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HIGGS BOSON DISCOVERY PROSPECTS AT THE TEVATRON

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Preliminary results from a Fermilab study of the sensitivity for Higgs boson production at the upgraded Tevatron are presented. The study extends previous results by systematically combining results for all decay channels, considering the production of higher mass Higgs bosons and interpreting the results in the context of supersymmetric Higgs production as well as Standard Model production. New analysis methods significantly improve the sensitivity. With 20 fb^{-1} of accumulated data, the Higgs discovery reach can be extended to $M_H = 180$ GeV.

The Standard Model (SM) of particle physics has been studied with very high precision over the course of the past ten years, and no significant deviations have been found. Despite this, our understanding of the origin of electroweak symmetry breaking is still incomplete. This arises in large part because the only remaining undetected SM particle, the Higgs boson, mediates electroweak symmetry breaking in the SM. The Fermilab Tevatron $p\bar{p}$ collider, with $\sqrt{s} = 2.0$ TeV, will give the highest available center of mass energy until 2005. This paper contains preliminary results from a six month study conducted jointly by the Fermilab theory group and the CDF and DØ experiments to explore the sensitivity to Higgs production at the Tevatron. The goal is to quantify the Higgs discovery potential at the Tevatron in Run II (starting in 2000) and possible extensions. Results are presented as the luminosities required to exclude a Higgs boson at the 95% confidence level, or to establish either 3σ or 5σ excesses over predicted backgrounds.

The starting points for this study are the Higgs mass constraints expected from LEP2[1] and previous Fermilab studies[2 3]. This study extends the previous Fermilab results by (a) including additional SM decays in the mass regions previously explored, (b) testing the sensitivity for Higgs masses $M_H > 135$ GeV, (c) systematically combining results from all channels, (d) interpreting the results as supersymmetric (SUSY) Higgs production and (e) considering additional decay modes arising from SUSY models. In addition, a detector simulation was developed which gives significantly more realistic event reconstruction than for previous studies.

1 Production, Decay, Event Generation and Detector Simulation

The production cross sections[4] and decay branching ratios for Higgs bosons are shown in Fig. 1. These plots indicate that the highest cross section production modes are $p\bar{p} \to H$ via gluon fusion, and the Higgs radiation processes $p\bar{p} \to WH$ and $p\bar{p} \to ZH$. The Higgs boson decays dominantly to the most massive kinematically allowed final state. For $M_H < 135$ GeV, the dominant decay mode is $H \to b\bar{b}$ with a branching ratio of roughly 80%. For $M_H > 135$ GeV, the dominant mode is $H \to WW$, where one W may be off the mass shell. Thus, searches for

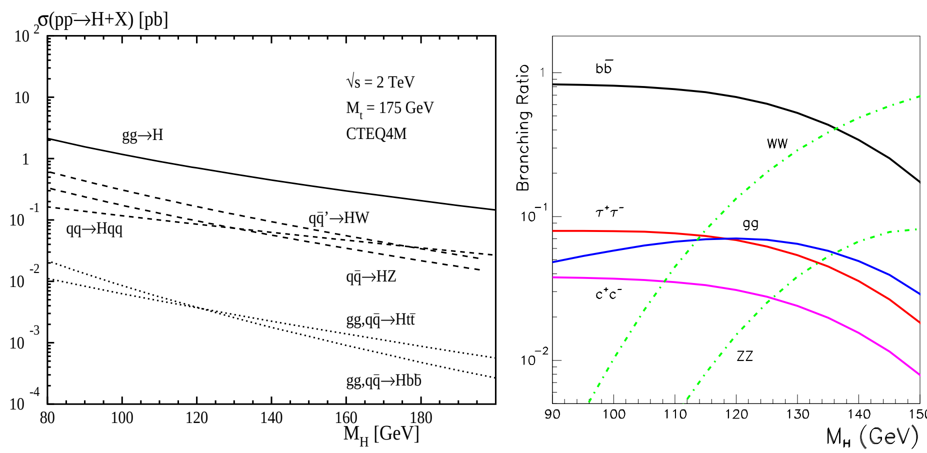

Figure 1. Production cross sections and decay branching ratios for the SM Higgs boson as a function of mass.

lower mass Higgs will seek final states with at least two b jets, and the higher mass searches will have multiple (possibly virtual) W bosons. For most of the mass range in question, the $p\bar{p} \to H$ mode has very poor signal to noise ratio, and the more useful modes are the $p\bar{p} \to WH$ and $p\bar{p} \to ZH$ modes with the W or Z decaying to leptons.

