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FERMILAB-Conf-99/156-E
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Higgs Searches in Run 2 at the Tevatron

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July 1999

Published Proceedings of the *13th Les Rencontres de Physique de al Valle D'Aosta: Results and Perspectives in Particle Physics*, La Thuile, Valle d'Aoste, Italy, February 28-March 6, 1999

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

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HIGGS SEARCHES IN RUN 2 AT THE TEVATRON

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Abstract

In Run 2 at the Tevatron, the upgraded CDF and D0 experiments will have greatly improved sensitivity in the search for the Higgs bosons of the Standard Model and minimal supersymmetry. In the past year the Higgs Working Group of the Tevatron Run 2 SUSY/Higgs Workshop has estimated the discovery and exclusion reach for the Higgs, combining all possible search channels and utilizing all the upgraded features of both detectors. The results give strong motivation to continue the next run of the Tevatron into Run 3, with an eventual goal of up to 20 fb^{-1} or more delivered per experiment.

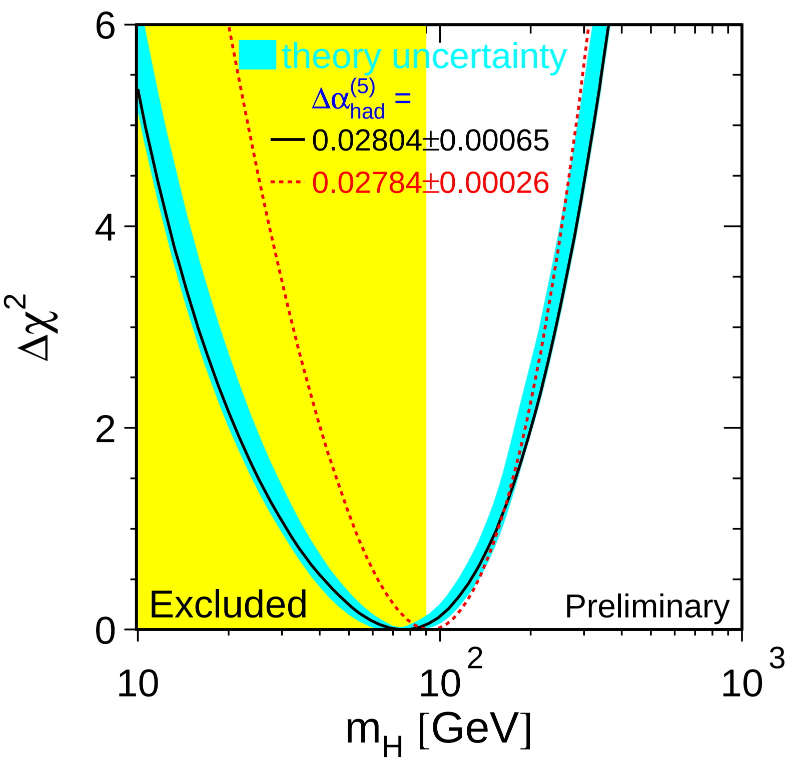

Figure 1: Result of LEP Electroweak Working Group fits to available experimental data, showing fit χ^2 as a function of SM Higgs mass. The light shaded region indicates the region excluded by direct searches from LEP 2.

1 Motivation

The great success of the Standard Model (SM) in accounting for diverse experimental observations gives strong motivation for the existence of a neutral scalar Higgs boson. The most recent fits to all available experimental data from the LEP Electroweak Working Group [1)] indicate that if there is a single SM neutral Higgs, it could be light, with a central value in the range 90-100 GeV as shown in Figure 1. The direct searches from LEP rule out a SM Higgs with mass less than 95 GeV at 95% CL [2)] and the combined fits rule out a SM Higgs with mass larger than about 265 GeV at 95% CL. The four LEP 2 experiments expect to eventually discover or rule out a SM Higgs with mass up to about 106-109 GeV, and so the mass range from 110-200 GeV is especially interesting for the Tevatron to explore in Run 2 and beyond.

Both CDF and DØ are undergoing major upgrades in preparation for Run 2, which will commence in mid-2000. In Run 2 the Tevatron will deliver 2 fb^{-1} integrated luminosity to each experiment, a factor of 20 more than the present Run 1 data sample. However, with new vertex detectors, better triggering, and other improvements, the improvement to the sensitivity for searches such as that for the Higgs will be roughly a factor of 50 compared with the full Run 1 sample. If the Tevatron continues into Run 3, the accelerator experts estimate that a sustained rate of 5 fb^{-1} per year could be attained. [3)]

The goal of the Higgs Group experimental studies is to estimate the discovery reach for the Standard Model and MSSM Higgs bosons in Run 2 and beyond at the Tevatron. This is ultimately experessed in terms of the integrated luminosity required to either exclude the Higgs with 95% confidence if it does not exist, or discover it with some statistical significance, 3σ or 5σ for example, if it does exist at some mass.

2 Simulation and Analysis Assumptions

Estimating the integrated luminosity thresholds for discovering or excluding the Higgs requires knowledge of the signal acceptance, identification efficiencies, and backgrounds. At the time of the Workshop, neither CDF nor DØ has had full simulation programs of the detector available. The Workshop participants agreed to estimate the Higgs reach based on an average of the expected CDF and DØ detector performance, as represented in a simple simulation, called SHW. This program starts with events generated using PYTHIA or ISAJET, and derives a final set of "physics objects" based on the charged tracks and calorimeter energy deposits which the final-state particles would leave in the detectors. The program has no simulation of magnetic deflection, z vertex spreading, secondary vertexting, or multiple interaction effects. Nevertheless it gives a reasonable estimate of the geomtetric and kinematic acceptances of the two detectors, as shown below.

Also, neither the final b-tagging efficiency nor the $b\bar{b}$ mass resolution for Run 2 is known, and part of the motivation for the Workshop was to determine the potential gain from future work on these very important factors in the Higgs reach. Studies of the tagging efficiency and mass resolution serve as the basis for the assumptions made in the individual signal channel studies and in the SHW simulation program. For the dijet mass resolution, in the analyses presented here we have assumed a 10% resolution. For b tagging, the analyses assume a parametrization which is a rising function of jet E_T, reaching a maximum of about 65% for "tight" tags, and nearly 80% for "loose" tags, with a mistag rate of a few percent.

