# D0 Results and Combined Tevatron Results on Standard Model Higgs

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## Abstract

Results from the D0 experiment on the search for the Higgs boson of the Standard Model (SM) are presented with particular emphasis on testing the compatibility with recent LHC results on the observation of a Higgs-like particle. The D0 SM Higgs results, their combination and the Tevatron combination of CDF and D0 SM Higgs results are summarized. The article also puts recent developments in a historical context. The combined results from the Tevatron experiments give a local p-value of 0.4% for the background-only hypothesis at a mass of 125 GeV indicating that the combined Tevatron data strongly prefer the presence of a new particle with Standard Model Higgs-like properties in this mass region.

*Keywords:* Higgs, Standard Model, Tevatron, LHC

## 1. Introduction

In July 2012, we were finally confronted with the experimental observation at the LHC of a new particle that may well be the Higgs boson of the Standard Model [1, 2]. The new particle reportedly has a mass of around 125 GeV and the evidence is strongest for decays to $\gamma\gamma$ and four leptons (compatible with ZZ*).

In this paper I review results on SM Higgs searches from the D0 experiment at the Tevatron and present the current combined results from CDF and D0 with an emphasis on testing the compatibility with the LHC observations. Firstly I will put these matters in the historical context of the theoretical and experimental development of the Standard Model and summarize what we think we already knew about the SM Higgs prior to the LHC observation.

## 2. Historical Perspective

In 1964 there was no experimental evidence for most of the elementary particles of what has become the Standard Model of particle physics. But in 1964, there were theoretical developments pointing towards the possibility of a novel scalar particle [3, 4, 5] and what has be-

come known as the Higgs mechanism for the generation of elementary particle masses. The discovery of neutral currents in 1973 firmed up the status of the Standard Model as the model of particle interactions. Later in the decade there was the discovery of charm, beauty and the tau-lepton. It took until the 80's for the direct discovery of the new bosons, the W and Z with the Sp$\bar{\text{p}}$S and the gluon with the experiments at PETRA. Experiments at SLC and LEP measured the number of neutrino generations in the early 90's. With a growing ability to meld reliable theoretical predictions with precision experiments, the last two decades have established the Standard Model as essentially the law of nature for physics at centre-of-mass energies below about 200 GeV. These precision experiments pointed towards the top quark mass being relatively heavy. Direct discovery of the top quark came from the Tevatron experiments in 1995 in pair production with partonic centre-of-mass energies exceeding 350 GeV.

During the last two decades, the Standard Model paradigm has been extremely well tested, but one piece was still missing. The missing piece was the direct observation of the scalar particle, commonly named the Standard Model Higgs boson, which is posited to give

mass to the elementary particles and to explain how the W and Z bosons acquire a mass that is so much greater than that of the massless photon. The SM Higgs boson's mass is not predicted by the model, and it has taken many years to finally have the accelerator and experimental facilities to comprehensively test the existence of such a SM Higgs boson at all conceivable mass values, assuming the expected decay modes of the Standard Model.

Over the years, versions of the Standard Model with particular ranges for the Higgs mass have been excluded[1] using results from *direct* searches at accelerators. For example Higgs masses below 60 GeV were excluded comprehensively in the LEP1 era, then Higgs masses up to 114.4 GeV at LEP2 [6], and more recently, the Tevatron was able to start excluding Higgs masses in a wide region centered near 165 GeV ($147 < m_\mathrm{H} < 179$) GeV using primarily WW decay modes [7]. It should be noted that the Tevatron limits in the 110-140 GeV region are considerably weaker than would be expected for background only. The constraints that could be placed on the SM Higgs mass using global fits to electro-weak precision observables such as asymmetries, the W mass and top mass from LEP, SLC and the Tevatron have been of considerable importance. Using the measurements from Spring 2012, including the precision W mass measurements from the Tevatron, the 95% CL upper limit on the SM Higgs mass was set at 152 GeV [8]. Therefore before the results announced this summer, we had acquired knowledge independently from LHC that if the Standard Model was to survive, the SM Higgs mass must be somewhere essentially in the 114-147 GeV range.

