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Standard Model Higgs Sensitivity Status with Summer 2005 Channels

The CDF Higgs Working Group

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Abstract

The combined sensitivity of CDF's current Standard Model Higgs boson searches is presented. The expected limits on the production cross section times the relevant Higgs boson branching ratios are computed for the $W^{\pm}H \to \ell^{\pm}\nu b\bar{b}$, $ZH \to \nu\bar{\nu}b\bar{b}$, $gg \to H \to W^{+}W^{-}$ and $W^{\pm}H \to W^{\pm}W^{+}W^{-}$ channels as they stand as of the presentations to the Summer 2005 conferences (specifically, SUSY05 and EPS05). While the $ZH \to \ell^{+}\ell^{-}b\bar{b}$ channel is still under development, preliminary neural nets and acceptances are included in this sensitivity estimation. Correlated and uncorrelated systematic uncertainties are taken into account, and the luminosity requirements for 95% CL exclusion, 3σ evidence, and 5σ discovery are computed for median experimental outcomes. The sensitivity of these predictions to the inclusion and omission of systematic uncertainties is explored. A list of improvements required to achieve the sensitivity to a SM Higgs as quantified in the Higgs Sensitivity Working Group's note is provided.

1 Introduction

Working groups with members of the CDF and D0 collaborations have twice convened to estimate the expected sensitivity of the Tevatron Higgs searches to a Standard Model Higgs boson signal as a function of the Higgs boson mass [1, 2]. The later estimation [2] was commissioned at the start of Run II in order to use the more realistic Monte Carlos which became available, and the first data to help calibrate the detector responses and backgrounds. Each report includes calculations of the estimated amounts of luminosity required for a combination of all of CDF's channels and D0's channels to exclude at 95% CL, assuming a Higgs boson is not present, as well as the luminosity requirements for a combined 3σ evidence and 5σ discovery. The luminosity threshold requirements are shown in Figures 1 and 2.

The second estimation predicted less required luminosity for exclusion and discovery for three main reasons:

- Kinematic shapes were fitted instead of cuts applied and events counted.
- The expected improvements in signal separation with neural nets was estimated.
- Systematic uncertainties were ignored.

Taking the last point into account, it was considered that the actual sensitivity with systematic errors included would be comparable to, or slightly better than, the first calculation [1]. Both calculations of the sensitivity extrapolated the performance of the search channels, taking into account that work would be done to improve the sensitivity of the searches as the data are collected.

The first analyses have been conducted on CDF and updated for 300 pb^{-1} of data using in the $W^{\pm}H \rightarrow \ell^{\pm}\nu b\bar{b}$ [3] and $ZH \rightarrow \nu\bar{\nu}b\bar{b}$ [4] channels, and using somewhat less data in the $gg \rightarrow H \rightarrow W^{+}W^{-}$ [5] and $W^{\pm}H \rightarrow W^{\pm}W^{+}W^{-}$ [6] channels. The luminosities used in each channel are listed in Table 1. The exercise presented here is to compute the sensitivities of each of the channels separately and combined, and to compare that with the estimation of the Higgs Sensitivity Working Group [2], and to identify the differences between the assumptions of the predictions and the actual search channels prepared for the Summer 2005 conferences. These differences represent avenues of work which are needed to improve the sensitivity of the combination to the level needed to test for the existence of the SM Higgs boson.

2 Sensitivity by Channel

The expected signal and background rates, shape distributions and uncertainties were collected from each of the channel analysis teams and combined using the CL$_{\rm s}$ technique [8] to find the expected limits on the cross-section multiplied by the branching fractions. Candidate information was not included, and so the combined observed limit is not presented; only the sensitivity calculations are performed [1].

2.1 The $W^{\pm}H \to \ell^{\pm}\nu b\bar{b}$ Channel

The $W^{\pm}H \to \ell^{\pm}\nu b\bar{b}$ analysis selects events satisfying the signal topology requirements by requiring the presence of a high-p_t lepton, missing transverse energy, and two jets, at least one of which has a b tag. The results of this search are described in [3]. The reconstructed mass distribution in the single-tagged analysis is used in computing the expected limits, with each bin counted as an independent counting experiment. Systematic errors are taken on the background and signal rates, but the shapes are not varied. Each bin is assumed to have fully correlated systematic uncertainties with all other bins of the mass distribution, and correlations between the sources of uncertainty in this channel and those of other channels are taken into account.

The median expected cross-section times branching ratio limit is shown in Figure 3 as a function of m_H, along with the calculation in [3], and compared to the SM expectation. The calculations of the expected limit are similar, even though a median expectation with $\mathrm{CL_s}$ was used in this case while [3] uses a Bayesian calculation. An exercise was done breaking the signal and background estimations into two disjoint subsets, one subset consisting of events with just one b-tag, and the other subset with events with two b-tags. Figure 4 shows the median expected rate limits for the single-tag analysis as compared to the combination of the single and double-tagged subsets, showing an approximately 10% improvement for the latter case.