We emphasize, however, that obtaining optimal b-tagging efficiency, Higgs mass resolution, and experimental backgrounds will ultimately rely, in each exper-

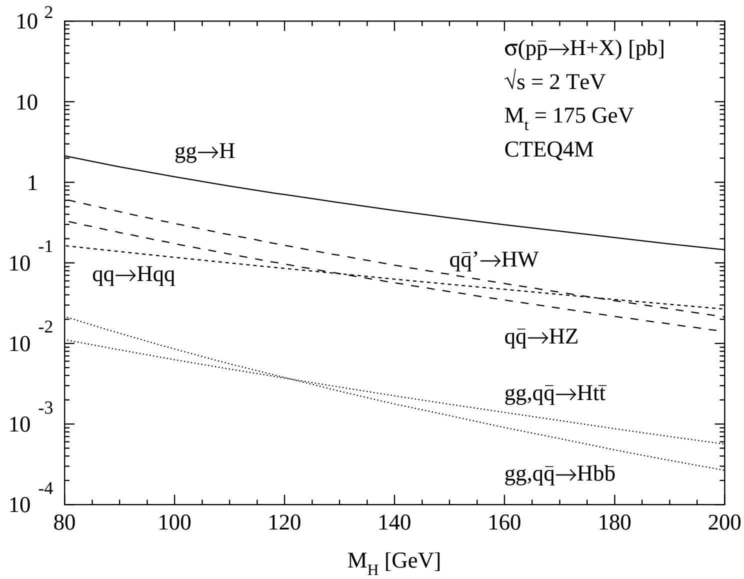

Figure 2: Cross sections for the production of a Standard Model Higgs as a function of Higgs mass, for various production modes.

iment, upon detailed studies of the data to be collected in Run 2. The aim here is to show how the final results depend on these crucial factors, with reasonably optimistic projections for what we might ultimately attain with a great deal of hard work in the coming years.

3 Higgs Production at the Tevatron

Standard Model Higgs bosons are produced singly or in conjunction with a W or Z at the Tevatron with cross sections in the range 0.1-1.0 pb. Figure 2 shows the SM Higgs production cross sections as a function of Higgs mass for these and other Higgs production mechanisms at the Tevatron. [4] As the figure indicates, the cross section is largest for single Higgs production from gluon fusion, with the WH and ZH modes lower by nearly an order of magnitude. Nevertheless, as shown below, the sensitivity is greater for the WH and ZH modes, since for single Higgs production the background from dijet events is too large.

4 Standard Model Higgs Search Channels: m_H = 90-130 GeV

The searches for the SM Higgs divide into the Higgs mass regions below and above about 135 GeV, the mass at which the dominant Higgs decay modes change over from $b\bar{b}$ to WW. At lower masses, the decay mode of the accompanying W or Z determines the final state. The largest cross section times branching ratio is to quark pairs, giving a $q\bar{q}b\bar{b}$ final state. The next largest is the case where $W \to \ell\nu$ (the $\ell\nu b\bar{b}$ chanel), followed by the cases where one has $Z \to \ell^+\ell^-$ and $Z \to \nu\bar{\nu}$ ($\ell^+\ell^- b\bar{b}$ and $\nu\bar{\nu}b\bar{b}$). Each of these four channels is discussed below. The second-largest Higgs decay mode is to tau pairs, for Higgs masses below about 130 GeV. Given that this branching ratio is an order of magnitude lower than that to $b\bar{b}$, however, studies of these modes have not shown them to have enough sensitivity to play a significant role in the Higgs search.

4.1 The $\ell\nu b\bar{b}$ final state

The selection for WH events where $W \to \ell\nu$ relies on events entering on a high-p_T lepton (e or μ) trigger; we assume that such a trigger in Run 2 will be fully efficient for leptons with 20 GeV/c transverse momentum or more. As in the published Run 1 analysis, one demands a high-p_T e or μ, missing transverse energy ($\not\!\!E_T$) greater than 20 GeV, and two b-tagged central jets, one passing the "tight" b-tagging cuts and the other the "loose" cuts. Extra jets are vetoed to reduce the background from $t\bar{t}$ events. The largest remaining background is from $Wb\bar{b}$, with non-negligible contributions from single top and WZ.

Three analyses were performed on this channel (and the next two channels discussed below). In the first, denoted "CDF," the CDF Run 1 simulation was used to obtain kinematic and geometric acceptance, with scale factors applied to represent improved b-tagging efficiency, silicon coverage, and $b\bar{b}$ mass resolution. The second used a nearly identical analysis selection and the SHW simulation to estimate the signal and background acceptances. In the third analysis, a neural network was trained to separate signal and background for each hypothesized Higgs mass, using as input the kinematic variables of the lepton, missing energy, and the jets.

In this channel and the other low-mass SM Higgs channels described here, the expected signal and background are based on a counting method for simplicity, cutting in a window around the hypothesized Higgs mass. In the real experiment, however, one will employ a full mass spectrum fit to signal and background.

As Table 1 shows, the CDF and SHW analyses have quite similar results, giving some confidence that the SHW simulation is reasonably accurate. The neural network method, however, results in a significant improvement in sensitivity over the standard "cuts" method, and will be pursued with real data.

The main focal points for future work in this channel should be to attain the assumed 10% mass resolution through careful studies, to obtaint he best possible b-tagging efficiency, and to measure the background as accurately as possible from actual data, particularly the $Wb\bar{b}$ background.

4.2 The $\nu\bar{\nu}b\bar{b}$ final state

The case where one has ZH events with $Z \to \nu\bar{\nu}$ is of nearly equal sensitivity to the $\ell\nu b\bar{b}$ final state. These $\nu\bar{\nu}b\bar{b}$ events are quite distinct, with two 15-GeV–p_T b-tagged jets (one tight, one loose again) and large missing transverse energy. Events with additional isolated high-p_T tracks are removed, and no extra jets are allowed. Here the main backgrounds are from $Zb\bar{b}$ and ZZ events.