The top-quark discovery (production of a new heavy particle with strong interactions) was made by CDF and D0 using data-sets of around 0.1 fb$^{-1}$ in p$\bar{\mathrm{p}}$ collisions at $\sqrt{s}$ = 1800 GeV. Almost two decades later, the Tevatron experiments have accumulated final data-sets of around 10 fb$^{-1}$ at 1960 GeV and the general-purpose LHC experiments, ATLAS and CMS, have acquired pp data-sets of 5 fb$^{-1}$ at 7000 GeV and now a growing data-set at 8000 GeV (results from 5 fb$^{-1}$ at 8000 GeV were reported at this conference) with much more expected at energies approaching 14 TeV in years to come.

With the data-sets in hand, the ATLAS and CMS experiments and the Tevatron experiments combined, have enough data to test the existence of the SM Higgs boson in the allowed mass region. The LHC publications from the 7 TeV run [9, 10], led to mass exclusions in the 129

to 541 GeV mass interval at at least 95% CL by each experiment with an indication of a signal-like excess near 125 GeV. By this summer, the potentially habitable zone for a SM Higgs had thus narrowed to [114,129] GeV.

## 3. New Results

New results were reported by the Tevatron experiments on July 2$^{\mathrm{nd}}$ 2012 at Fermilab and those documented and referenced in [11] form the essence of my presentation at the BEACH 2012 conference. The Tevatron is a p$\bar{\mathrm{p}}$ collider at 1.96 TeV. The leading production mechanisms are gluon-gluon fusion, associated production with a W and Z, and vector-boson fusion. The Tevatron results are mostly sensitive to b$\bar{\mathrm{b}}$ and WW decays which is complementary to the LHC results which are most sensitive to $\gamma\gamma$ and ZZ. The results, specifically from CDF, are also summarized in these proceedings together with an introduction to the Tevatron searches [12].

Results from D0 on the individual "low-mass" channels with associated production with leptonically decaying W or Z and decay of Higgs to b$\bar{\mathrm{b}}$ are now published [13, 14, 15] as is the corresponding D0 combination paper for b$\bar{\mathrm{b}}$ decay modes [16] and the corresponding Tevatron combination paper of CDF and D0 results on b$\bar{\mathrm{b}}$ decay modes [17]. The overall finalization of results with the 10 fb$^{-1}$ data-set is progressing rapidly, with final results on SM Higgs from both experiments and the combined Tevatron results expected soon. The combined results of CDF and D0 on constraining WW decay modes were published with an earlier data-set [18].

New results from the LHC experiments claiming the observation of a new particle were announced on July 4$^{\mathrm{th}}$ 2012 at CERN. The LHC observation papers are now published based on 7 TeV and 8 TeV data [1, 2]. These papers indicate production of a new particle with a mass of 126.0 ± 0.4 ± 0.4 GeV (ATLAS) and 125.3 ± 0.4 ± 0.5 GeV (CMS) with signal strengths in reasonable agreement with the SM expectation. The Tevatron searches are mainly done with channels with relatively poor mass resolution. It is sufficient to test Higgs masses at discrete values of the Higgs mass in steps of 5 GeV. The Tevatron papers report results for Higgs masses in the [100,200] GeV range. For the purposes of comparing with the LHC results, very much the question of the moment, I have therefore focussed on the Tevatron results for a Higgs with a mass of 125 GeV.

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[1] Unless otherwise stated exclusions are given at 95% CL

Table 1: D0 Higgs search channels with observed and expected sensitivities for a 125 GeV SM Higgs.

| Channel | $R_{95}^{exp}$ | $R_{95}^{obs}$ |
|---|---|---|
| $H \to WW \to \ell^+\ell^- \not{E}_T$ | 3.6 | 4.6 |
| $ZH \to \nu\nu b\bar{b}$ | 3.9 | 4.3 |
| $WH \to \ell\nu b\bar{b}$ | 4.1 | 4.5 |
| $ZH \to \ell^+\ell^- b\bar{b}$ | 5.1 | 7.1 |
| $H \to \gamma\gamma$ | 8.2 | 12.6 |
| $3\,\ell$ (WH, ZH) | 11.1 | 19.3 |
| $e^\pm\mu^\pm$ (WH) | 11.6 | 7.8 |
| $\tau\tau$ | 12.8 | 15.7 |
| Total | 1.70 | 2.94 |