2.2 The $ZH \to \nu\bar{\nu}b\bar{b}$ Channel

The $ZH \to \nu\bar{\nu}b\bar{b}$ analysis selects events with a large amount of missing transverse energy and two jets, at least one of which must have a b tag. Additional kinematic requirements and lepton vetoes reduce the QCD background and backgrounds with electroweak gauge bosons present. The results of this search are described in [4]. The numbers of events for the expected signal and background after a mass window cut which moves with the Higgs boson mass under test are used to compute the sensitivity. They are linearly interpolated between the model points listed in [4].

The median expected cross-section times branching ratio limit is shown in Figure 5 as a function of m_H, along with the calculation in [4], and compared to the SM expectation. The

[1] The observed limits for each of the channels is close to the expected limit and so the combined observed limit is expected to be similar to expectations as well. The $ZH \to \ell^+\ell^- b\bar{b}$ channel is still in its blind phase.

calculations of the expected limit are similar, even though a median expectation with CL_s was used in this case while [4] uses a Bayesian calculation.

2.3 The $ZH \to \ell^+\ell^- b\bar{b}$ Channel

The $ZH \to \ell^+\ell^- b\bar{b}$ analysis selects events which have two charged leptons e or μ of opposite sign; the invariant mass of the dilepton pair is required to be consistent with m_Z. Two or three jets may be present in the event, at least one of which must be b-tagged. The results of this search are described in [7]. The neural net output distribution for the signal and background was used as the discriminant variable. Each bin of the neural net output histogram was considered as a separate search channel.

The median expected cross-section times branching ratio limit is shown in Figure 6 as a function of m_H compared to the SM expectation. The NN output histograms were provided at only one value of m_H and so the limit on the cross-section times the branching ratio is constant, at 2.2 pb.

2.4 The $gg \to H \to W^+W^-$ Channel

The results of the $gg \to H \to W^+W^-$ search are described in [5]. The histograms of $\Delta\phi_{\ell\ell}$ are used as the discriminant variable input to the limit calculation – each bin is a separate counting experiment. The shapes are interpolated [9] between m_H points, as are the signal rates and background rates. The analysis uses m_H-dependent cuts, and so the background rates depend on the m_H under test.

2.5 The $W^\pm H \to W^\pm W^+W^-$ Channel

The results of the $W^\pm H \to W^\pm W^+W^-$ search are described in [6]. It is a single counting experiment – there are no discriminant variables whose histograms have different s/b ratios to use. The acceptance is interpolated between the m_H points listed in [6].

The median expected cross-section times branching ratio limit is shown in Figure 8 as a function of m_H compared to the SM expectation and to the computation of [6].

2.6 Sensitivity to $m_H = 115$ GeV

Table 2 lists the median expected limits on the production cross section multiplied by the Higgs boson decay branching ratio for a Higgs boson of mass $m_H = 115$ GeV. These expected limits give an idea of the relative importance of each of the channels to the sensitivity of the combined search.

3 Sensitivity of the Channels when Combined

The CL_s method is used on the collection of the five SM Higgs search channels to compute the multiplicative scale factor s_{95} on the total signal which can just barely be expected to be excluded in a median experimental outcome. This procedure doesn't make much physical sense, as there isn't a well-motivated physical model which scales all of the production mechanisms for SM Higgs bosons in the same way, but it provides a technical benchmark of how far we are from the SM in our sensitivity. The results of this combination are shown in Figure 9. It must be shown as a multiplicative factor of the SM prediction because of the different SM predictions used for each search channel.

The signal and background rates in each channel are scaled so that they all correspond to the expectations in 300 pb^{-1}. Figure 10 shows the expected rate limit compared to the SM prediction after the luminosities have been scaled together, and showing the effect of including and ignoring systematic uncertainties.

Figure 11 shows the luminosity requirements for 95% CL exclusion, 3σ evidence and 5σ discovery, for the five CDF channels combined, with the acceptances, resolutions, backgrounds, and uncertainties as they stand today, except that systematic uncertainties are expected to scale inversely with the square root of the integrated luminosity. The band widths indicate the effect of taking into account and ignoring systematic uncertainties. For a Higgs boson with $m_H = 115$ GeV, it takes approximately 46 fb^{-1} to expect to exclude it at the 95% CL in a median experiment with the channels that we have now. Ignoring systematic uncertainties, it would take 37 fb^{-1} to exclude a 115 GeV SM Higgs boson in a median experiment assuming a Higgs boson is not actually present. This latter number is for more direct comparison with the predictions of the HSWG [2].