In Run 1 such events were selected with the inclusive $\not{E}_T > 35$ GeV trigger; in Run 2 a trigger designed to select events with large $\not{E}_T$ and jets with heavy flavor content will greatly improve the acceptance. In the analyses presented here, the CDF analysis assumes the Run 1 trigger efficiency, where as the SHW and neural network (NN) analyses assume a fully efficient trigger. This is reflected in the results shown in Table 1.

4.3 The $\ell^+\ell^- b\bar{b}$ final state

In the mode where we have ZH with $Z \to \ell^+\ell^-$, the events are selected from the low-p_T (10-GeV/c) dilepton trigger sample. One demands the presence of an e^+e^- or $\mu^+\mu^-$ pair with invariant mass consistent with that of the Z, recoiling against two jets of 20 and 15 GeV E_T, with one tight and one loose b-tag respectively. The backgrounds here are dominated by real Z's, produced in conjunction with $b\bar{b}$ pairs or W's decaying hadronically.

4.4 The $q\bar{q}b\bar{b}$ final state

In the all-hadronic modes where we have WH and ZH with the W or Z decaying to $q\bar{q}$ pairs, the background from 4-jet processes with heavy flavor production is overwhelming. The main discriminating power comes from the $b\bar{b}$ mass resolution, and the kinematics of the heavy flavor production; the $b\bar{b}$ pairs in QCD processes tend to be at lower p_T than in WH and ZH events. As Table 1 shows, for an analysis based on SHW and backgrounds normalized to Run 1 DØ data, the sensitivity is very low in this case.

channel	rate	Higgs mass (GeV/c^2) 90	100	110	120	130
$\ell\nu b\bar{b}$ (CDF)	S	8.4	6.6	5.0	3.7	2.2
	B	48	52	48	49	42
	$S/\sqrt{B}$	1.2	0.9	0.7	0.5	0.3
$\ell\nu b\bar{b}$ (SHW)	S	10	8	5	4	3
	B	75	68	57	58	52
	$S/\sqrt{B}$	1.1	1.0	0.7	0.5	0.4
$\ell\nu b\bar{b}$ (NN)	S	8.8	6.5	3.8	3.1	2.2
	B	30.6	24.0	18.0	22.0	27.8
	$S/\sqrt{B}$	1.6	1.3	0.9	0.7	0.4
$\nu\bar{\nu}b\bar{b}$ (CDF)	S	2.5	2.2	1.9	1.2	0.6
	B	10.0	9.3	8.0	6.5	4.8
	$S/\sqrt{B}$	0.8	0.7	0.7	0.5	0.3
$\nu\bar{\nu}b\bar{b}$ (SHW)	S	8.9	6.7	4.6	3.2	2.1
	B	36	32	25	17.2	13.2
	$S/\sqrt{B}$	1.5	1.2	0.9	0.8	0.6
$\nu\bar{\nu}b\bar{b}$ (NN)	S	12	7.5	4.2	2.5	2.0
	B	86	51	23.6	13.2	16.8
	$S/\sqrt{B}$	1.3	1.1	0.9	0.7	0.5
$\ell^+\ell^-b\bar{b}$ (CDF)	S	1.0	0.9	0.8	0.5	0.3
	B	3.6	3.1	2.5	1.8	1.1
	$S/\sqrt{B}$	0.5	0.5	0.5	0.4	0.3
$\ell^+\ell^-b\bar{b}$ (SHW)	S	1.5	1.2	0.9	0.6	0.4
	B	4.9	4.3	3.2	2.3	1.9
	$S/\sqrt{B}$	0.7	0.6	0.5	0.4	0.3
$\ell^+\ell^-b\bar{b}$ (NN)	S	0.9	1.1	0.6	0.5	0.2
	B	2.4	8.4	3.9	4.2	2.0
	$S/\sqrt{B}$	0.6	0.4	0.3	0.24	0.14
$q\bar{q}b\bar{b}$ (SHW)	S	8.1	5.6	3.5	2.5	1.3
	B	6800	3600	2800	2300	2000
	$S/\sqrt{B}$	0.10	0.09	0.07	0.05	0.03

Table 1: Summary of low-mass Standard Model Higgs search channel sensitivities used in the combined integrated luminosity threshold calculations. The values of S and B are expressed as the number of events expected in 1 fb^{-1}, and $S/\sqrt{B}$ is a pure number. Here we assume an improved Run 2 $m_{b\bar{b}}$ resolution of 10%. "SHW" indicates the analyses based on teh SHW simulation, "NN" indicates the SHW neural-network-based analyses, and "CDF" indicates the analyses based on extrapolations from the CDF Run 1 conditions to Run 2 detector geomentry and efficiencies.

5 Standard Model Higgs Search Channels: m_H = 120-190 GeV

For SM Higgs masses above about 135 GeV the decay mode $H \to WW$ dominates, and provides a means to potentially observe the Higgs. The main problem to overcome here is the roughly 10 pb cross section for vector boson pair production; the rates for Higgs are 10-100 times smaller. Three channels have been shown to be of potential use in this mass regime: like-sign lepton pairs with jets, dileptons with missing transverse energy, and trilepton final states. Table 2 summarizes the results of the analyses described in the following subsections. All the analyses use the SHW simulation.

5.1 The $\ell^\pm\ell^\pm jj$ search channel

The production of a SM Higgs decaying to WW, produced in conjunction with a vector boson, gives rise to WWW and ZWW final states. In the case of WWW, for example, if the two like-sign W's decay to an e or μ, then one has a distinct, low-background signature with two leptons of the same charge, two jets, and missing transverse energy.

To select such events one demands two leptons (e or μ) with 10 GeV $\mathrm{p_T}$, having the same charge, and two jets with $\mathrm{p_T} > 15$ GeV, and at least 10 GeV $\not{E}_\mathrm{T}$. Events with a third jet with $\mathrm{p_T} > 30$ GeV, or a fourth with $\mathrm{p_T} > 15$ GeV are removed to reduce $t\bar{t}$ background. Although present, the SM triple gauge boson production background is small compared with that from $t\bar{t}$, $WZjj$, and fake electrons.

