

Searches for a High-Mass Standard Model Higgs Boson at the Tevatron

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We present the results of searches for the Standard Model Higgs boson decaying predominantly to W^+W^- pairs, at a center-of-mass energy of $\sqrt{s}=1.96$ TeV, using up to 8.1 fb^{-1} of data collected with the CDF and D0 detectors at the Fermilab Tevatron collider. The analysis techniques and the various channels considered are discussed. These searches result in the first single experiment exclusion across the Higgs mass ranges of $[158,168]$ GeV and $[163,168]$ GeV for CDF and D0 respectively.

1 Introduction

The search for the mechanism of electroweak symmetry breaking and a Standard Model (SM) Higgs boson has been a major goal of particle physics for many years. Within the Higgs sector of the SM, the mass of the Higgs boson (m_H) is a free parameter. Constraints on m_H come from direct searches at the LEP experiments¹ which conclude that $m_H > 114.4$ GeV at 95% Confidence Level (CL), and indirect constraints using precision electroweak measurements which require $m_H < 185$ GeV at 95% CL².

Higgs searches at the Tevatron collider are a subject of intense study. By combining CDF and D0 results, the SM Higgs mass range between 158 and 175 GeV was excluded at 95% CL using up to 6.7 fb^{-1} of data³.

These proceedings present the status of the searches by CDF and D0 for a SM Higgs boson with $m_H \in [130, 200]$ GeV and using up to 8.1 fb^{-1} of data collected until the winter of 2010. All limits will be given at 95% CL

2 Higgs boson production and decays

At the Tevatron, the dominant production mode is via the gluon fusion process, $gg \rightarrow H$, with a cross section ranging between 840-190 fb for a Higgs mass between 130-200 GeV. The associated

production, $q\bar{q} \rightarrow VH$ ($V = W, Z$), and vector boson fusion, $q\bar{q} \rightarrow Hq\bar{q}$, processes with cross sections ranging between 180-32 fb and 57-22 fb respectively for the aforementioned Higgs mass range, are also considered in order to maximise the sensitivity of the searches.

For a Higgs mass $m_H > 135$ GeV, the main decay mode is to a pair of W bosons while for $m_H < 135$ GeV Higgs decays mainly to a pair of b-quarks. This distinction is what defines the high mass and low mass Higgs searches at the Tevatron.

3 Search channels

The high mass searches at CDF and D0 require at least one electron or a muon in the final state in order to suppress the QCD background. Given this requirement all possible decay modes are considered to maximise the signal acceptance. The di-lepton+missing transverse energy (E_T^{miss}) channel requires two electrons or muons (plus neutrinos) of opposite charge in the final state. This represents a small WW decay branching ratio, $\approx 6\%$ (including $\tau \rightarrow e, \mu$ decays), but a clean signature offering the highest sensitivity of all the high mass channels. Decays of one of the W bosons to a τ lepton and the other to an electron or muon, with a subsequent hadronic decay of the τ (τ_h) are also considered offering an additional branching ratio of $\approx 4\%$. The lepton+jets channel requires one W boson to decay hadronically and the other leptonically. This represents a significant WW decay branching ratio, $\approx 30\%$, however suffers from a large W+jets background. Dedicated $q\bar{q} \rightarrow VH$ searches are also performed by looking for the SM suppressed signature of at least two leptons (electrons, muons) with one same charge pair originating from leptonic decays of the three vector bosons in the final state.

4 Search strategy

The high mass analyses are each split into categories based on the reconstructed lepton flavour, quality or jet multiplicity. This is done in order to take advantage of the differences in the detector response between the various lepton types, and between the kinematics of the signal production mechanisms and the background processes.

As the signal final states contain neutrinos, selections based on large E_T^{miss} are used, also accounting for energy mis-measurements. D0 employs Multivariate (MVA) techniques at this stage to reduce low E_T^{miss} backgrounds while maximising signal acceptance, by taking advantage of the different correlations for signal and backgrounds between the input variables. Selecting events with a high MVA response score, improves the sensitivity by up to 30% compared to conventional square selections. Figure 1 shows the E_T^{miss} distribution for di-electron+ E_T^{miss} events and the response of the MVA trained against the large Z+jets background.

Even after all selections, the signal/background (S/B) ratio is still in the range of 0.1-1% for $m_H = 165$ GeV. This requires the use of MVA discriminants, either boosted decision trees or artificial neural networks, to provide further discriminating power by using their response to derive limits on the Higgs boson yield for the cases where no signal-like excess is observed.