4 Necessary Channel Improvements

The current channels as we have them are insufficient to test for the presence or absence of the Standard Model Higgs boson. Improvements must be made to increase the acceptance, reduce the background, and to separate the selected events into disjoint subsets with different s/b ratios, and to combine them together. Furthermore, the results must be combined with D0's results.

The Higgs Sensitivity Working Group report [2] lists changes which can be made to the analyses which can get us to the desired level of sensitivity. Much of this work has already been done to improve our resolutions – to increase our lepton acceptance to the forward region, and to develop neural nets, although this work has not yet been incorporated into the Higgs boson searches.

The factors on the expected amount of luminosity needed to get exclusion at the 95% CL, 3σ evidence and 5σ discovery can be estimated for most of the improvements. For acceptance increases, the backgrounds are expected to increase faster than the signal increases, because as we expand our acceptance to forward regions of the detector or to include leptons of lower quality, a larger fraction of background is expected to creep in. For this estimation, the estimations are taken from the HSWG report's Sections 2.3 and 4.2 (for the Neural Net factor). A listing of improvements and their factors in luminosity is given in Table 3. For the HSWG note, systematic uncertainties were neglected. In Table 3, this factor is listed, but it is not meant that this factor can be regained. It is already assumed in the luminosity projections that the systematic uncertainties will scale inversely with the square root of the integrate luminosity. Furthermore, accounting of the shape uncertainties may make the systematic errors larger.

Dijet Mass Resolution Improvements in the resolution of the reconstructed invariant mass of two jets containing B hadrons affects the $W^{\pm}H \rightarrow \ell^{\pm}\nu b\bar{b}$, $ZH \rightarrow \nu\bar{\nu}b\bar{b}$ and $ZH \rightarrow \ell^{+}\ell^{-}b\bar{b}$ channels' sensitivity, and thus, the combination in the same way. The amount of luminosity required to exclude or discover a Higgs boson scales linearly with the width of the reconstructed mass peak in signal events. The current resolution is estimated at approximately 17%, and the target resolution [2] is 10%, for a factor of 1.7 in luminosity. An initial version of an algorithm combining tracks and calorimetry is already available at CDF and is currently being tested.

The dijet mass resolution in double-b-tagged events is already seen to be better than that in the single-tagged sample, due to combinatoric effects, and this narrower resolution for this subsample has not been included in the sensitivity calculation.

Neural Nets In [2], D0 estimated that applying a Neural net to the $ZH \rightarrow \nu\bar{\nu}b\bar{b}$ channel reduces the required luminosity for exclusion or discovery by a factor of 1.75. A similar study was done for the $W^{\pm}H \rightarrow \ell^{\pm}\nu b\bar{b}$ channel, bearing out the same conclusion. Neural nets allow the introduction of additional discriminating information which can separate the signal from the backgrounds, and variables which are not distinguishing enough to cut on can still contribute. It is anticipated that using a neural net output histogram instead of the dijet mass histogram as the input to the limit-setting procedure will make optimal use of the varying degrees of separation of signal from background as a function of the neural net output.

A neural net has already been included in the $ZH \rightarrow \ell^{+}\ell^{-}b\bar{b}$ channel's contribution to the sensitivity. An exercise was done in which the required luminosity for discovery and exclusion were computed for this channel alone in two cases – using the neural net output histogram in the limit-setting procedure, and using the dijet mass histogram in the limit-setting procedure. It was found that the neural net reduced the required luminosities by a factor of 2.0 relative to the dijet-mass-only case. This observation gives us further confidence in the gains expected in the other channels when neural nets are employed. The neural-net factor for the $ZH \to \ell^+\ell^- b\bar{b}$ channel is set to unity here since the neural net is already included in the sensitivity calculation presented here.

Track-Only Leptons This factor of 1.4 in acceptance is estimated in [2], and corresponds to including events with two jets, a b tag, missing transverse energy, and one high-p_t isolated track. A large fraction of the $W^\pm H \to \ell^\pm \nu b\bar{b}$ signal have $W \to \tau\nu_\tau$ decays, and the single track in the dominant one-prong tau decays is often a hadron. Furthermore, electrons and muons may simply not be identified as such due to the detector acceptance. Addition of track-only lepton candidates will recover many of these signal events. It is anticipated that additional backgrounds will be present in this sample. In order to preserve the s/b ratio of the existing sample of data without diluting it by adding in events selected with the track-only lepton requirements, it is recommended that these events be analyzed as a separate channel. The trigger and the background estimation tools are expected to be similar to those of the $ZH \to \nu\bar{\nu}b\bar{b}$ channel.

Since the $ZH \to \ell^+\ell^- b\bar{b}$ channel currently relies heavily on lepton identification for two lepton candidates, it is anticipated that expanding the acceptance to include track-only leptons in this channel will improve the sensitivity even more. An additional channel, in which the Z decays to a pair of tau leptons, would increase the acceptance (but also at a cost of increased background, so it should be treated as a distinct channel with different s/b).

