Tevatron Higgs Results

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Abstract. We present the latest results of searches for the production of Higgs bosons at the Tevatron collider in the D0 and CDF experiments. Cross section times branching ratios have been measured in many different topological channels and have been interpreted in both the standard model and other models. No evidence for the production of Higgs bosons has been observed, but limits have been set. The D0 and CDF searches in the standard model have been combined and for the first time we set limits on the production of standard model Higgs bosons in the mass range of 160 GeV to 170 GeV at the 95% confidence level.

Keywords: Higgs Boson, Hadron Collider, Tevatron
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INTRODUCTION

The collider experiments at the Tevatron Run 2 [1], D0 [2] and CDF [3], have been collecting data from proton anti-proton collisions at a center of mass energy of 1.96 TeV since 2001. We have been using this data to shed light on the Higgs mechanism [4] and the origin of mass. As of today, there have been no direct observations of a Higgs boson. Until recently, the best direct limits on the production of a Higgs boson predicted by the standard model [5, 6] come from the LEP experiments [7], namely that the mass of this particle must be larger than 114 GeV at the 95% confidence level. For the first time, recent analyses of Run 2 data by D0 and CDF have led to direct limits on the mass of the standard model Higgs boson, excluding at the 95% C.L. the region between 160 GeV and 170 GeV. Limits have also been placed on Higgs bosons in two-doublet models, such as the minimal supersymmetric standard model [8]. These results are summarized below.

DATA SETS

As of the time of this writing, the Tevatron experiments have collected over 6 pb^{-1} of integrated luminosity since the beginning of Run 2 [9] (see Figure 1). The various different analyses from the two experiments use different amounts of data depending on things such as the status in certain runs of the particular subdetectors needed for that channel, and the reprocessing of data at the time of the analysis. The D0 and CDF Higgs

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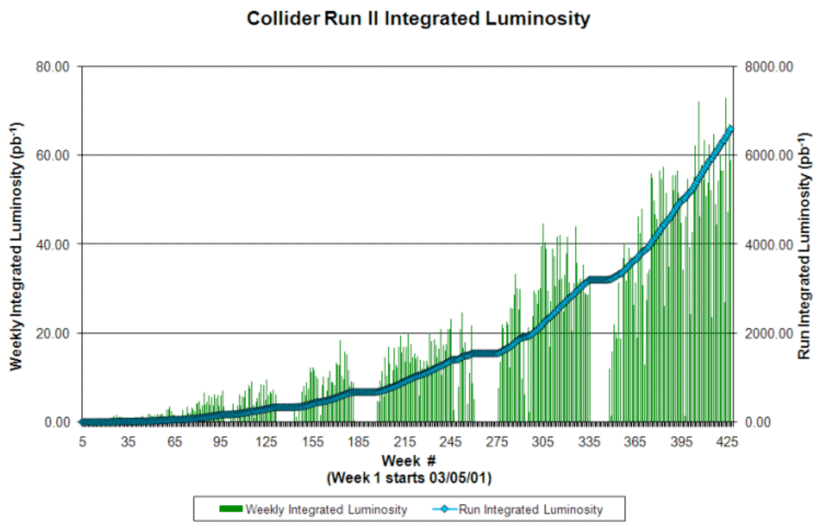

FIGURE 1. Luminosity delivered to each experiment by the Run 2 Tevatron [9]. At the time of this writing, both D0 and CDF have collected over 6 pb^{-1} of data. The Tevatron continues to perform exceptionally well, delivering data at an increasing rate.

searches use between 1 and 4 fb^{-1} of integrated luminosity, depending on the analysis, as shown in Table 1.

TABLE 1. Integrated luminosities used by the various analyses summarized in these proceedings.

Analysis	Integrated Lumi. (fb^{-1}) for D0, CDF
$WH \to \ell \nu b\bar{b}$	2.7, 2.7
$ZH \to \ell^+\ell^- b\bar{b}$	3.1, 2.7
$ZH \to \nu\bar{\nu} b\bar{b}$	1.2, 2.1
$H \to \gamma\gamma$	4.2, –
$W/Z + H \to qqbb$	–, 2.0
$t\bar{t}H \to t\bar{t}b\bar{b}$	2.1, –
$gg \to H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	3.0-4.2, 3.6
$gg \to h, A \to \tau^+\tau^-$	1.0-2.2, 1.8
$gb \to bh, bA \to bb\bar{b}$	1.9, 2.6

Both experiments have detailed simulations of their detectors based on the GEANT3 package [10]. Descriptions of the individual event generators used for each analysis can be found in the reference to that given analysis, but for the most part, both experiments rely heavily on the PYTHIA generator [11] for standard model Higgs signals, ALPGEN [12] and PYTHIA for backgrounds involving top, or electroweak bosons, and other generators such as MC@NLO [13] and COMPHEP [14] for other backgrounds. Backgrounds involving multijet final states are typically measured in the data. These event generators are used to model the kinematic distributions of the processes, whereas the cross sections and Higgs branching ratios are taken from other calculations.

