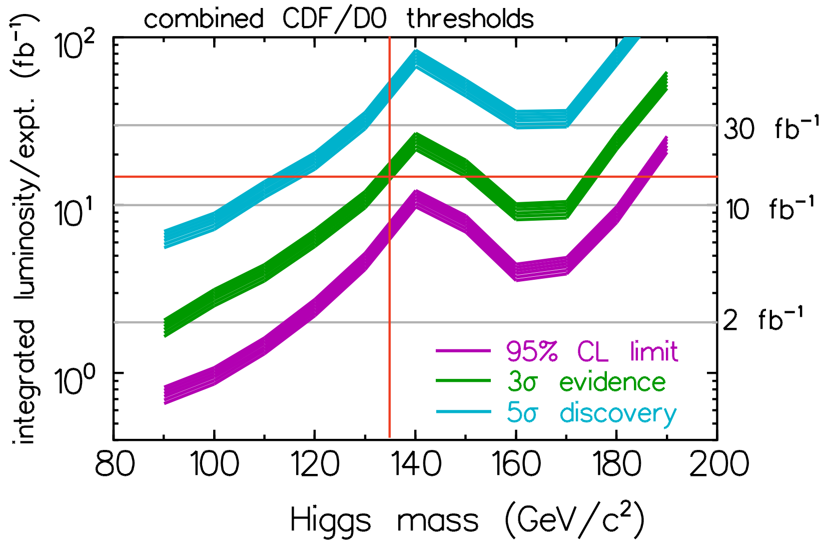

Figure 4: Integrated luminosity needed per experiments (CDF and DØ) to exclude a SM Higgs boson at 95% CL or to achieve 3σ (5σ) evidence (discovery), as a function of the Higgs mass. The result is based on the combined statistics of both experiments. The bands are extended upward by 30% to accommodate detector uncertainties and systematic errors.

4 MSSM High Boson Searches

The study performed by the Higgs Working Group at Fermilab [6] shows that the Tevatron will also set tight limits on, or even discover the Higgs sector.

The MSSM Higgs sector is populated by five physical bosons: two CP-even scalars (named h and H, where h is the lighter one), one CP-odd scalar A and one charged Higgs pair ($H^{\pm}$). All Higgs masses at tree level can be expressed in terms of two parameters, that are usually chosen to be m_A and $\tan(\beta) \equiv v_u/v_d$, where v_u and v_d are the vacuum expectation values of the Higgs field doublets, coupled the up and the down-type fermions.

Figure 5 shows the MSSM scalar h and H boson masses as a function of m_A, with $\tan(\beta)$ as a parameter [6]. One can see that the light CP-even Higgs is expected to be in the mass region below 120 GeV/c^2. Since it also has similar BR as the SM Higgs, the search for this Higgs boson is very much as the search for SM Higgs.

At large $\tan(\beta)$ the ϕ (ϕ is a common notation for h and H) and A couplings to $b\bar{b}$ are

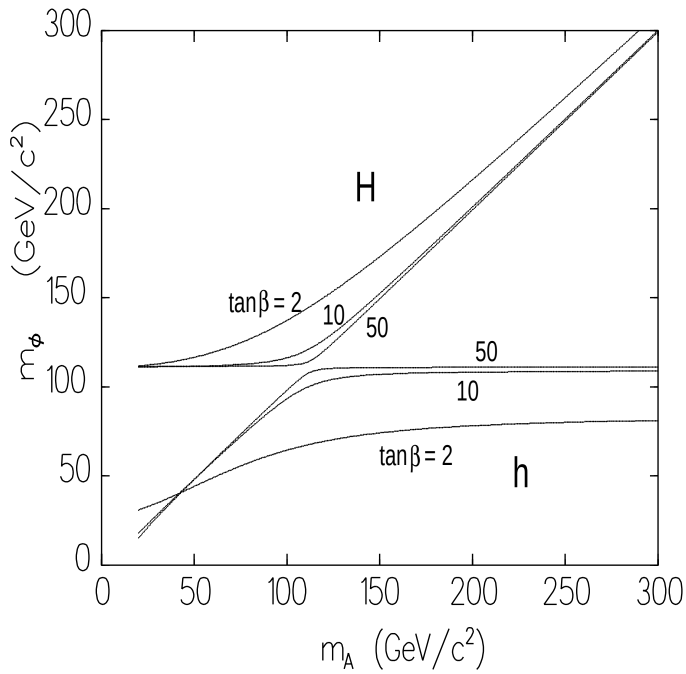

Figure 5: Lightest (m_h) and heaviest (m_H) CP-even Higgs masses as function of CP-odd Higgs m_A for three choices of $\tan(\beta)$ = 2, 10 ,50. In these assumptions the mass of the Lightest Higgs, m_h, does not exceed 120 GeV/c^2.

enhanced [12]. The search signature is characterized by $b\bar{b}b\bar{b}$ final state. Asking for four high p_T jets with a high b-quark content (at least 3 b-tagged jets) is the main criteria to suppress the huge QCD backgrounds. The resulting distribution, examined for a peak, is a combination of all possible di-jet masses computed from the b-tagged jets.