## 4. D0 Search Results

In addition to the papers listed above, there are a number of D0 papers that have been published in the recent past with various final states, with close to the final dataset and analysis [19, 20, 21, 22]. The various channels listed in order of expected sensitivity for a 125 GeV SM Higgs (D0 analysis) are shown in Table 1 together with the expected sensitivity value and the observed limit in units of the expected final-state cross-section for that channel ($\sigma_{SM}$) based on [11].
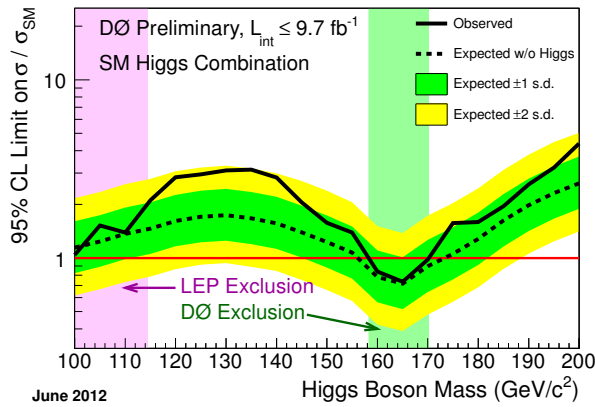


Figure 1: Observed and expected 95% CL upper limits on the ratio to $\sigma_{SM}$ as functions of the tested Higgs boson mass for the D0 analyses.

The five channels with highest expected sensitivity find signal-like excesses in data for $m_H$ = 125 GeV. However, no individual channel shows a significant excess. Taken together the combined D0 search results lead to an expected limit of 1.70 $\sigma_{SM}$ at 125 GeV while an observed limit of 2.94 $\sigma_{SM}$ is set. The overall p-value, the probability of an ensemble of background-only experiments resulting in as signal+background-

like a result, is estimated to be 4%. The limits as a function of Higgs mass are shown in Figure 1.
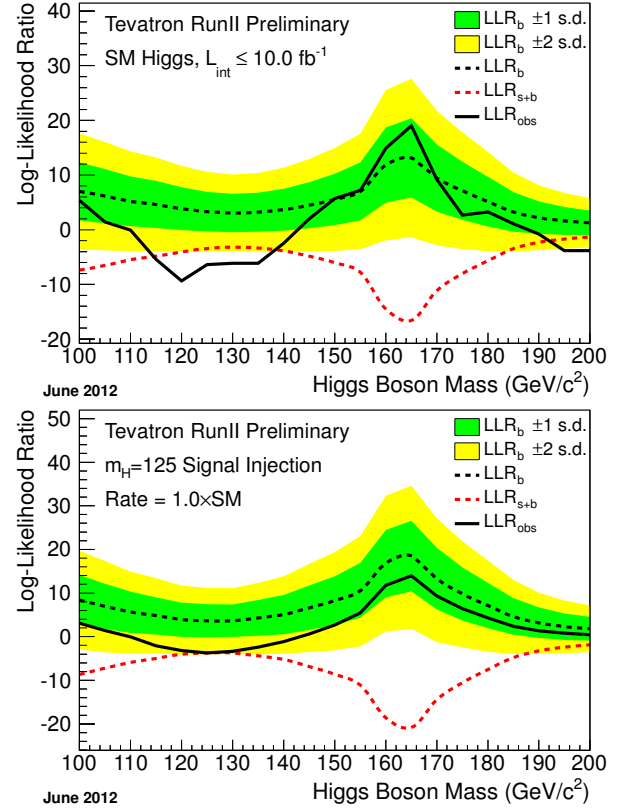
## 5. Combined Tevatron Results





Figure 2: Upper Plot: Distributions of the log-likelihood ratio as a function of tested Higgs boson mass. Lower Plot: Distributions of the log-likelihood ratio as a function of tested Higgs boson mass in the presence of a 125 GeV SM Higgs with SM rate.