STANDARD MODEL HIGGS SEARCHES

The current limit on the mass of the standard model Higgs boson, $m_H > 114$ GeV at 95% C.L., sets the approximate starting point for the Tevatron searches. Since this mass is not predicted by the standard model, we try to cover as much of the phase space of potential production and decay modes as possible. By now, the Tevatron analyses are quite sophisticated and comprehensive, and between the two experiments there are more than 70 independent channels.

Electroweak Fits

Besides the direct mass limits from LEP, combined electroweak fits by the LEP Electroweak Working Group [15] put an upper limit on the mass of the standard model Higgs boson. If the direct limits from LEP are taken into account during the fit, shown in Figure 2, the upper limit on the Higgs mass is $m_H < 191$ GeV. Combined searches

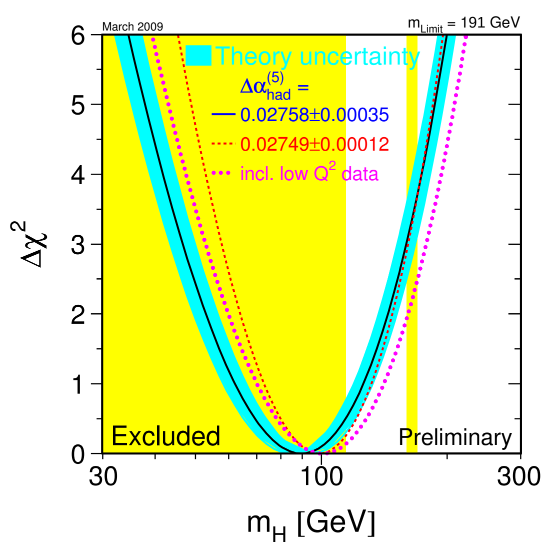

FIGURE 2. Latest (March 2009) combined electroweak fits from the LEP Electroweak Working Group. Taking into account the direct limits from LEP on m_H, the fit puts an upper limit on the mass of the standard model Higgs boson of $m_H < 191$ GeV at 95% C.L. [15].

from D0 and CDF, which will be described in the following section, are now beginning to constrain the standard model Higgs mass as well.

Direct Searches

No single channel alone is currently able to discover or exclude (at 95% C.L.) the standard model Higgs in the D0 and CDF searches. It is only by taking advantage of the full information from the many complementary channels from both experiments that we are able to put direct limits on the mass of the Higgs. The basic strategy is to be as efficient and comprehensive as possible in our search channels. In the $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, the standard model Higgs could be produced in a variety of ways and decay into a variety of particles, as shown in Figure 3.

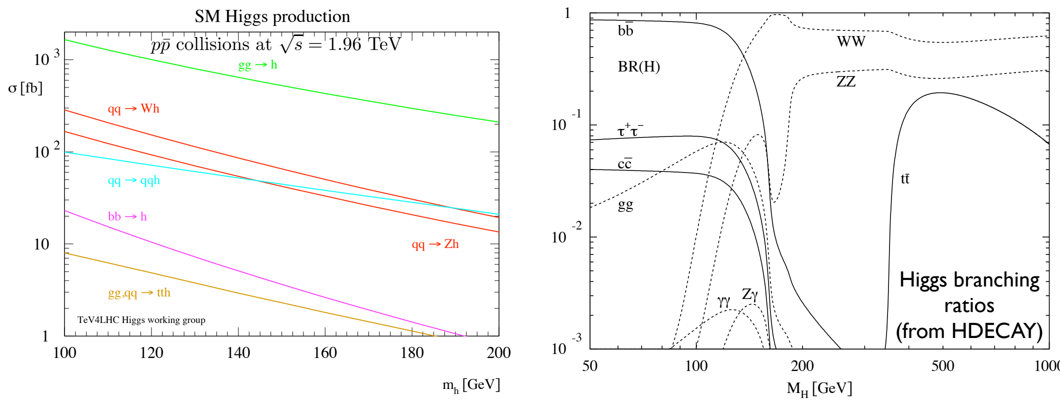

FIGURE 3. Cross sections [16] and branching ratios [17] of the standard model Higgs at the Tevatron.