4.1 Di-lepton+ E_T^{miss} channel

The signature of this channel is two high p_T oppositely charged isolated leptons and E_T^{miss} . A small angular separation, is also expected due to the spin-0 nature of the Higgs boson, which in turn gives rise to the spin-correlation between the final-state leptons. In contrast, leptons from the irreducible $Z \rightarrow WW$ background are predominantly back-to-back. Figure 2 shows the $\Delta R_{\ell\ell} = \sqrt{\Delta\phi_{\ell\ell}^2 + \Delta\eta_{\ell\ell}^2}$ distribution for a di-lepton+ E_T^{miss} data sample with zero reconstructed jets. Full use of this topological distinction is made by using variables such as $\Delta R_{\ell\ell}$ and $\Delta\phi_{\ell\ell}$ as inputs to the MVA discriminants. CDF also makes use of likelihood ratios constructed from

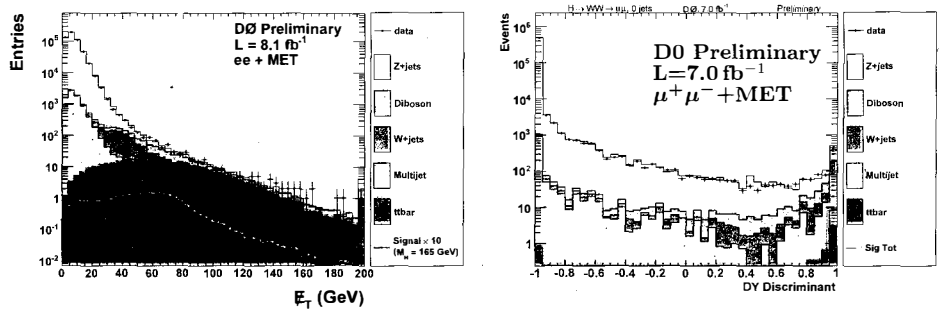


Figure 1: Left: Distribution of E_T^{miss} di-electron + E_T^{miss} events. Right: MVA discriminant trained to discriminate between signal and Z+jets in di-muon + E_T^{miss} events.

matrix-element probabilities as input variables to the MVA discriminants. Such a likelihood ratio is shown on the right plot of Figure 2.

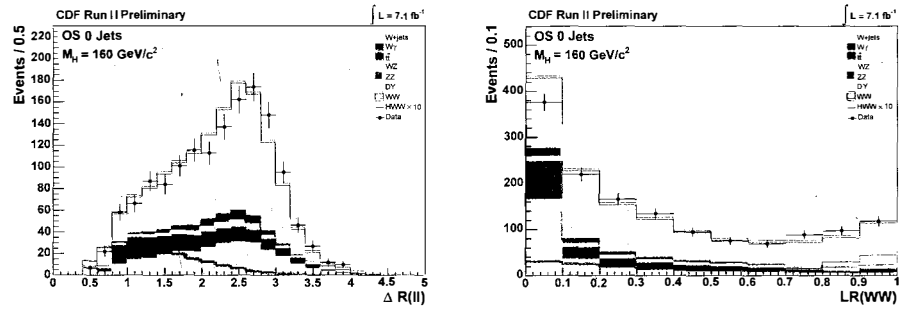


Figure 2: Left: $\Delta R_{\ell\ell}$ distribution in di-lepton + E_T^{miss} events. Right: Distribution of the matrix element likelihood ratio in di-lepton + E_T^{miss} events.

This channel is further split according to jet multiplicity into 0, 1 or more than 1 reconstructed jets in the final state. This enables the training of the MVA discriminant to focus on the different signal and background compositions in each of the jet multiplicity categories, such as WW for the 0 jet, Z + jets for the 1 jet and $t\bar{t}$ for the 2 jet where b-tagging information is used to suppress this background. The statistical analysis of the MVA final discriminant does not exhibit any excess with respect to the background expectations and limits are set. It is worth noting that the CDF limit was obtained including the same sign di-lepton and tri-lepton searches described in section 4.4 Using 7.1 and 8.1 fb^{-1} of CDF and D0 data respectively, the observed (expected) limits on the Higgs boson yield for $m_H=165$ GeV are for CDF $\sigma_{95} \sigma_{\text{SM}}=0.92(0.93)$ and D0 $\sigma_{95} \sigma_{\text{SM}}=0.91(0.97)$, excluding this mass hypothesis. It is worth noting that the CDF limit was obtained including the same sign di-lepton and tri-lepton searches and the di-lepton + E_T^{miss} with a τ_h as described in sections 4.2 and 4.4.