Events used in these analyses were generated using the PYTHIA[5], ISAJET[6] or COMPHEP[7] programs. The generated four-vectors were input to a detector simulation program[8], SHW, developed for the workshop. SHW uses parameterized resolutions for tracking and calorimeter systems and particle identification to perform simple reconstruction of tracks, calorimeter-based jets, vertices and trigger objects. The resolutions and for particle identification efficiencies used are based on CDF and DØ internal studies.

The SHW program was verified by comparing SHW selection efficiencies with data or with well-established CDF or DØ Run I simulations. The most stringent test was a comparison of nearly identical analyses of the $p\bar{p} \to WH \to (\ell\nu)(b\bar{b})$ channel. Two analyses of this channel have been performed, one based on a Run I CDF simulation with the geometrical acceptance extended to correspond to the Run II CDF detector and the second based purely on SHW. The first analysis predicts 5.0 signal events and 62.8 background events/fb^{-1} for $M_H = 110$ GeV. The second predicts 4.5 signal and 62.5 background events for the same conditions.

2 Low Mass Higgs Searches ($M_H < 135$ GeV)

For $M_H < 135$ GeV, the dominant decay mode is $H \to b\bar{b}$. Analyses have been performed for all $p\bar{p} \to WH$ and $p\bar{p} \to ZH$ final states.[a] The possible final states

[a] The mode $p\bar{p} \to H \to b\bar{b}$ was considered, but the signal to noise was too poor for it to have any useful sensitivity when compared to the $p\bar{p} \to WH$ and $p\bar{p} \to ZH$ modes.

Table 1. Numbers of expected signal (S) and background (B) events for each low-mass channel in 1 fb^{-1}. A 30% improvement in mass resolution over that from SHW has been assumed. See the text for details.

		Higgs Mass (GeV/c^{-1})				
Channel	Rate	90	100	110	120	130
	S	2.5	2.2	1.9	1.2	0.6
$\nu\bar{\nu}b\bar{b}$	B	10	9.3	8.0	6.5	4.8
	$S/\sqrt{B}$	0.8	0.7	0.7	0.5	0.3
	S	8.4	6.6	5.0	3.7	2.2
$l\nu b\bar{b}$	B	48	52	48	49	42
	$S/\sqrt{B}$	1.2	0.9	0.7	0.5	0.3
	S	1.0	0.9	0.8	0.5	0.3
$l^+l^-b\bar{b}$	B	3.6	3.1	2.5	1.8	1.1
	$S/\sqrt{B}$	0.5	0.5	0.5	0.4	0.3
	S	8.1	5.6	3.5	2.5	1.3
$q\bar{q}b\bar{b}$	B	6800	3600	2800	2300	2000
	$S/\sqrt{B}$	0.10	0.09	0.07	0.05	0.03

are: (1) $p\bar{p} \to WH \to \ell\nu b\bar{b}$, (2) $p\bar{p} \to ZH \to \nu\bar{\nu}b\bar{b}$, (3) $p\bar{p} \to ZH \to \ell^+\ell^- b\bar{b}$ and (4) $p\bar{p} \to WH \to q\bar{q}b\bar{b}$ or $p\bar{p} \to ZH \to q\bar{q}b\bar{b}$. The primary backgrounds to these channels are $W + b\bar{b}$ and $Z + b\bar{b}$ with the $b\bar{b}$ pair from gluon radiation, single top quark production and top quark pair production.

These analyses begin with a preliminary selection based on the number and type of final state objects. For example, the $p\bar{p} \to WH \to \ell\nu b\bar{b}$ analysis requires a charged lepton with $E_T > 20$ GeV, missing transverse energy $\vec{\not{E}}_T > 20$ GeV and two b-tagged jets having $E_T > 15$ GeV. Similar selections are applied for the other channels. After the basic selection, a requirement is made that the mass of the reconstructed $b\bar{b}$ system be within (typically) 2σ of the generated Higgs mass. Additional clean up requirements are also made. As an example, in the $p\bar{p} \to ZH \to \nu\bar{\nu}b\bar{b}$ channel, there can be no isolated tracks with $p_T > 15$ GeV. This rejects events with high-p_T leptons that failed the lepton identification. The resulting number of signal and background events corresponding to 1 fb^{-1} of data are given in Table 1. The $p\bar{p} \to WH \to \ell\nu b\bar{b}$ and $p\bar{p} \to ZH \to \nu\bar{\nu}b\bar{b}$ modes offer the best sensitivity with the $p\bar{p} \to ZH \to \ell^+\ell^- b\bar{b}$ mode not far behind. The all-hadronic final state provides less sensitivity.