These searches seek to take advantage of signals from Higgs bosons produced in association with vector bosons, $q\bar{q} \to WH, ZH$, through gluon fusion, $gg \to H$, and through vector boson fusion, $q\bar{q} \to q'\bar{q}'H$. In the mass range studied, 100 GeV to 200 GeV, the following important decay modes are used: $H \to b\bar{b}$; $H \to W^+W^-$; $H \to \tau^+\tau^-$; and $H \to \gamma\gamma$.

The identification of "b-jets" coming from the decay of the Higgs vastly improves the signal sensitivity in the $H \to b\bar{b}$ channels. CDF uses a secondary vertex tagger [18] or a probability built from the confidence level that all tracks in the jet are consistent with the primary vertex [19], whereas D0 uses an artificial neural network with inputs from the vertex information, impact parameters of the tracks in the jet and other kinematic information about the jet [20]. In the "W plus 2 jets" channel in D0, for instance, by requiring two b-tags, we improve the signal to background ratio by a factor of 30. These b-tag algorithms are used in the standard model and beyond the standard model searches with Higgs decays into b quarks.

In the $WH \to \ell\nu b\bar{b}$ channels, the signature is one high transverse momentum (p_T) charged lepton which is usually triggered on, missing energy from the neutrino, and b-tags. The CDF analysis [21, 22] requires the p_T of the lepton (electron or muon) to be greater than 20 GeV, the missing transverse energy ($\not\!\!E_T$) to be greater than 20 GeV, two jets with transverse energies greater than 20 GeV and $|\eta_{\text{jet}}| < 2$ and 1 or 2 b-tags. The D0 analysis [23] requires $p_T > 15$ GeV, $|\eta_e| < 2.5$, $|\eta_\mu| < 2$, $\not\!\!E_T > 20$ GeV, 2 or 3 jets > 25 or 20 GeV, $|\eta_{\text{jet}}| < 2.5$, and 1 or 2 b-tags. Backgrounds in these channels come from W with jets, multijet events, and top quark production. D0 uses a neural network to combine this event information and expects a limit of 6.4 times the standard model cross section ($\sigma_{\text{SM}}^{\text{Higgs}}$) for the mass hypothesis of $m_H = 115$ GeV and observes a limit of 6.7 times the standard model cross section. CDF uses a neural network to combine boosted decision tree and matrix element information and expects a limit of $4.8 \times \sigma_{\text{SM}}^{\text{Higgs}}$ and observes a limit of $5.6 \times \sigma_{\text{SM}}^{\text{Higgs}}$ for the same mass hypothesis. All of these and subsequent cross section limits are at the 95% C.L.

In the $ZH \rightarrow \ell^+\ell^- b\bar{b}$ channels, the signature is two high p_T charged leptons, 2 or more jets and b-tags. In the CDF analysis [24] the following requirements are made: $p_T > 18$ GeV for the lepton; $|\eta_e| < 2.8$; $|\eta_\mu| < 2.0$; 2+ jets $> 25, 15$ GeV; $|\eta_{\text{jet}}| < 2$; and b-tags are used to create 6 different samples with different signal to background. For the D0 analysis [25], the following is required: $p_T > 10$ GeV; $|\eta_e| < 2.5$; $|\eta_\mu| < 2.0$; 2+ jets $> 20, 15$ GeV; $|\eta_{\text{jet}}| < 2.5$ 1 tight or 2 loose b-tags. Backgrounds in this channel come mainly from Z with jets; multijet events and top production. D0 uses boosted decision trees to expect a limit of $8.0 \times \sigma_{\text{SM}}^{\text{Higgs}}$ for $m_H = 115$ GeV and observes a limit of $9.1 \times \sigma_{\text{SM}}^{\text{Higgs}}$. CDF uses neural a network to reject Zbb and top events and expects a limit of $9.9 \times \sigma_{\text{SM}}^{\text{Higgs}}$ for $m_H = 115$ GeV and observes a limit of $7.1 \times \sigma_{\text{SM}}^{\text{Higgs}}$.