4.2 Di-lepton + E_T^{miss} channel with a τ_h

Additional signal acceptance can be obtained by considering hadronically decaying τ leptons from W decays. Muon(electron) + τ_h channels are a new addition to the D0 high mass program. In contrast to CDF, D0 splits these channels into ≤ 1 or > 1 jets due to the different signal

production mechanisms and background compositions. The ≤ 1 jet category does not include an electron+ τ_h final state due to the very large backgrounds and the > 1 jet is also part of the low mass Higgs searches.

Both CDF and D0 see no excesses with respect to the background expectation in the statistical analysis of the respective MVA discriminants and therefore set limits. Using 7.1 fb^{-1} of data CDF obtains an observed (expected) limit for $m_H=165 \text{ GeV}$ of $\sigma_{95} \sigma_{\text{SM}}=28.4(13.1)$. For the muon+ $\tau_h+E_T^{\text{miss}} \leq 1$ jet and using 7.3 fb^{-1} D0 obtains a corresponding observed (expected) limit of $\sigma_{95} \sigma_{\text{SM}}=6.6(6.8)$. The lepton+ $\tau+E_T^{\text{miss}} > 1$ jet uses 4.3 fb^{-1} of D0 data and obtains an observed (expected) limit for $m_H=165 \text{ GeV}$ of $\sigma_{95} \sigma_{\text{SM}}=12.4(12.3)$.

4.3 Lepton+jets channel

The signature of this channel is one isolated high p_T electron or muon, high E_T^{miss} and two high p_T jets⁴. For $m_H \geq 160 \text{ GeV}$, the Higgs decays to two on-shell W bosons, thus offering the ability to reconstruct the kinematics of the full event including the longitudinal momentum of the neutrino, up to a two-fold ambiguity. Although this signature suffers from large W+jets backgrounds, the large branching ratio of hadronic W boson decays provide 52 expected signal events surviving all selections in 5.4 fb^{-1} of D0 data. The statistical analysis of the MVA discriminant does not exhibit any excess with respect to the background expectation and limits are set. Using 5.4 fb^{-1} of data, D0 obtains an observed (expected) limit for $m_H=165 \text{ GeV}$ of $\sigma_{95} \sigma_{\text{SM}}=5.2(5.1)$.

4.4 Same charge di-leptons and tri-leptons

In these channels, the defining characteristic is the presence of at least two isolated high p_T electrons or muons which can form a pair of the same charge, and high E_T^{miss} . Charge misidentification can lead to a significant migration of opposite sign charge backgrounds into the same sign region. Therefore high quality tracking criteria are also required to suppress this instrumental background. CDF also requires the presence of at least 1 jet in the same charge di-lepton final state, since the decay of the third boson will most likely result in the production of an additional jet.

In contrast to CDF, D0 does not include a dedicated tri-lepton search. Tri-lepton events can occur naturally in $WH \rightarrow WWW$ events with all Ws decaying leptonically, or in $ZH \rightarrow ZWW$ where the Z and one of the Ws decay leptonically and the other hadronically. This distinction allows the separation of tri-lepton events into cases where the same flavour opposite sign leptons, form an invariant mass compatible to the Z mass or not. If a mass compatible to the Z mass is found, the probability that one of the Ws decayed hadronically, allows this channel to be further split by requiring one or more than one reconstructed jets in the event. If more than one jets are found then the event is fully reconstructed and the mass of the Higgs can be determined. CDF ensures orthogonality between the same charge di-lepton and tri-lepton search by vetoing the presence of a third lepton in the di-lepton case. As D0 has no dedicated tri-lepton search, no such veto is required. Figure 3 shows the invariant mass distributions in same charge di-lepton and tri-lepton events after all selections.

No excess was observed in the statistical analysis of same charge di-lepton and tri-lepton MVA discriminants, with respect to the background expectation, and thus limits are set. The same charge di-lepton and tri-lepton limits of CDF are combined with the the di-lepton+ E_T^{miss} searches of Section 4.1. The most sensitive channel is the same charge di-lepton + $E_T^{\text{miss}} > 1$ jets which gives an observed (expected) limit for $m_H=165 \text{ GeV}$ of $\sigma_{95} \sigma_{\text{SM}}=7.7(4.5)$ for 7.1 fb^{-1} of CDF data. The observed (expected) limit of the same charge di-lepton channel of D0, using 5.4 fb^{-1} of data for $m_H=165 \text{ GeV}$ is $\sigma_{95} \sigma_{\text{SM}}=7.2(7.0)$.