5.2 The $\ell^+\ell^-\nu\bar{\nu}$ search channel

At large masses, as shown in Figure 2, the production of single Higgs via gluon fusion still dominates; at a mass of 160 GeV the production cross section is 400 fb, and the branching ratio to WW is over 90%. Thus one is driven to consider the very distinct events in which both W's decay to leptons (e or μ), which is a combined branching of about 5%.

The main challenge is to overcome the very large background from WW, WZ, ZZ, and $t\bar{t}$ production. First one makes an initial event selection, requiring two leptons with $\mathrm{p_T} > 10$ GeV/c (5 GeV/c for a second muon), less than 160° apart in azimuth (to remove Drell-Yan). Then a likelihood is formed from the values of six kinematic variables, and a cut is made which reduces the background dramatically. Finally one forms the transverse mass M_T and a "cluster mass" M_C

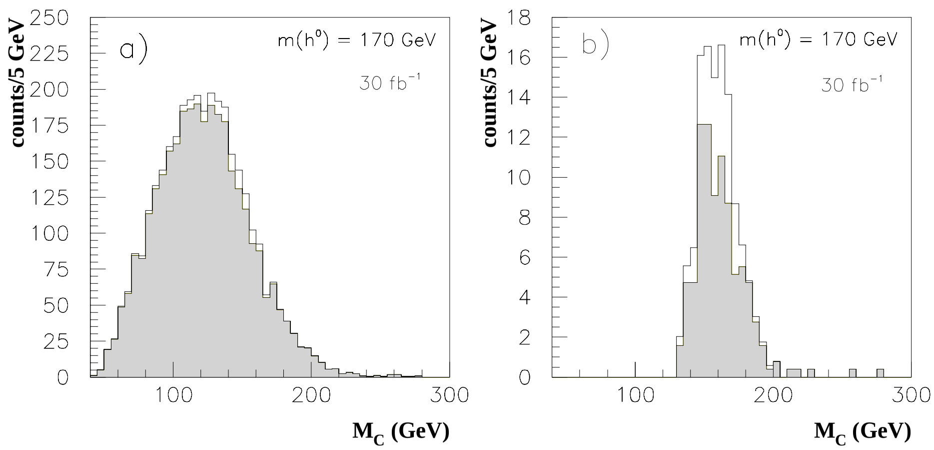

Figure 3: Cluster transverse mass distributions for the leading WW background (shaded) and the background plus the signal $gg \to h \to WW \to \ll$ with $m_H = 170$ GeV (histogram) (a) before the optimized cuts and (b) after the cuts.

defined respectively as

$$M_T \;=\; 2\sqrt{p_T^2(\ell\ell) + m^2(\ell\ell)} \tag{1}$$

and

$$M_C \;=\; \sqrt{p_T^2(\ell\ell) + m^2(\ell\ell)} \; + \not{E}_{\mathrm{T}} \;\; . \tag{2}$$

The distributions of M_C before and after the optimized cuts appears in Figure 3, and illustrates the separating power for the signal compared to the leading background, WW. In the real experiment one would measure the background in the signal-poor case, and extrapolate it into the signal-rich case with sufficient precision for a counting experiment.

5.3 The $\ell^\pm \ell'^\pm \ell^\mp$ search channel

At large Higgs masses, with WWW and ZWW final state, one can also consider searching for trilepton events; this channel is known from searches for charginos and neutralinos, for example, to have quite low expected backgrounds. One removes events with lepton pair masses consistent with that of the Z, and requires that the lepton "triple dot product" defined as

$$c_3 \equiv \frac{p_{x1}p_{x2}p_{x3} + p_{y1}p_{y2}p_{y3} + p_{z1}p_{z2}p_{z3}}{p_1 p_2 p_3}, \tag{3}$$

channel	rate	Higgs mass (GeV/c^2) 120	130	140	150	160	170	180
$\ell^\pm \ell'^\pm \ell^\mp$	S	0.011	0.025	0.039	0.050	0.057	0.033	0.033
	B	0.025	0.025	0.025	0.025	0.025	0.025	0.025
	$S/\sqrt{B}$	0.07	0.16	0.25	0.32	0.36	0.21	0.21
$\ell^+ \ell^- \nu\bar{\nu}$	S	-	-	2.6	2.8	1.5	1.1	1.0
	B	-	-	44	30	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	0.08	0.15	0.29	0.36	0.41	0.38	0.26
	B	0.58	0.58	0.58	0.58	0.58	0.58	0.58
	$S/\sqrt{B}$	0.11	0.20	0.38	0.47	0.54	0.50	0.34

Table 2: Summary of high-mass Standard Model Higgs search channel sensitivities; all results are based on SHW studies. The values of S and B are expressed as the number of events expected in 1 fb^{-1}, and $S/\sqrt{B}$ is a pure number.

be less than -0.75. Also, in this case one can make use of "golden" combinations with same-sign leptons of the same type (e.g. $e^+e^+\mu^-, \mu^-\mu^-e^+$, etc.). Events must satisfy this topology or pass one of a number of other criteria.

In the end, however, the small branching ratio leads to quite small numners of expected events, though the background is also small, as shown in table 2. Thus this channel brings little additional sensitivity unless the integrated luminosity is very large.

6 Combined Channel SM Higgs Results

As the sections above show, there is no single search channel for the Higgs which one might call "golden"; to maximize the sensitivity of the Higgs search it is necessary to combine the results of all the channels. Here we present the results of combining all Standard Model Higgs search channels, from both experiments, in terms of the integrated luminosity needed to exclude the Higgs at 95% CL (assuming it is not there) or discover it at the 3σ or 5σ level if it is.

The statistical method employed here for combining channels is a straightforward Bayesian approach based on calculating the joint likelihood for a given experimental outcome as a function of the Higgs cross section. Basically, the result of each search channel is treated as a counting experiment, and for a given outcome there is some Poisson probability. For all channels in both experiments, these probabilities are multipled together to form the joint likelihood. This likelihood can be expressed as a function of the Higgs signal cross section, and can be used to set 95% CL limits or discovery significances. To take into account all possible experimental outcomes, the integrated luminosity thresholds quoted below represent those values for which the desired statistical threshold is met in 50% of of all possible outcomes.