Including *WH* signal in the *ZH* search Sometimes the lepton in $W^\pm H \to \ell^\pm \nu b\bar{b}$ signal events escapes into an uninstrumented region, or remains unidentified, buried inside a jet. A simple improvement to what was done for the summer is to see how many $W^\pm H \to \ell^\pm \nu b\bar{b}$ events are expected to be selected by the $ZH \to \nu\bar{\nu}b\bar{b}$ selection cuts. In the future, as a track-only lepton sample separated and forward leptons are added, the requirement of non-overlap means that some signal will be merely reclassified from one channel to another as we learn more about their kinematics. We must include all of the expected signal contributions that are there of course.

Forward Leptons This factor of 1.3 also comes from [2], and represents the additional acceptance for signal events in the $W^\pm H \to \ell^\pm \nu b\bar{b}$ channel. It is expected to enhance the $ZH \to \ell^+\ell^- b\bar{b}$ channel's acceptance as well but will not have an effect on the $ZH \to \nu\bar{\nu}b\bar{b}$ (except perhaps to remove some overlapping signal). The rapidity distribution of the leptons in $Wb\bar{b}$ background events is more spread out to the forward regions than those in the WH signal. The s/b ratio is expected to be lower for events identified with a forward lepton, and the expected higher rate of fake leptons in the forward region makes the problem more challenging. It may be prudent to treat events selected with a forward lepton in a separate sample due to the lower s/b in this sample.

B-tag improvements Loose b tags, tight b tags, ultra-tight b tags, and neural net b tags are available for use in CDF. The only option that has been explored in the existing channels which require b-tagging is the use of a single tight tag. Mixtures of single and double tags with varying degrees of tag quality allow the selected sample of events to be split up into subsets of varying s/b. When combined statistically to form exclusion limits or discovery figures of merit, these samples contribute more sensitivity than if they are simply added arithmetically in bins of another variable, such as the dijet mass. It is anticipated that the most powerful use of b-tagging information is to include the output of b-tag neural networks as inputs in the channel selection neural networks.

We have computed in the $W^{\pm}H \to \ell^{\pm}\nu b\bar{b}$ the expected gain in sensitivity when the sample is split into two subsamples: events with only one b-tag and events with two b-tags. A factor of 1.2 is obtained in the expected luminosity from this procedure.

It has also been found that requiring one tight b-tag plus an additional loose b-tag on the other jet actually reduces the sensitivity of the search as compared to requiring just one tight b-tag on one jet and making no requirement on the other. A more optimal strategy may be to split the sample into several pieces: tight-tight, tight-loose, tight-no-tag, loose-loose, and loose-no-tag. A neural-net b-tagger output variable for both jets will allow even finer gradations in b-tag quality which can help us separate subsamples with different s/b.

Forward b-tagging The loss of acceptance in the z-side of many of the silicon ladders which cover the forward region of CDF has reduced the expected improvement due to forward b-tags. Additional b-tagging acceptance affects the subsamples in different ways – a double-tagged subsample will gain more rapidly from extended b-tag acceptance than a single-tagged sample. Forward b-tags are expected to have a higher fraction of non-b contamination than central b-tags, and so an optimization is needed on the information from the other jet's b-tag in the case that one jet has a forward b-tag.

Cut optimization Further optimizations of analysis cuts before the neural network step can help separate signals from backgrounds. Vetoes on additional leptons and jets need to be studied, as well as fiducial cuts on energies and angles of reconstructed objects. The neural nets under study now are in development, and new variables are constantly being sought. There is also freedom in which subsamples to train the neural nets on, and how many neural nets to train.

Combination with D0 A factor of 2.0 in luminosity is expected to be gained by combining CDF and D0's Higgs search results.

Additional Factors Some factors have not been included in Table 3. These include the gains expected by including $H \to \tau$ decays in the VH channels, improvements in the performance of the central b-tagging, further cut optimization, and improved resolution on the missing transverse energy. We also plan on extending the $gg \to H \to W^+W^-$ channel's coverage down to $m_H = 110$ GeV or lower.

5 Expected Sensitivity

The luminosity factors described here affect different the search channels in different ways, and some are difficult to estimate before the tools are fully brought to use. Some factors do not multiply together naively, such as the improvement due to track-only leptons and the improvement due to forward leptons, as there is insufficient forward tracking.

A naive geometric mean of the factors from the analysis improvements is approximately 20. This means that we should be able to, when combined with D0, to exclude a SM Higgs boson of mass $m_H = 115$ GeV at the 95% CL in a median experimental outcome, in approximately 2.4 fb^{-1} of data, if all of these improvements are implemented. This scale factor multiplies the luminosity needed for exclusion, 3σ evidence, and 5σ discovery approximately equally, due to the large numbers of events at high integrated luminosities and the fact that the statistical fluctuations are approximately Gaussian.