An additional multivariate analysis using neural networks has been performed for the $p\bar{p} \to WH \to \ell\nu b\bar{b}$ channel. Such analyses have been used with considerable success by DØ in the top quark mass[9] and all-hadronic $t\bar{t}$ cross-section analyses[10], and exploit correlations within an event in an automatic manner. The left panel of Fig. 2 shows the number of predicted signal and background events for $p\bar{p} \to WH \to \ell\nu b\bar{b}$ analyses. Each point in the figure represents one possible analysis. The band labelled "rgsearch" corresponds to hypothetical analyses performed using selections using the standard technique of sequential requirements applied to event variables, with each requirement a single-valued comparison such

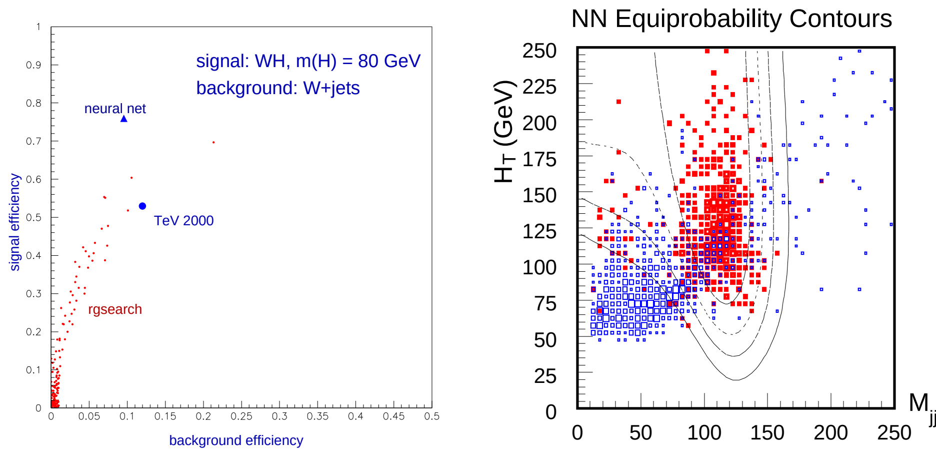

Figure 2. The left panel shows predicted signal and background selection efficiencies from the neural network analysis. Each point corresponds to a possible event selection. The point labelled "neural net" is the result from the multivariate analysis described in the text. The right panel shows neutral network output equal probability contours in the H_T vs. M_{jj} plane. H_T is the scalar sum of all jet energies, and M_{jj} is the invariant mass of the tagged dijet system. The open (closed) boxes are background (signal) events.

as $\vec{\not{E}}_T > 20$ GeV. The point labelled "TeV 2000" is the result from a previous Fermilab study[2]. The point labelled "neural net" is the result from the multivariate analysis. The signal/$\sqrt{\text{background}}$ measure of the search sensitivity is improved by about a factor of two in the neural network analysis. Similar gains are expected in all other channels in this mass range.

Results have also been obtained for potential improvements in mass reconstruction and b-jet tagging efficiency. The analyses were repeated after artifically improving the reconstructed dijet mass resolution in steps up to a 50% better resolution. The results in Table 1 include an improvement in mass resolution of 30%. This level of improvement is possible when information such as charged track energy is used in the mass reconstruction in assocation with the calorimeter-based jet energies currently used. Such an improvement has already been realized in a preliminary Run I CDF analysis of the $p\bar{p} \to Z \to b\bar{b}$ channel[11]. Improved mass resolution offers considerable benefits because for a selection with a fixed signal expectation, the background will decrease as the resolution improves.

The effect of improved b-jet tagging has also been explored by artificially improving the second jet tagging efficiency by up to a factor of two. The gains from this improvement are not as important as those from mass resolution improvements because both signal and background increase with improved tagging efficiency.

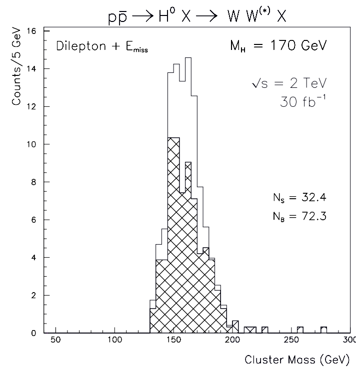

Figure 3. The cluster mass variable for background (shaded region) and for signal and background together (open region) for the $l^+l^-\nu\bar{\nu}$ analysis.