The results of all the channels studied are summarized in Tables 1 and 2. The tables show the expected signal S, the expected background B, and the sensitivity $S/\sqrt{B}$ in each channel as a function of the assumed Higgs mass. In all the low-mass channels, we have taken the numbers from assuming a 10% resolution in $m_{b\bar{b}}$.

The tables indicate that of the low mass channels, the $\ell\nu b\bar{b}$ and $\nu\bar{\nu}b\bar{b}$ have the most sensitivity. Also, while the dilepton mode adds significantly to the sensitivity, the all-hadronic channel brings little information to the final combination.

In comparing the different analyses, it is clear that the neural network technique results in enhanced sensitivity in the $\ell\nu b\bar{b}$ channel, but not as much in the $\nu\bar{\nu}b\bar{b}$ case. Note however that the NN- and SHW-based channel analyses do not take into account trigger inefficiency for events which otherwise pass the selection; this should be no problem in the $\ell\nu b\bar{b}$ and $\ell^+\ell^- b\bar{b}$ cases but may be a slight problem at low masses in the $\nu\bar{\nu}b\bar{b}$ case.

For the high-mass channels, the $\ell^+\ell^-\nu\bar{\nu}$ channel has the most sensitivity, whilst the $\ell^\pm\ell^\pm jj$ channel has nearly as good sensitivity over a broader mass range. The $\ell^\pm\ell'^\pm\ell^\mp$ channel has competetive sensitivity, but with its very low expected signal it contributes significantly only at the highest integrated luminosities.

For consistency and simplicity we perform determinations of the integrated luminosity thresholds combining the low-mass and high-mass SHW analyses only. In the combination we assume that both experiments' is used by doubling each channel: we generate separate pseodoexperimental outcomes for each channel in each experiment, and combine all the results together in the final likelihood.

To take into account reasonable systematic errors, we incorporate into the likelihood a relative uncertainty on the background for each channel which is the smaller of 10% of the expected background or $1/\sqrt{LB}$, where L is the integrated luminosity and B is the expected number of background events in 1 fb^{-1}. Such an assumption is typical of the level of uncertainty experienced in new particle searches at colliders. Note that if one does not let the systematic error decrease with integrated luminosity, numerical instability can result. More importantly, in the real experiments as the integrated luminosity increases the experimenters will have better control of the systematic errors, and will in all likelihood harden the selection criteria to improve the sensitivity while maintaining tolerable systematic uncertainties.

Without the inclusion of these systematic errors, the integrated luminosity thresholds are approximately 30-50% smaller.

Figure 4 shows the integrated luminosity required to either exclude the SM Higgs at 95% CL or discover it at the 3σ or 5σ level of significance, as a function of Higgs mass. The integrated luminosity in the plot is the delivered integrated luminosity per experiment, but the result is the combination of both experiments. (The thresholds for a single experiment are very close to a factor of two higher.)

As the plot shows, the required integrated luminosity increases exponentially with Higgs mass to 140 GeV/c^2, beyond which the high-mass channels play a domminant role. In Run 1 (2 fb^{-1}) the 95% CL limits will barely extend the expected LEP-II limits, but with 10 fb^{-1} in Run 3, the SM Higg can be excluded up to 190 GeV/c^2 if it does not exist in that mass range.

In Run 3, if a SM Higgs exists with mass less than 180 GeV/c^2, the combined sensitivity of CDF and DØ will yield an observation at the 3σ level up to 180 GeV/c^2 mass with 20 fb^{-1}. However, a 5σ discovery does not appear possible below just under 120 GeV/c^2.

Of course, breakthroughs in technique are always possible, and have indeed been the norm in the past. For example both the Higgs search in LEP-I and the top quark search in Run 1 at the Tevatron exceeded the expectations of studies prior to machine turn-on. The studies presented here should be taken as cautiously optimistic: Using full mass spectrum fits, using neural network techniques, improvements to the trigger efficiencies, the addition of other channels (tau decay modes, single Higgs production) and improvements to the mass resolution and tagging effiency beyond that projected here may all serve to significantly improve the discovery potential for the Higgs at the Tevatron.

7 Search for MSSM Higgs

The discovery reach for Higgs bosons in extensions to the Standard Model has also been stusied in the Workshop, focusing on two main areas, namely interpreting the SM Higgs results in the supersymmetric parameter space, and searching for enhanced production of neutral Higgs in conjunction with $b\bar{b}$ pairs.

7.1 MSSM limits from the SM Higgs Search

In the MSSM one has five physical Higgs states: two neutral scalars (h and H), one neutral pseudoscalar (A), and two charged Higgses ($H^{\pm}$). The masses and couplings of these bosons are governed in the Minimal Supersymmetric Standard Model (MSSM) by two parameters, which we can take as m_A and $\tan\beta$ (the ratio of the vacuum expectation values of the two Higgs doublets). For much of the MSSM parameter space the h and H can behave like the SM Higgs, and the results of the SM Higgs search applies directly. In general, though, the phenomenology of the Higgs sector depends in detail on the various couplings of the Higgs bosons to gauge bosons, Higgs bosons and fermions. The couplings of the two CP-even Higgs bosons to W and Z pairs (denoted VV) are given in terms of the angles α and β by

$$g_h VV = g_V m_V \sin(\beta - \alpha) \quad (4)$$

$$g_H VV = g_V m_V \cos(\beta - \alpha) \quad (5)$$

$$g_A VV = 0 \quad (6)$$

where $g_Z = g$ and $g_W = g/\cos\beta$. Here α is an angle which results from the diagonalization of the CP-even Higgs squared-mass mixing matrix, and calculable from the values of $\tan\beta$ and m_A. Thus the production cross section of Wh and Zh, for example, is suppressed rtelative to the Standard Model cross sections for WH_{SM} and ZH_{SM} by the factor $\sin^2(\beta - \alpha)$. Likewise the cross sections for WH and ZH are suppressed by the factor $\cos^2(\beta - \alpha)$.