References

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Channel	$\int \mathcal{L}dt$ (pb^{-1})	Reference
$W^{\pm}H \to \ell^{\pm}\nu b\bar{b}$	319	[3]
$ZH \to \nu\bar{\nu}b\bar{b}$	289	[4]
$gg \to H \to W^+W^-$	184	[5]
$W^{\pm}H \to W^{\pm}W^+W^-$	194	[6]

Table 1: Integrated luminosities by channel.

Channel	Expected Limit on $\sigma\times$Br [pb^{-1}]	SM $\sigma\times$Br [pb^{-1}]	ratio
$W^{\pm}H \to \ell^{\pm}\nu b\bar{b}$	6.14	0.136	45
$ZH \to \nu\bar{\nu}b\bar{b}$	3.77	0.079	48
$ZH \to \ell^+\ell^-b\bar{b}$	2.14	0.079	27
$W^{\pm}H \to W^{\pm}W^+W^-$	14.9	0.015	993
Combined			19.1

Table 2: Median expected limits on the production rate times the relevant decay branching ratio for the CDF Higgs boson search channels which are sensitive to a test mass $m_H = 115$ GeV, compared against SM predictions. The ratio in the last column is the expected limit divided by the SM prediction. The cross section is the $p\bar{p} \to VH$ cross section, and the branching ratio is only the $H \to b\bar{b}$ branching ratio, or the W^+W^- branching ratio, in the case of the $W^{\pm}H \to W^{\pm}W^+W^-$ channel. The integrated luminosities are given in Table 1; the $ZH \to \ell^+\ell^-b\bar{b}$ channel is taken to have 300 pb^{-1} of integrated luminosity. The combination is done assuming all channels have 300 pb^{-1} of integrated luminosity.

Improvement	$W^{\pm}H \to \ell^{\pm}\nu b\bar{b}$	$ZH \to \nu\bar{\nu}b\bar{b}$	$ZH \to \ell^+\ell^-b\bar{b}$
m_H Resolution	1.7	1.7	1.7
Neural Nets	1.75	1.75	1.0
Forward Leptons	1.3	1.0	1.6
Track-Only Leptons	1.4	1.0	1.6
Forward B-tags	1.1	1.1	1.1
Continuous b-tags	1.5	1.5	1.5
WH events in ZH	1.0	2.7	1.0
Product of above	9	13	7
CDF+D0 Combination	2.0	2.0	2.0
Combined Product	18	27	14

Table 3: Luminosity factors expected from analysis improvements.

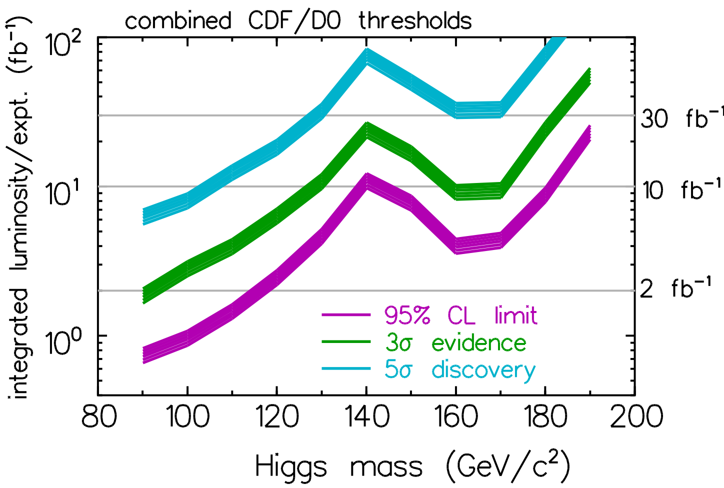

Figure 1: SUSY/Higgs Working Group estimations of the luminosity required for 95% CL exclusion, 3σ evidence, and 5σ discovery for the combined CDF+D0 search channels. (2000).