3 High Mass Higgs Searches ($M_H > 135$ GeV)

Previous Fermilab studies have focussed on the lower mass Higgs states decaying mainly to $b\bar{b}$. This study includes analyses designed for final states in which the Higgs decays to WW or ZZ instead of $b\bar{b}$, as appropriate for $M_H > 135$ GeV (*c.f.* Fig. 1). Three final states are considered: (1) three leptons, $l^\pm l'^\pm l^\mp$, arising primarily from $p\bar{p} \to WH \to WWW$, (2) dileptons and neutrinos, $l^+l^-\nu\bar{\nu}$, from $p\bar{p} \to H \to WW$ and (3) like-sign dileptons plus jets, $l^\pm l^\pm jj$, from $p\bar{p} \to WH \to WWW$ and $p\bar{p} \to ZH \to ZWW$[12]. The dominant backgrounds are from SM production of WW, WZ, ZZ, $W(Z)+$ jets, $t\bar{t}$ and multijet events with misidentification of jets. The SM sources dominate the detector effects.[b]

As for the low mass analyses, the initial selections are based on simple variables related to the boson decay product kinematics. However, to reach usable sensitivity, the analyses then use either (a) requirements typically relating to angular correlations arising from spin differences between signal and background or (b) likelihood methods. In both cases new variables have been designed. Figure 3 shows one such variable used in the $l^+l^-\nu\bar{\nu}$ analysis, the cluster mass $M_C \equiv \sqrt{p_T^2(\ell\ell) + m^2(\ell\ell)} + |\vec{\not\!\!E}_T|$. A result of the tuning is that the signal and background have similar mass distributions, so these analyses must be treated as simple counting experiments. The numbers of expected signal and background events for the high-mass channels are given in Table 2.

The results in the low and high mass regions have been combined to form a single unified result. Figure 4 shows the luminosities required for 95% CL exclusion, 3σ evidence and 5σ discovery as a function of SM Higgs mass. These curves include statistical and systematic errors[c] and the several channels are combined using the

[b] In general, the backgrounds arising from detector effects use conservative misidentification probabilities based on Run I analyses by both experiments.
[c] The systematic errors are assumed to scale with luminosity. The scaling is expected to hold at least until 2% relative systematic errors are reached. Systematic uncertainties at this level do not

Table 2. Numbers of expected signal (S) and background events (B) in 1 fb^{-1} for the high-mass channels.

Channel	Rate	Higgs Mass (GeV/c^{-1}) 120	130	140	150	160	170	180
	S	0.04	0.08	0.11	0.12	0.15	0.10	0.09
$l^{\pm}l'^{\pm}l^{\mp}$	B	0.73	0.73	0.73	0.73	0.73	0.73	0.73
	$S/\sqrt{B}$	0.05	0.09	0.13	0.14	0.18	0.12	0.11
	S	–	–	2.6	2.8	1.5	1.1	1.0
$l^+l^-\nu\bar{\nu}$	B	–	–	44	30	4.4	2.4	3.8
	$S/\sqrt{B}$			0.39	0.51	0.71	0.71	1.9
	S	0.1	0.20	0.34	0.53	0.45	0.38	0.29
$l^{\pm}l^{\pm}jj$	B	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	$S/\sqrt{B}$	0.11	0.22	0.37	0.57	0.49	0.41	0.31

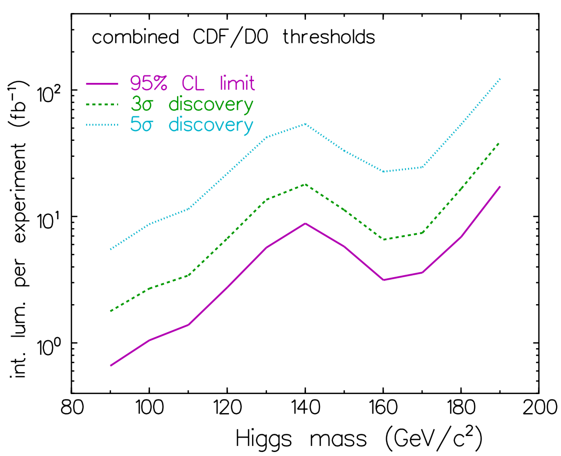

Figure 4. Luminosity required to achieve 95% confidence level exclusion, 3σ evidence and 5σ discovery as a function of Higgs mass. The results use all channels and assume results from both CDF and DØ having equal sensitivity. The experimental uncertainties used are described in the text.

prescription of reference [13]. With 20 fb^{-1} of data there is discovery or evidence capability up to $M_H \approx 180$ GeV.