The relationships between the MSSM Higgs masses, illustrated graphically in Figure 5, guarantee that there is a Higgs with nearly SM-like couplings at a mass below about 120 GeV, where this number could be lower depending on the stop quark mixing.

The simplest approach, then, to search for the MSSM neutral Higgses at the Tevatron is to use the search channels for SM production of VH_{SM}. Where the cross section limit is lower than that of the corresponding MSSM production, one can exclude or discover the MSSM Higgs at that mass.

The first step is to calculate, for each Higgs mass and for a given integrated luminosity, the value R of the ratio of the production cross section at which one can expect (50% of the time) to exclude or discover the Higgs to the SM cross section. For different m_A and $\tan\beta$, then, one can compare the values of R thus obtained to the theoretical values at those parameter values. Figure 6 shows the values of R for 95% CL limits and 5σ discovery as a function of Higgs mass, based on the four low-mass SM Higgs search channels.

Figures 7, 8, and 9 show the regions of the MSSM parameter space $\tan\beta$ versus m_A in which one can exclude or discover the Higgs, as a function of the delivered integrated luminosity per experiment, combining the data from both ex-

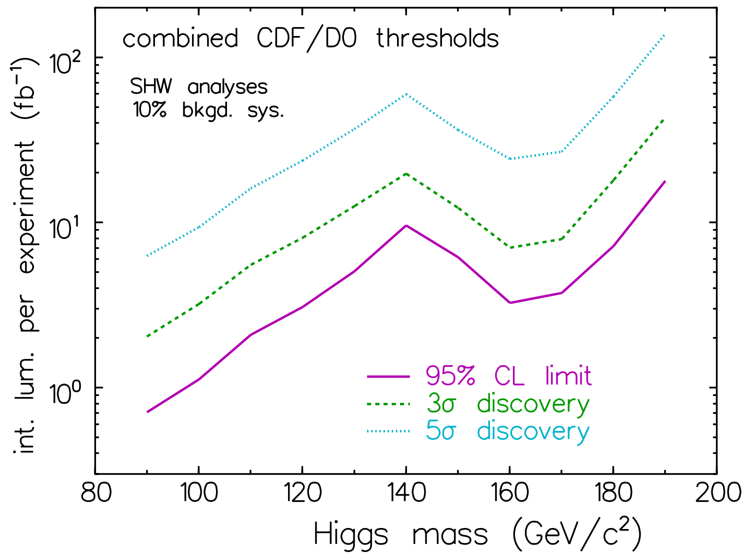

Figure 4: Integrated luminosity delivered per experiment required to either exclude the SM Higgs at 95% CL or discover it at the 3σ or 5σ level, as a function og Higgs mass. This represents the combination of all the SHW-based channels, using the neural network selection for the $\ell\nu b\bar{b}$, $\nu\bar{\nu}b\bar{b}$, and $\ell^+\ell^- b\bar{b}$ channels, combining the statistical power of both experiments.

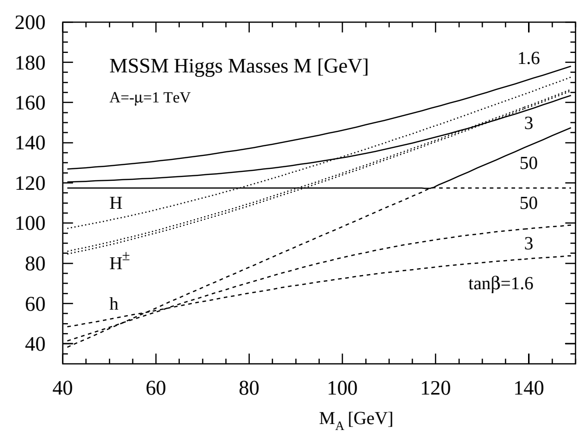

Figure 5: Masses of the h, H, and $H^{\pm}$ as a function of m_A, for various values of $\tan\beta$.

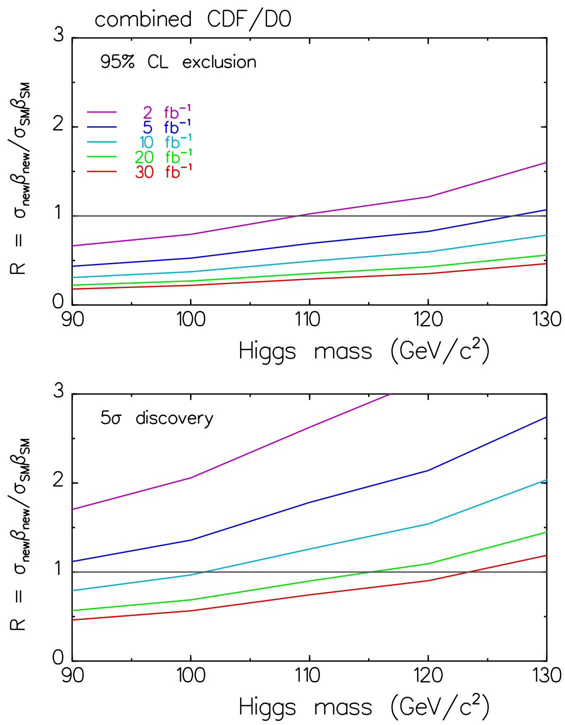

Figure 6: Values of R, the ratio of the Higgs cross section at which one can set 95% CL limits (top plot) or make a 5σ discovery (bottom plot) to the SM cross section, as a function of Higgs mass.

periments. The three pairs of figures are evaluated for different MSSM parameter assumptions which affect the stop quark mixing.

As the plots show, with 5 fb^{-1} one can exclude most of the parameter space for either minimal or maximal stop mixing; to discover the MSSM Higgs in most of the space at 5σ significance requires about 20 fb^{-1}. However for the case $A = -\mu$ =1.5 TeV the difficult region at large $\tan\beta$ becomes large due to the suppression of the $\phi b\bar{b}$ coupling.