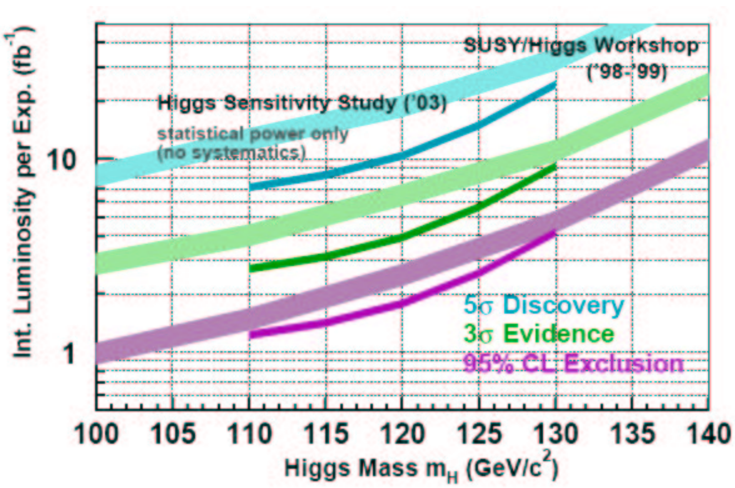

Figure 2: Higgs Sensitivity Working Group estimations of the luminosity required for 95% CL exclusion, 3σ evidence, and 5σ discovery for the combined CDF+D0 search channels, compared against the earlier SUSY/Higgs Working Group's calculation.

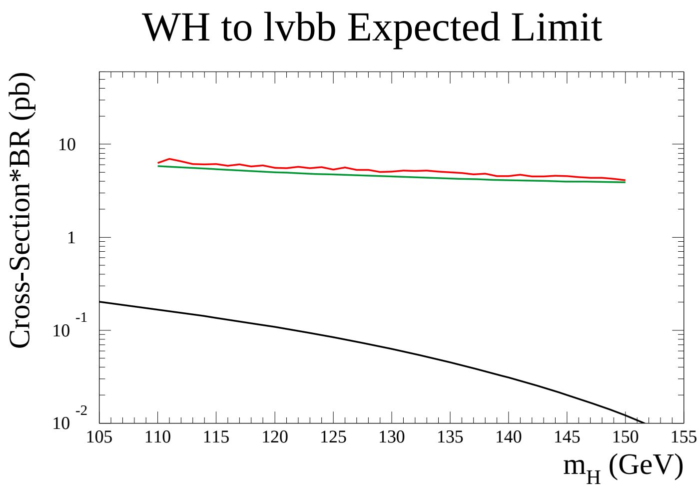

Figure 3: The expected limit on the production cross-section times the Higgs decay branching ratio as a function of m_H for the $W^{\pm}H \to \ell^{\pm}\nu b\bar{b}$ channel. The $\mathrm{CL_s}$ calculation is compared against that of [3] and the SM prediction.

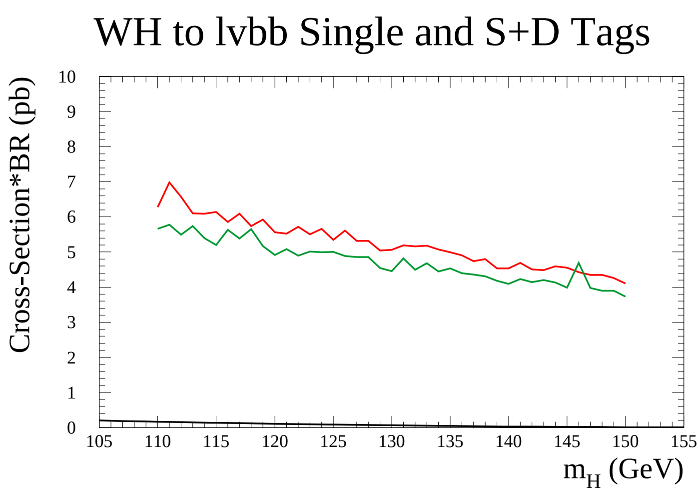

Figure 4: The expected limit on the production cross-section times the Higgs decay branching ratio as a function of m_H for the $W^{\pm}H \to \ell^{\pm}\nu b\bar{b}$ channel, assuming the absence of a Higgs boson. The expected limits are shown separately for the current single-tagged analysis [3] and a combination of disjoint single-tag and double-tag subsamples. The SM prediction is shown as the black solid line at the bottom.

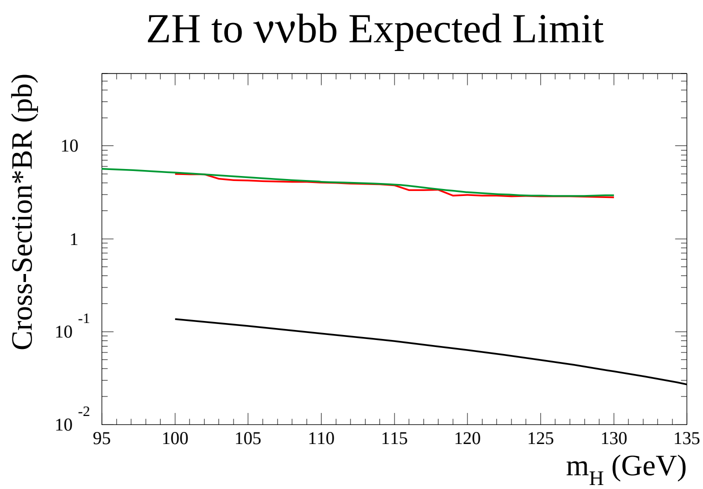

Figure 5: The expected limit on the production cross-section times the Higgs decay branching ratio as a function of m_H for the $ZH \to \nu\bar{\nu}b\bar{b}$ channel, assuming the absence of a Higgs boson. The $\mathrm{CL_s}$ calculation is compared against that of [4] and the SM prediction.