In the $ZH \rightarrow \nu\bar{nu} b\bar{b}$ channel, the signature is two high p_T b-jets and large $\not{E}_T$. This analysis also accepts a large fraction of $WH \rightarrow \ell\nu b\bar{b}$ signal when the charged lepton is not found. Backgrounds come from top and Z or W with jets. The CDF analysis [26] requirements are: $\not{E}_T > 50$ GeV; 2+ jets $> 25, 20$ GeV; $|\eta_{\text{jet}}| < 2.0$; b-tags similar to WH analysis. The D0 requirements [27] are: $\not{E}_T > 50$ GeV; 2+ jets > 20 GeV; $\Delta\phi_{\text{jets}} < 165°$; $|\eta_{\text{jet}}| < 2.5$; b-tags like WH. D0 uses boosted decision trees and expects a limit of $8.4 \times \sigma_{\text{SM}}^{\text{Higgs}}$ for $m_H = 115$ GeV and observes a limit of $7.5 \times \sigma_{\text{SM}}^{\text{Higgs}}$. CDF, using a neural network, expects a limit of $5.6 \times \sigma_{\text{SM}}^{\text{Higgs}}$ and observes a limit of $6.9 \times \sigma_{\text{SM}}^{\text{Higgs}}$.

D0 has searched for the signature of $H \rightarrow \gamma\gamma$ which would appear as two high p_T photons that create an invariant mass equal to the Higgs mass. Backgrounds to these diphoton signals are Drell-Yan events with both electrons misidentified as photons, photon plus jet events and dijet events with jets misidentified as photons. No excess in diphoton events or a resonance are seen, with an expected limit of $18 \times \sigma_{\text{SM}}^{\text{Higgs}}$ and an observed limit of $13 \times \sigma_{\text{SM}}^{\text{Higgs}}$ for $m_H = 115$ GeV.

Searches for the standard model Higgs boson have also been performed by CDF [28] in the fully hadronic final states coming from $WH \rightarrow q\bar{q}' b\bar{b}$ and $ZH \rightarrow q\bar{q} b\bar{b}$. QCD background dominates this channel, but there are also sizable contributions from top, WZ and Wbb. Data driven methods are used to categorize the likelihood of an event coming from signal or a background process. No evidence of signal is seen, as in the other searches. An expected limit of $37 \times \sigma_{\text{SM}}^{\text{Higgs}}$ for $m_H = 115$ GeV is predicted while a limit of $38 \times \sigma_{\text{SM}}^{\text{Higgs}}$ is measured.

D0 searches for evidence of $t\bar{t}H \rightarrow t\bar{t}b\bar{b}$ [29]. In this channel, there are many b-jets in the final state (nominally four). Besides requiring 3 or more b-tags, D0 exploits the kinematic differences between the signal and the dominant background of $t\bar{t}$ production. With no excess over background predictions, an expected limit of $45 \times \sigma_{\text{SM}}^{\text{Higgs}}$ for $m_H = 115$ GeV is set, while the observed limit is $64 \times \sigma_{\text{SM}}^{\text{Higgs}}$.

In the higher mass regions with the Higgs decay into a pair of W bosons dominates, both experiments have performed very sensitive searches in the channels $gg \rightarrow H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$. The signature of these events is two oppositely signed charged leptons, $\not{E}_T$, and angular correlations between the leptons from spin correlation ($\Delta\phi_{\text{lep}}$ is a good discriminator). This channel is also sensitive to leptonic tau decay modes as well. Backgrounds come predominantly from Z/γ^* decays, top, diboson and W + jets as well as QCD events. The CDF analysis [30] requires the following: 0, 1 or 2 jets;

$p_T > 20, 10$ GeV for the leptons which must also have an opposite charge; invariant mass of the dilepton system (M_{ll}) > 16 GeV; $\not{E}_T$ along the lepton direction > 25 GeV for $ee, \mu\mu$ and > 15 GeV for $e\mu$. The D0 analysis [31] requires: $p_T > 10$ GeV for muons and $p_T > 15$ GeV for electrons; leptons oppositely charged; $M_{ll} > 15$ GeV; and some opening angle requirements. Despite this being the most sensitive channel at the Tevatron at the current time, no signal is observed. D0 expects a limit of $1.7 \times \sigma_{\rm SM}^{\rm Higgs}$ with an observed limit of $1.3 \times \sigma_{\rm SM}^{\rm Higgs}$ for $m_H = 165$ GeV. CDF expects a limit of $1.5 \times \sigma_{\rm SM}^{\rm Higgs}$ and observes a limit of $1.3 \times \sigma_{\rm SM}^{\rm Higgs}$ for this same mass hypothesis.