7.2 Enhanced SUSY Higgs production at large $\tan\beta$

In the MSSM, the basic $b\bar{b}\phi$, $\phi = h, H, A$ couplings are proportional to $1/\tan\beta$ at large $\tan\beta$, and thus can lead to enhanced production of MSSM neutral Higgses produced in conjunction with a $b\bar{b}$ pair. If, for example, the value of $\tan\beta$ is near $m_t/m_b \sim 35$, then the production of $Ab\bar{b}$ is enhanced by over a factor of 1000 compared with the Standard Model production of $Hb\bar{b}$. Thus by searching for events

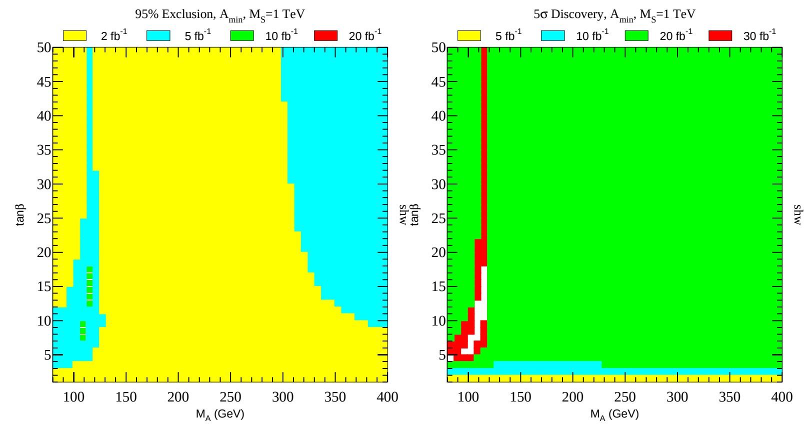

Figure 7: Regions of the MSSM parameter space $\tan\beta$ versus m_A in which one can (left) exclude at 95% CL or (right) discover at 5σ the MSSM Higgs, assuming minimal stop mixing.

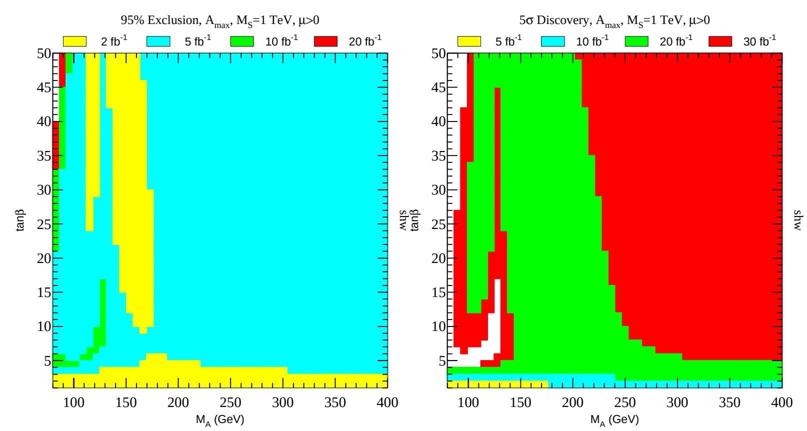

Figure 8: Regions of the MSSM parameter space $\tan\beta$ versus m_A in which one can (left) exclude at 95% CL or (right) discover at 5σ the MSSM Higgs, assuming maximal stop mixing.

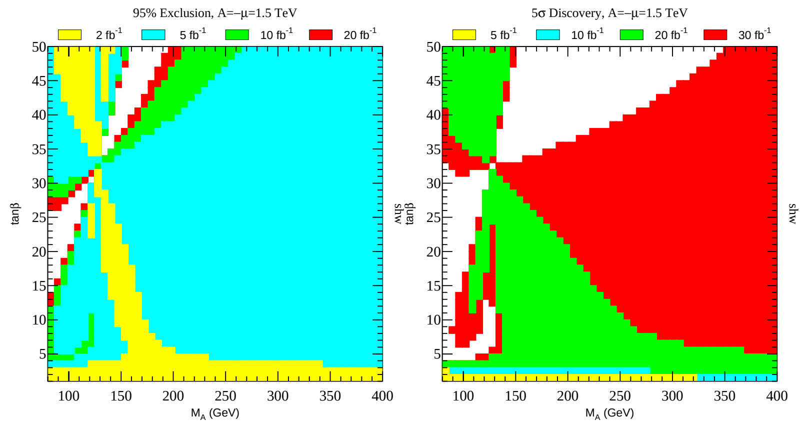

Figure 9: Regions of the MSSM parameter space $\tan\beta$ versus m_A in which one can (left) exclude at 95% CL or (right) discover at 5σ the MSSM Higgs, assuming $A = -\mu =$1.5 TeV.

with $b\bar{b}b\bar{b}$ final states, one can be sensitive to a large range of the MSSM parameter space.

Two analyses of the integrated luminosity needed to rule out or discover the MSSM Higgs in this channel were performed, one for the CDF experiment, and one for DØ . Starting from quite different input assumptions and methods, the two $b\bar{b}b\bar{b}$ analyses arrive at quite similar estimates for the exclusion and discovery reach for the MSSM scalar and pseudoscalar Higgses at large $\tan\beta$. The results of the two analyses appear in Figures 10 and 11.

The first main difference is that the analyses use different Monte Carlo generators, both developed during the Workshop. The DØ analysis uses COMPHEP, whereas the CDF analysis uses a generator developed from a modified version of PAPAGENO with PYTHIA fragmentation. The cross sections and kinematic distributions from the two generators agree reasonably well.

The two kinematic selections proceed along similar lines, both demanding four jets. The DØ analysis demands a minimum jet transverse momentum of 30 GeV/c and leading and next-to-leading jet p_T's which increase with Higgs mass. The CDF analysis demands $\sum(E_T) > 125$ GeV and four jets with a minimum of 15 GeV transverse energy.[1]

Though there are potentially four taggable b jets in the signal, both analyses require three tags for optimal sensitifvity. The DØ analysis assumes a b tagging

[1]This is motivated by the Run 1 trigger requirements, which may loosen for Run 2 if the experiment uses the SVT to tag secondary vertices in three-jet events.

