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Combined Search for the Standard Model Higgs Boson at D0 in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present the combination of the searches for the standard model Higgs boson at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV using the full Run II dataset collected with the D0 detector at the Fermilab Tevatron collider. The major contributing processes include associated production ($WH \to \ell\nu b\bar{b}$, $ZH \to \nu\nu b\bar{b}$, $ZH \to \ell\ell b\bar{b}$, and $WH \to WWW^*$) and gluon fusion ($gg \to H \to WW^*$). The significant improvements across the full mass range resulting from the larger data sets, improved analyses and inclusion of additional channels are discussed. The combination of all channels results in significantly improved sensitivity across the 100-200 GeV mass range.

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1. Introduction

The simplest proposed mechanism to explain electroweak symmetry breaking in the standard model (SM), the Higgs mechanism, involves the introduction of a complex doublet of scalar fields that accounts for the longitudinal polarizations and masses of the electroweak bosons, as well as the fermion masses via Yukawa couplings to the fields [1]. The Higgs mechanism also gives rise to a single scalar boson, the Higgs boson (H), but does not provide a prediction for its mass. Precision electroweak data, including the latest W boson mass measurements at the CDF [2] and D0 [3] experiments at the Fermilab Tevatron Collider, constrain the mass of a SM Higgs boson to $M_H < 152$ GeV at 95% Confidence Level (C.L.) [4]. The ATLAS [5] and CMS [6] experiments at the CERN Large Hadron Collider (LHC) limit the SM Higgs boson to have a mass between 122 GeV and 127 GeV at 95% C.L. Below, we present the combination of Higgs searches at the D0 experiment, using datasets corresponding to integrated luminosities of up to 9.7 fb^{-1}.

2. Summary of Searches

There are three main classes of Higgs boson searches at D0. Searches in the first class are primarily sensitive to $H \to b\bar{b}$ decay, the dominant decay mode for a SM Higgs boson of mass $M_H = 125$ GeV. They are restricted to Higgs boson masses of 150 GeV and below. Searches in the second class are primarily sensitive to $H \to WW^*$ decays, while those in the third are centered on $H \to \gamma\gamma$ decays. They are performed over the mass range $100 \le M_H \le 200$ GeV.

2.1 Searches with $H \to b\bar{b}$ Decays

The most sensitive Higgs boson searches in the remaining allowed mass range are the searches for Higgs boson production in association with a vector boson V ($V = W, Z$) decaying leptonically and the Higgs boson decaying to a $b\bar{b}$ pair: the $WH \to \ell\nu b\bar{b}$ ($\ell = e, \mu$), $ZH \to \ell\ell b\bar{b}$, and $ZH \to \nu\nu b\bar{b}$ searches [7, 8, 9]. Each analysis is characterized by an initial $V \to$leptons selection along with at least two additional jets. To reduce the otherwise overwhelming SM backgrounds the analyses apply a b-jet identification algorithm (b-tagger) to selected jets in order to distinguish between jets coming from b-quark fragmentation. To further enhance sensitivity to Higgs boson production, each analysis divides events into various sub-channels according to lepton flavor and quality, jet multiplicity, and the number and quality of b-tagged jets. Each analysis also trains a Boosted Decision Tree (BDT) or Random Forest (RF) final discriminant using various well-modeled kinematic and topological variables. These final discriminants are the inputs to the final statistical analysis and limit setting.

2.2 Searches with $H \to WW^*$ Decays

The second category of Higgs boson search at D0 consists of searches primarily seeking $H \to WW^*$ decay. Of these, the most sensitive are the searches in which both W bosons decay to $\ell\nu$ [10]. These analyses are primarily sensitive to Higgs boson production via gluon fusion and select two charged leptons and large missing transverse energy ($\not{E}_T$). These searches employ multiple techniques to improve sensitivity, such as creating sub-channels based on jet multiplicity, and employing dedicated BDTs to reject Drell-Yan background. The analyses also train dedicated

BDT-based final discriminants. A separate search considers events where one or more of the W bosons decays to $\tau\nu$ [11].

There are searches in trilepton final states that are most sensitive to $VH \rightarrow VWW^*$ production where all bosons decay leptonically. One search is in the $ee\mu$ and $\mu\mu e$ final states [12]. Another is in a same-sign $e\mu$ final state ($e^{\pm}\mu^{\pm}+X$) [13]. Another searches for two taus decaying to hadrons (τ_h) in addition to a muon [14]. The $ee\mu, \mu\mu e,$ and $e^{\pm}\mu^{\pm}+X$ analyses use BDT-based final discriminants while the $\tau_h\tau_h\mu$ search uses the summed p_T of all physics objects.

We also perform searches in final states where one of the W bosons decays to hadrons. The first of these requires a charged lepton, $\not\!\!E_T$, and 2 or more jets in the final state [15]. The second is a search primarily sensitive to $VH \rightarrow VWW^* \rightarrow \ell\nu jjjj$ production, leading to a lepton, $\not\!\!E_T$, and four or more jets in the final state [16]. The four-jet analysis has identical lepton, $\not\!\!E_T$, and jet selection criteria as the $WH \rightarrow \ell\nu b\bar{b}$ search, but requires additional jets and vetoes on the tight b-tagging requirements of the WH analysis to reject $t\bar{t}$ backgrounds. Both the $\ell\nu jj$ and $\ell\nu jjjj$ searches train RFs as their final discriminants.

2.3 Searches with $H \rightarrow \gamma\gamma$ Decays

D0 also performs a search in the two-photon final state for Higgs boson production [17]. The analysis selects two photons and employs a Neural Network to discriminate between photons and quark or gluon jets. In the di-photon mass region near the expected signal peak, the search employs a BDT trained against signal and standard model backgrounds as the final discriminant, while those events outside the di-photon mass window are included as separate subchannels using the di-photon mass as the discriminating variable, resulting in less degradation in signal sensitivity from systematic uncertainties.