Tevatron Higgs Combination

Finally, the Tevatron New Phenomena and Higgs Working Group [32] has performed a global combination [33] of all the Higgs searches mentioned above. This combination uses 75 statistically independent final states from the searches above to set a limit on the production of the standard model Higgs using a Bayesian technique. As shown in

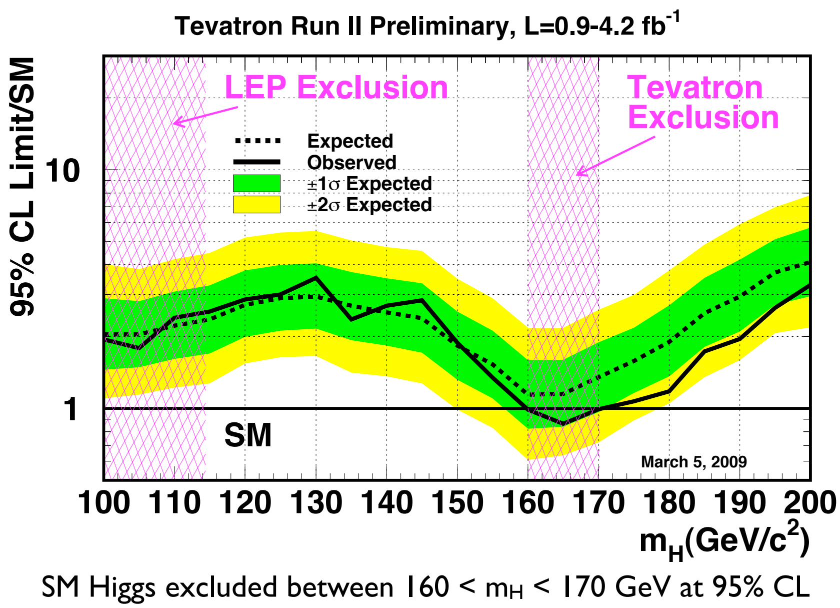

FIGURE 4. 95% confidence level upper limits on the ratio of the excluded cross section to the standard model cross section, $\sigma_{\rm SM}^{\rm Higgs}$. The observed limit is shown as the solid line, the median (background-only hypothesis) is shown as the dashed line. The green and yellow bands show the 68% and 95% probability regions where the limits can fluctuate in the absence of a signal [33].

Figure 4, the mass region between 160 GeV and 170 GeV is excluded at the 95% C.L.

NON-STANDARD MODEL HIGGS SEARCHES

Since we have never observed a Higgs boson, it is possible that if it exists, things are more complicated, or at least different, from what the standard model predicts. Very briefly, we discuss the D0 and CDF searches for Higgs production in the minimal supersymmetric standard model.

In this model, there are five physical Higgs particles: two neutral scalars (h and H); one pseudoscalar (A) and a charged pair ($H^{\pm}$). We only show results from the searches for h and A production in the decay modes involving τ leptons or b quarks. In the $\tau^+\tau^-$ final state, D0 [34] looks for inclusive tau tau events with at least one lepton decay. They use the invariant mass of the combined tau, tau, $\not\!\!E_T$ vectors to search for evidence of the signal. The CDF analysis [35] is similar to the D0 analysis and uses the invariant mass of the tau-tau system is used as a final variable. Both experiments have a tau trigger sensitive to events with one leptonic and one hadronic tau decay. Neither experiment see any evidence of a signal in these channels and set limits in the phase space of the mass of the A, m_A, and the ratio of the vacuum expectation values of the Higgs doublets, $\tan\beta$ in a couple benchmark scenarios. These limit plots can be found in the references cited above. The hadronic final state is also used, where the Higgs bosons would be produced in association with a b quark and then would decay into a pair of b-jets. This final state of three or four b-jets makes b-tagging very important to these analyses. Again, no evidence for these signals is found, but in fact high values of $\tan\beta$ are now ruled out for all values of m_A up to 200 GeV. These limit plots can be found in the D0 [36] and CDF [37] analyses. D0 also looks in the mode where the MSSM Higgs is produced in association with b quarks but then decays into a pair of taus [38]. These results will be combined together in a similar way as the standard model Higgs searches describe above, but at the time of this writing, a public result is not available.

CONCLUSION

CDF and D0 continue to perform a comprehensive program of searches for the production of Higgs bosons at the Tevatron. The Tevatron accelerator continues to perform very well, and both experiments look forward to continued data taking and exciting new results in the near future.

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