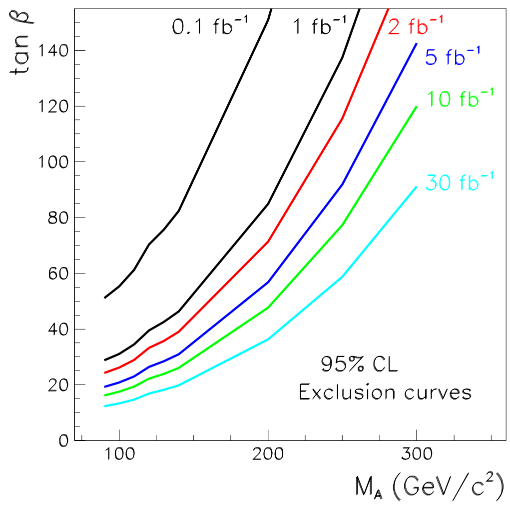

Figure 10: Thresholds in the plane of $\tan\beta$ versus m_A for the DØ analysis of $b\bar{b}b\bar{b}$.

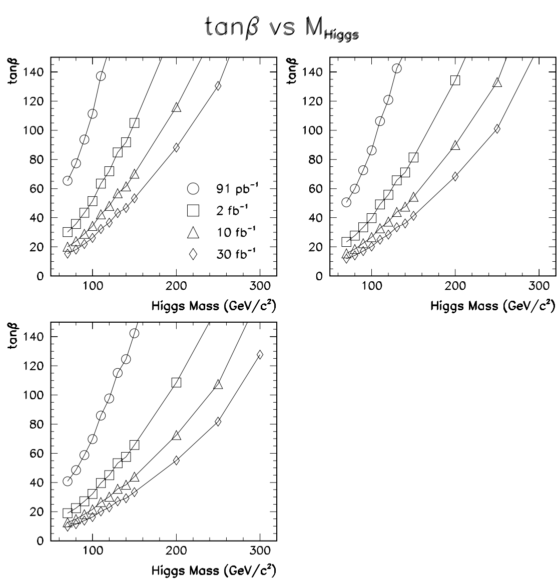

Figure 11: Thresholds in the plane of $\tan\beta$ versus m_A for the CDF analysis of $b\bar{b}b\bar{b}$.

efficiency based on the Monte Carlo study of section II.A.2, which has a maximum eficiency of 55%. The CDF analysis uses, conservatively, the Run 1 tagging efficiencies per taggable jet, but the much larger Run 2 detector geometry to determine taggability. This is perhaps the largest source of difference between the two analyses, since the cube of the tagging efficiency determines the signal rate.

By far the largest background comes from QCD $b\bar{b}jj$ production, and the simulations of its total rate is unreliable. The only weapons against it are the requirement of the third b tag and reconstrcting the Higgs mass. The DØ analysis relies on Monte Carlo simulations of the background, and the CDF analysis uses Monte Carlo scaled by a factor determined with Run 1 data. Given the different signal selections, it is difficult to say how well the two methods agree.

The two analyses also take different approaches to Higgs mass reconstruction. The DØ analysis uses all possible $b\bar{b}$ combinations in an event, and a 15% resolution (for the correct combination) based on the MC studies. The CDF analysis uses jets 1 and 2 at high Higgs masses, and jets 2 and 3 at lower Higgs masses. The assumed resolution is that of Run 1.

Both analyses assume rather conservative b tagging efficiency and mass resolution; these are quite likely to be better in the actual run. Furthermore, the role of an improved trigger should be studied further; the fact that in many events one of the b jets is very far forward could perhaps mean that it is optimal to require only three jets in the central region.

In any case, this search represents the main mode for discovering or ruling out the MSSM Higgs at large $\tan\beta$, and demonstrates one of the unique advantages of hadron colliders.

8 Conclusions

The search for the Higgs boson of the Standard Model and in supersymmetry is one of the primary goals of Run 2 at the Tevatron. Present fits to the world's electroweak data indicate that the Higgs is very likely to be light, close to 100 GeV in mass. With over an order of magnitude improvement in integrated luminsoty from the Tevatron, and with two upgraded detectors having excellent tracking and calorimetry, the sensitivity for this search will increase greatly.

The Higgs Working Group of the Tevatron Run 2 SUSY/Higgs Workshop has studied the discovery reach for the SM and MSSM Higgs in eight separate channels. Combining the results from these channels, and combining the data from both experiments, with 10 fb^{-1} a SM Higgs can be excluded at masses up to about 180

GeV; discovering it at the 5σ level, however, will take substantially more luminosity, probably more than the Tevatron can deliver before the LHC era.

When interpreted in the parameter space of the minimal supersymmetric standard model, however, depending on the nature of the stop quark mixing the Tevatron experiments are sensitive to nearly the entire MSSM space at much lower integrated luminosities, due to the fact that in the MSSM there is guaranteed to be a light Higgs. However there are pathological regions which are difficult to cover in the MSSM.

The Tevatron can also search for the MSSM Higgs by their production along with $b\bar{b}$ pairs, leading to a distinct event signature in which there are four b jets. This channel can complement the MSSM Higgs search using

Reaching these goals will require a great deal of experimental effort in improving the $b\bar{b}$ mass resolution, improving the b tagging, and improving the trigger efficiency for the Higgs final states. The payoff, though, is clearly potentially enormous, and the results presented here give strong motivation both for these effort and for continuing the Tevatron collide program into Run 3, with the goal of delivering 20 fb^{-1} or more if possible.

References

1. The LEP Electroweak Working Group web site can be found at http://www.cern.ch/LEPEWWG/. The results here are from the Winter 99 summaries.

2. Tim Greening, these Proceedings.

3. John Marriner, Talk given at the Summary Meeting of the Tevatron Run 2 SUSY/Higgs Workshop, 19 Nov. 1998, Fermilab, Batavia, IL.

4. M. Spira, Fortschr. Phys. **46** (1998) 203; see also M. Spira, Higgs Boson Production and Decay at the Tevatron, paper submitted to the Tevatron Run 2 SUSY/Higgs Workshop, October 1998, DESY 98-159.