Results from CDF and D0 have been combined. Figure 2 shows the measured log-likelihood ratio (LLR) as a function of Higgs mass for the Tevatron combination. This can be interpreted as basically a hypothesis test of background-only vs signal+background. As can be seen, for masses in the 110-140 GeV region the data favour the signal+background hypothesis, while at larger masses, the data are compatible with background-only. In particular at 125 GeV, the data favour the signal hypothesis. Also shown is the median expected observed LLR in the presence of a 125 GeV SM Higgs. The relatively poor mass resolution means that a signal at 125 GeV is expected to lead to signal-like behaviour for a range of tested masses with a shape quite similar to what is observed.
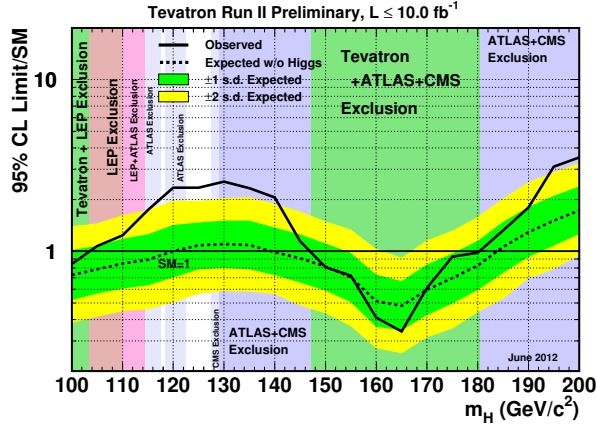
Figure 3: Observed and expected 95% CL upper limits on the ratio to $\sigma_{SM}$ as functions of the tested Higgs boson mass for the combined CDF and D0 analyses. Also indicated are the various limits from LEP and LHC experiments available prior to July 4th 2012.

Figure 3 shows the observed and expected 95% CL limits from the combination of all CDF and D0 results in [11]. It is clear that in the regions still allowed for a SM Higgs boson, the Tevatron data-set does not exclude a SM Higgs. For this preliminary combination presented in the summer, the overall median expected limit for background-only experiments is 1.08 $\sigma_{SM}$ for 125 GeV. At this mass, there is a significant excess which is more consistent with signal+background than background only. The overall p-value is estimated to be 0.4%.

The contributions from the various channels in the combined result for a 125 GeV Higgs is indicated in Figure 4. The overall signal strength combining the channels at 125 GeV is measured to be $1.35^{+0.60}_{-0.57}\sigma_{SM}$.

## 6. Summary

The Run II era of the Tevatron experiments' data-taking is over and close to final results from D0 indicate an excess of events at "low-mass" more consistent with the SM Higgs hypothesis than background-only with contributing indications in several channels. The background fluctuation probability for $m_H = 125$ GeV is 4% for D0. Combined results from CDF and D0 have 0.4% overall background fluctuation probability for $m_H = 125$ GeV. The breakdown by channel is consistent with the Standard Model Higgs. In particular the data are consistent with a significant Higgs coupling to $b\bar{b}$ as expected if the Higgs is also responsible for fermion mass generation. Results from the final analyses of the accumulated data-set are currently being pre-
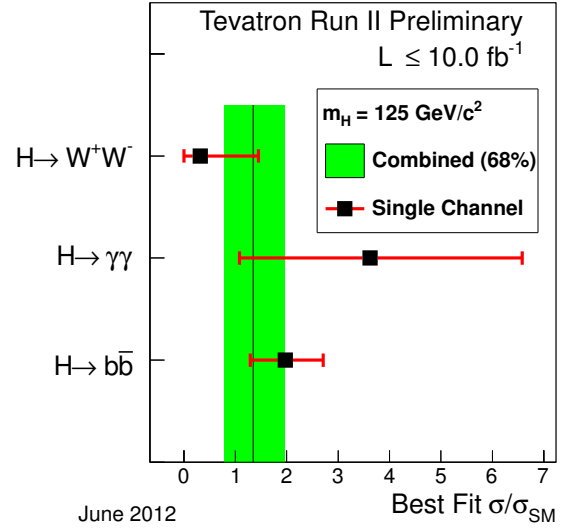


Figure 4: Best fit signal strength for a hypothesized 125 GeV Higgs boson mass for the combination (vertical line) and the three labelled sub-combinations.

pared. The most up-to-date Tevatron results on Higgs and other topics can be found at [23, 24].

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