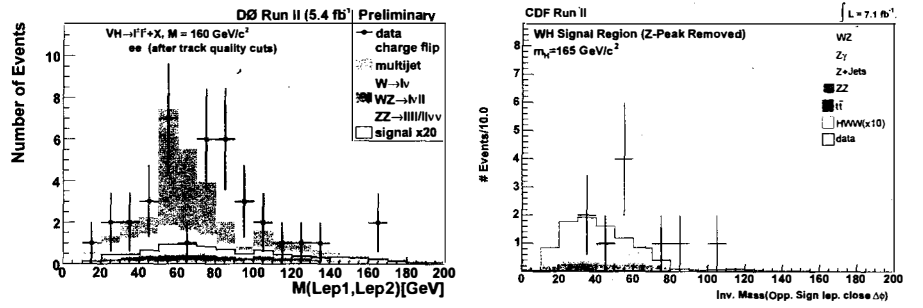


Figure 3: Left: invariant mass distributions between leptons in same charge di-lepton events. Right: Invariant mass of the opposite charge pair closest in ϕ in tri-lepton events with no compatible Z mass.

Table 1: Scale (μ_r, μ_f) and PDF uncertainties on $\sigma(gg \rightarrow H)$ for the three jet categories considered .

Uncertainty	0 jet	1 jet	>1 jet
Scale	7.0%	23.5%	33.3%
PDF	7.6%	13.8%	29.7%

5 Systematic uncertainties

The systematic uncertainties considered account for detector resolutions, reconstruction efficiencies, background normalizations and shapes both theoretical and data-driven. Where appropriate, these uncertainties are correlated between CDF and D0. Careful consideration has also been taken to account for the theoretical uncertainties related to the various Higgs production mechanisms and particularly for $gg \rightarrow H$, which is the main signal in the most sensitive di-lepton+ E_T^{miss} channel.

The Higgs boson signal is normalized to the most recent highest-order calculations available for all production mechanisms considered. The gluon fusion cross section, $\sigma(gg \rightarrow H)$, is calculated to NNLO in QCD with soft gluon resummation to NNLL⁵⁶ and uses the MSTW 2008 NNLO PDF set as it is the only NNLO set which results from a global fit to all relevant data⁷. Since the di-lepton+ E_T^{miss} analyses are split in categories depending on the number of reconstructed jets, the scale and PDF uncertainties on $\sigma(gg \rightarrow H)$ are estimated per jet category and correlated across these categories. These uncertainties are summarised in Table 1⁸⁹¹⁰.

6 Results

CDF and D0 set limits by combining all of the SM high mass channels with up to 8.1 fb^{-1} of integrated luminosity. Both experiments exclude a range of Higgs masses independently as shown in Figure 4. CDF excludes the range 158-168 GeV (160-167 GeV expected) and D0 excludes the range 163-168 GeV (160-168 GeV expected). This represents a significant milestone in Higgs searches and a testament to the comprehensive and aggressive search program of the Tevatron experiments. In order to further improve the sensitivity of these searches, CDF and D0 combined their individual high mass channels in the Tevatron high mass combination, which is discussed elsewhere in these proceedings¹¹.

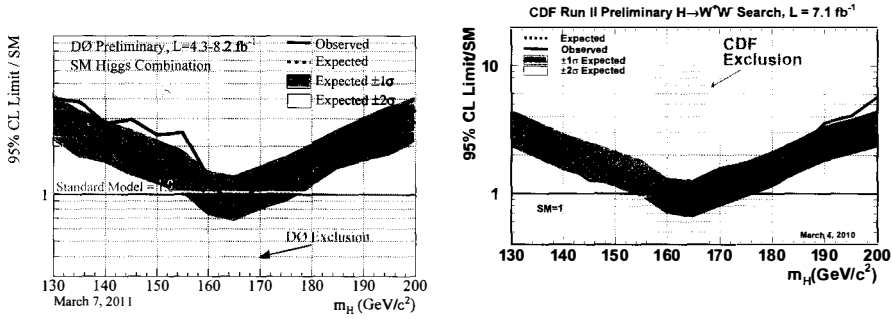


Figure 4: Combined limits using all of the SM high mass channels for D0 (left) and CDF (right). The CDF exclusion range is 158-168 GeV (160-167 GeV expected) at 95% CL and the D0 exclusion range is 163-168 GeV (160-168 GeV expected) at 95% CL.

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