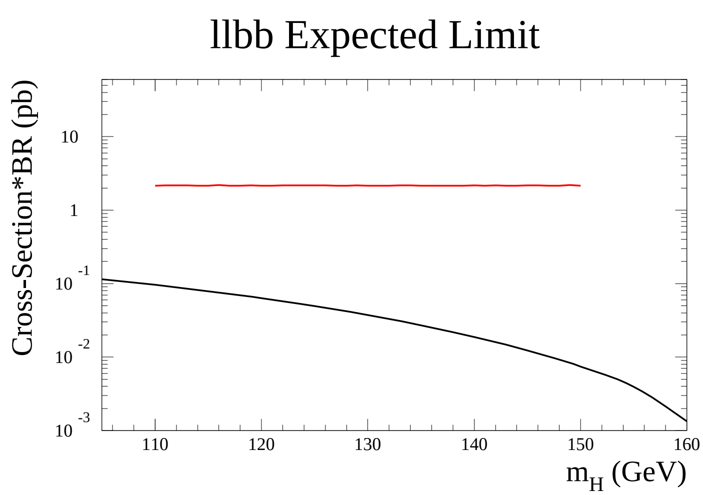

Figure 6: The expected limit on the production cross-section times the Higgs decay branching ratio as a function of m_H for the $ZH \to \ell^+\ell^- b\bar{b}$ channel, assuming the absence of a Higgs boson. The $\mathrm{CL_s}$ calculation is compared against that of [7] and the SM prediction.

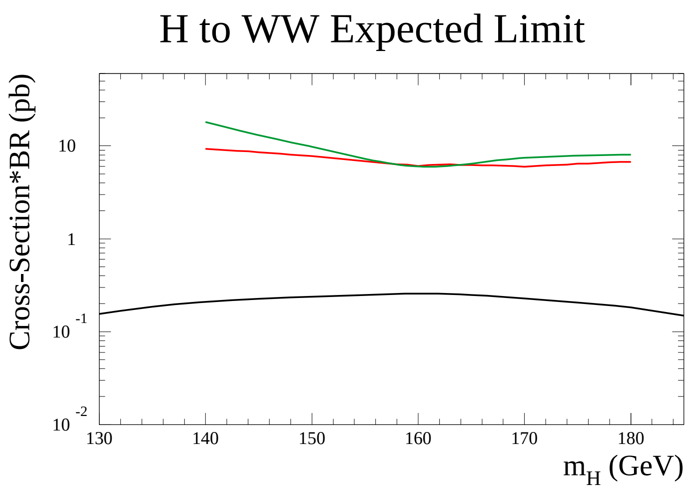

Figure 7: The expected limit on the production cross-section times the Higgs decay branching ratio as a function of m_H for the $gg \rightarrow H \rightarrow W^+W^-$ channel, assuming the absence of a Higgs boson. The $\mathrm{CL_s}$ calculation is compared against that of [5] and the SM prediction.

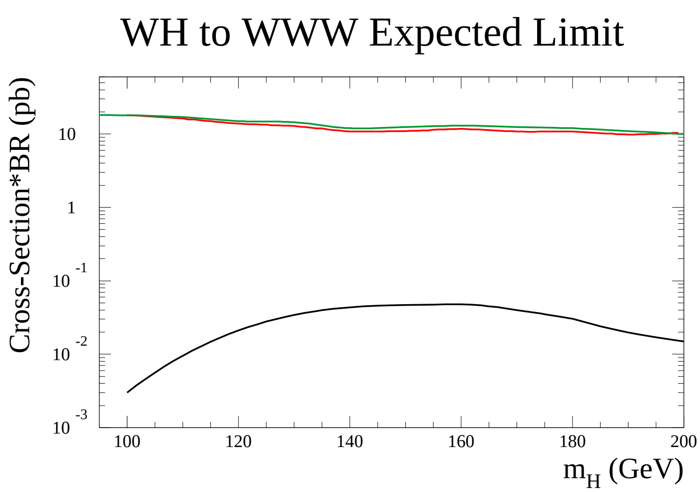

Figure 8: The expected limit on the production cross-section times the Higgs decay branching ratio as a function of m_H for the $W^{\pm}H \rightarrow W^{\pm}W^+W^-$ channel, assuming the absence of a Higgs boson. The $\mathrm{CL_s}$ calculation is compared against that of [6] and the SM prediction.