4 Search for Neutral Higgs Bosons in SUSY Models

Supersymmetric extensions of the SM give at least five physical Higgs states: two neutral scalars denoted h and H(with $M_h < M_H$), a single pseudoscalar A and a charged doublet $H^{\pm}$. Unlike most other supersymmetric particles, the masses of

limit the analyses.

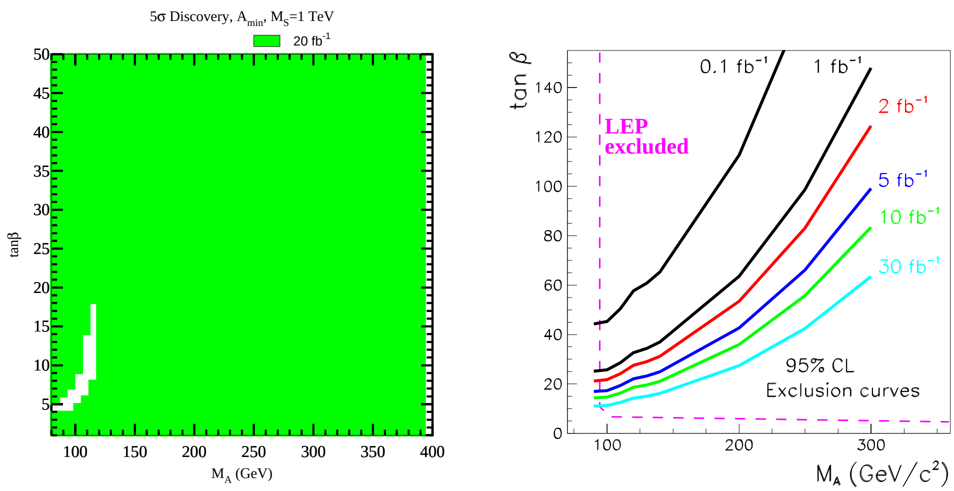

Figure 5. Exclusion contours for SUSY models. For the left panel the shaded region is excluded based on a reinterpretation of the SM searches in section two as SUSY Higgs production. This example shows the 5σ discovery region with an integrated luminosity of 20 fb^{-1}. The right panel shows the result from the $p\bar{p} \to hb\bar{b} \to b\bar{b}b\bar{b}$ analysis for large $\tan\beta$. The region above the curves is excluded.

the Higgs particles depend only on two parameters, typically chosen to be $\tan\beta$ and M_A (or M_h). Furthermore, the h boson should satisfy $M_h < 130$ GeV. For much of SUSY parameter space, the h decay is identical to that of the SM Higgs, and only the production cross section differs. Given this, the searches for low mass SM Higgs can be easily converted to searches for SUSY Higgs. The left-hand panel of Fig. 5 shows the 5σ discovery contour (for the set of channels discussed in Sect. 2) in the $\tan\beta$ vs. M_A plane for the case in which all non-Higgs SUSY masses are around 1 TeV, the systematic error is 10%, and CDF and DØ data are combined. One sees that for this example, SUSY models having $1 < \tan\beta < 50$ and $80 < M_A < 400$ GeV are covered, with the exception of the small window near $\tan\beta \approx 10$ and $M_A \approx 120$ GeV,

Within SUSY models, new Higgs production modes exist, some with couplings proportional to $\tan^2\beta$. For sufficiently large values of $\tan\beta$ these become the dominant production modes. One such mode is $p\bar{p} \to hb\bar{b}$[d]. This results in final states containing four b-flavored jets. Analyses of this channel have been carried out. These typically require four jets, three of which satisfy b-tag requirements. All possible mass combinations of b-jets are computed, and the resulting distribution is examined for a peak near the generated Higgs mass. The 95% C.L. exclusion contours in the $\tan\beta$ vs. M_A plane are shown in the right panel of Fig. 5 for several integrated luminosities.

[d] There are additional modes with A or H in place of h.

5 Conclusions

Studies of the experimental sensitivity to Higgs production for Tevatron Run II and beyond have been carried out. Both SM and supersymmetric Higgs production have been considered. It is found that with 4 fb^{-1} of data, SM Higgs can be excluded at 95% confidence over the interval $M_H < 125$ GeV and $155 < M_H < 175$ GeV. With 20 fb^{-1}, a SM Higgs boson will be seen as at least a 3σ excess over the full mass range $M_H < 180$ GeV. These results have been converted to limits on the SUSY parameter space.

Acknowledgments

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