The Tevatron potential for MSSM Higgs is summarized in Figure 6 [6]. This figure shows contour plots in the $\tan(\beta)$ versus m_A plane around regions of 95% exclusion and 5σ discovery for the maximal top squark mixing scenario and for different luminosities. The shadowed regions correspond to the process: $q\bar{q} \to V\phi, \phi \to b\bar{b}$. The regions in the upper left corner selected by the solid lines correspond to the search $gg, q\bar{q} \to b\bar{b}\phi, A$ where ϕ, A decay to $b\bar{b}$. Systematic uncertainties were not accommodated for .

5 Conclusions

Present fits to the combined electroweek data and LEP 2 limits indicate that the SM Higgs is likely to be in the region below 198 GeV/c^2. The Tevatron Run II gives

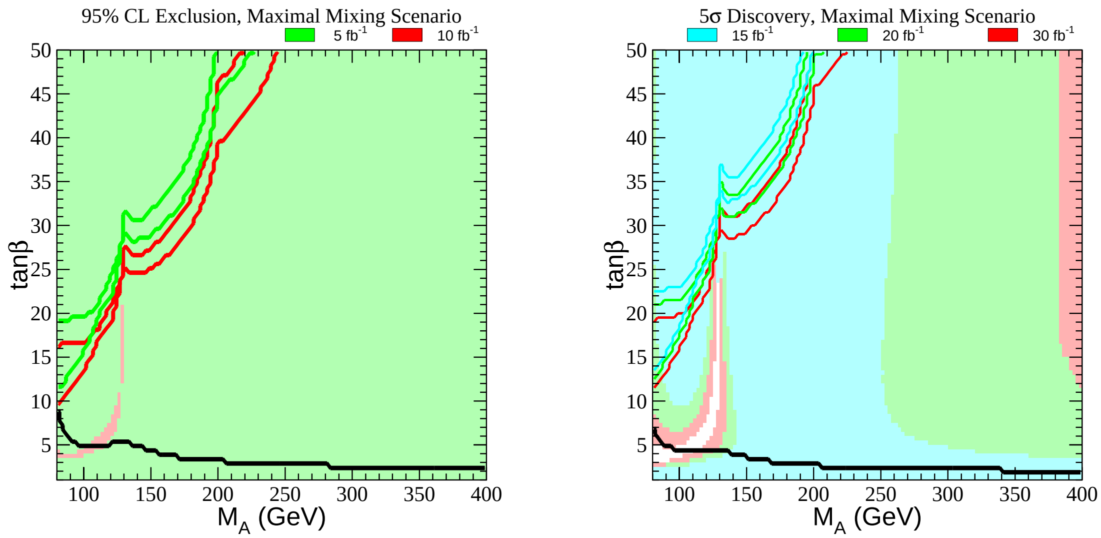

Figure 6: Regions of the MSSM parameter space $\tan(\beta)$ versus m_A in which one can exclude at 95% CL (left) or discover at 5σ the MSSM Higgs in assumption of the maximal top squark mixing.

an opportunity to explore this region. The discovery and exclusion reach based on the expected Run II Tevatron luminosity has been studied [6]. The results, summarized in this paper, indicate that the SM Higgs with mass below 190 GeV/c^2 can be excluded at 95% CL with 15 fb^{-1}, and can be discovered at 5σ if the mass is below 120 GeV/c^2. Discovery at the 5σ level in the region above then 120 GeV/c^2 or evidence at the 3σ level above 140 GeV/c^2 indicates the need for more luminosity. The upgraded Tevatron will also set tight limits on the Higgs sector in supersymmetric extension of the SM. If $\tan(\beta)$ is large, even discovery of the MSSM Higgs sector, if it exists, might be possible before LHC.

6 Acknowledgments

I would like to thank the organizers for this excellent conference and for their kind hospitality.

References

[1] The LEP Electro Week Group WEB page can be found at http://www.cern.ch/LEPEWWG.

[2] The LEP Higgs Working Group "Standard Model Higgs Boson at LEP: Results with the 2000 Data, Request for Running in 2001", http://lephiggs.web.cern.ch/LEPHIGGS/papers/doc_nov3_2000.ps.

[3] J.S. Conway, Proceedngs of the *13th Les Rencontres de Physique de la Vallee d'Aosta*, La Thuile, Vallee d'Aosta, Italy, February 28 - March 6, 1999.

[4] The CDF II Detector. Technical Design Report. **FERMILAB-Pub-96/390-E**.

[5] The D0 upgrade. The detector and its physics. **FERMILAB-Pub-96/357-E**.

[6] M. Carena *et al.*, Report of the Tevatron Higgs Working Group, hep-ph/0010338 and **FERMILAB-CONF-00-279-T**.

[7] M. Spira, Fortschr. Phys. **46**, 203 (1998) and hep-ph/9810289.

[8] J. Konigsberg, these proceedings.

[9] A. Bocci, Master's Thesis, http://fnalpubs.fnal.gov/archive/1998/thesis/t-bocci.ps.

[10] P. Bhat, R. Gilmartin and H.B. Prosper, **FERMILAB-PUB-00-006**.

[11] T. Han, A.S. Turcot and R. Zhang, Phys. Rev. **D59**, (1999).

[12] M. Roco, **FERMILAB-CONF-00-203-E**.