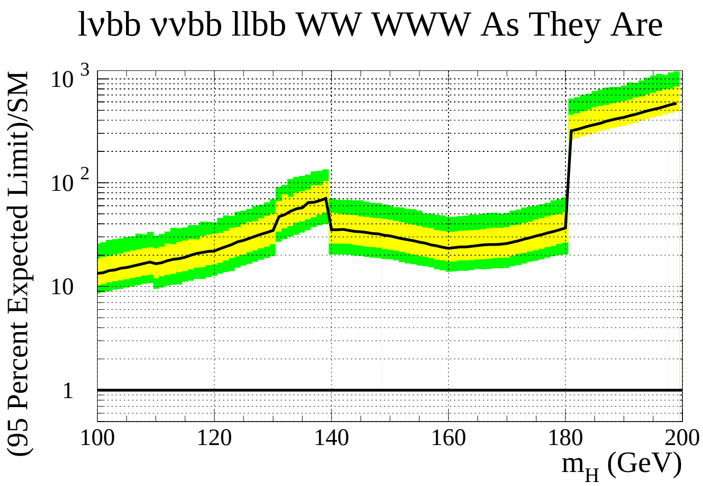

Figure 9: The expected limit on the multiplicative scale factor of SM Higgs boson production for all five channels combined, as a function of m_H, assuming the absence of a Higgs boson. The yellow and green bands show the $\pm1\sigma$ and $\pm2\sigma$ expectations, which fluctuate depending on the possible data which may be observed.

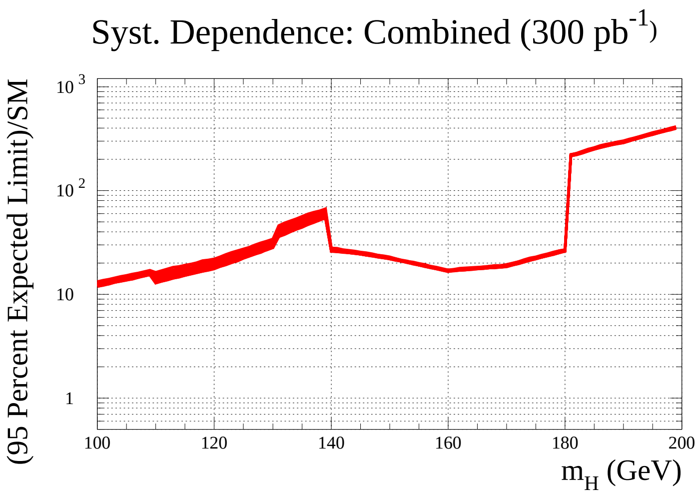

Figure 10: The expected limit on the multiplicative scale factor of SM Higgs boson production for all five channels combined, as a function of m_H. Each channel's signal and background expectations have been scaled to 300 pb^{-1}. The width of the bands shows the effect of including or ignoring systematic uncertainties.

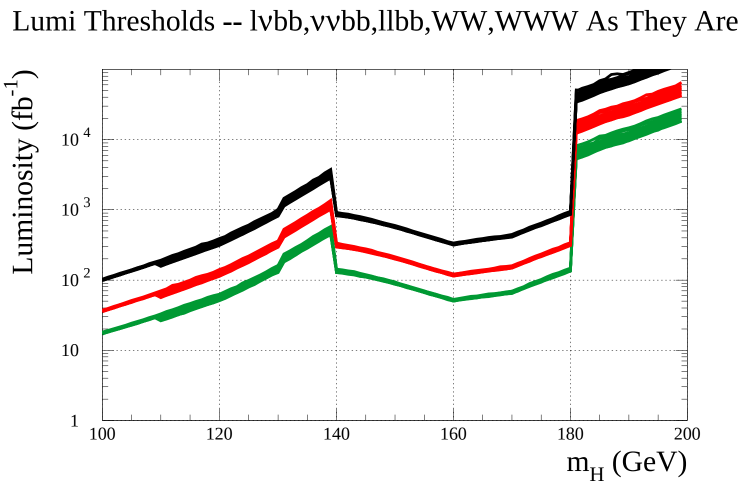

Figure 11: Calculation of the luminosity required for 95% CL exclusion, 3σ evidence, and 5σ discovery for the five CDF search channels combined. These do not take into account the expected improvements to the channels' sensitivity discussed in Section 4. Without improvements, and with only CDF channels, it would take 48 fb^{-1} to exclude at 95% CL a Higgs boson with $m_H = 115$ GeV, assuming it's not there. With the sensitivity improvements, and in combination with D0, it will take 2.4 fb^{-1} of integrated luminosity to exclude at 95% CL a Higgs boson with $m_H = 115$ GeV, similar to the expectation in [1].