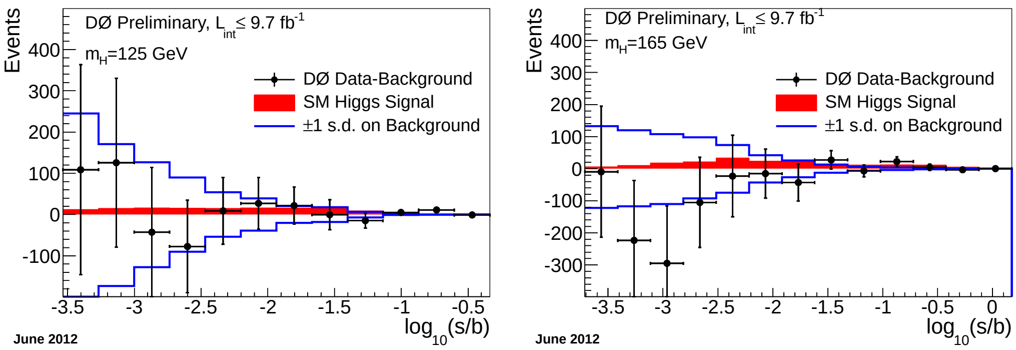
3. Results

The D0 combination utilizes the binned final variable distributions as described above. For visualization purposes, however, it can be useful to combine all of the discriminants into a single distribution. Figure 1 shows such a combination, obtained by combining the bins from each channel's final variable distributions according to their $\log_{10} s/b$ value (in order to group bins with similar sensitivity) and then subtracting the expected SM backgrounds from the data. Also shown are the expected signals and ± 1 standard deviation (s.d.) systematic uncertainties after fits to the background-only hypothesis. Figure 1a shows the result for $M_H = 125$ GeV and Fig. 1b shows the same for $M_H = 165$ GeV.

3.1 Limits

We perform the final statistical analysis and limit setting using the CL_s method with a negative log-likelihood ratio (LLR) test statistic [18]. The LLR also provides a measure of the sensitivity of an analysis, and is shown in Fig. 2 for the full combination. We define CL_s as $CLs = CL_{s+b}/CL_b$ where CL_{s+b} and CL_b are the confidence levels for the signal-plus-background hypothesis and the background-only hypothesis, respectively. Systematic uncertainties are treated as Gaussian uncertainties, constrained by their priors, on the expected number of signal and background events,

PoS(ICHEP2012)048



(a) (b)

Figure 1: Background-subtracted data, expected SM Higgs boson signal, and ± 1 s.d. systematic uncertainties for all D0 Higgs boson searches combined at (a) $M_H = 125$ GeV and (b) $M_H = 165$ GeV.

not the outcomes of the limit calculations. This approach ensures that the uncertainties and their correlations are propagated to the outcome with their proper weights.

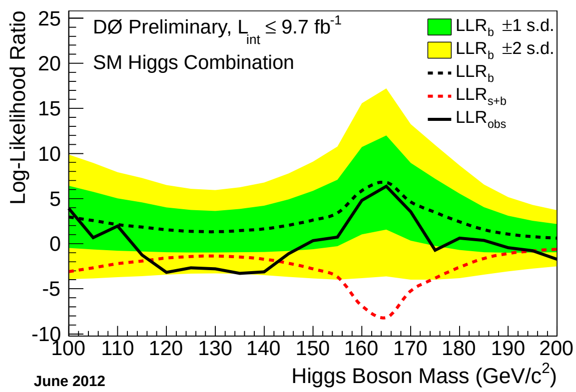


Figure 2: Log-likelihood ratio (LLR) for the summer 2012 D0 combination as a function of Higgs boson mass.

We do not observe significant evidence for Higgs boson production in the combination and proceed to set 95% C.L. upper limits on the Higgs boson production cross section over the mass range $100 \leq M_H \leq 200$ GeV, and express these limits as a ratio to the SM prediction at each mass. Figure 3 shows the limits as a function of Higgs boson mass. For $M_H = 125$ GeV, the observeded (expected) limit is a factor of 2.94 (1.70) above the SM prediction. We do observe a modest excess of approximately two s.d. in the range 120 – 140 GeV.

3.2 Analysis of Excess and Best Fit Higgs boson Cross Section

We study the nature of the excess in detail and find that it contains contributions from both the $H \rightarrow b\bar{b}$ and $H \rightarrow WW^*$ searches, as shown in the LLR distributions of Figure 4 for each of the two sub-combinations. We also perform a likelihood fit of the SM Higgs boson cross section to data at each Higgs boson mass, as shown in Fig. 5a. For a mass of 125 GeV we find a best fit cross section of 1.5 ± 0.9 times the SM prediction. As an additional comparison of our results to the SM we perform a signal injection test by replacing the observed data with pseudodata representing the

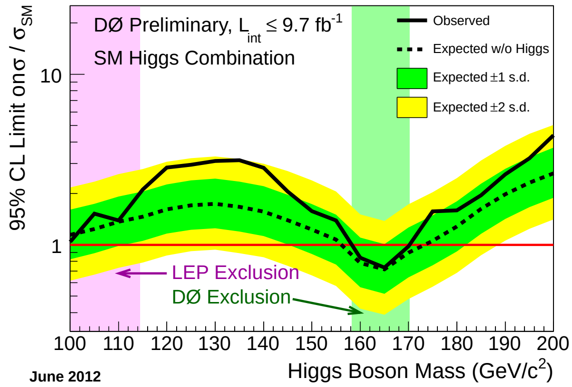
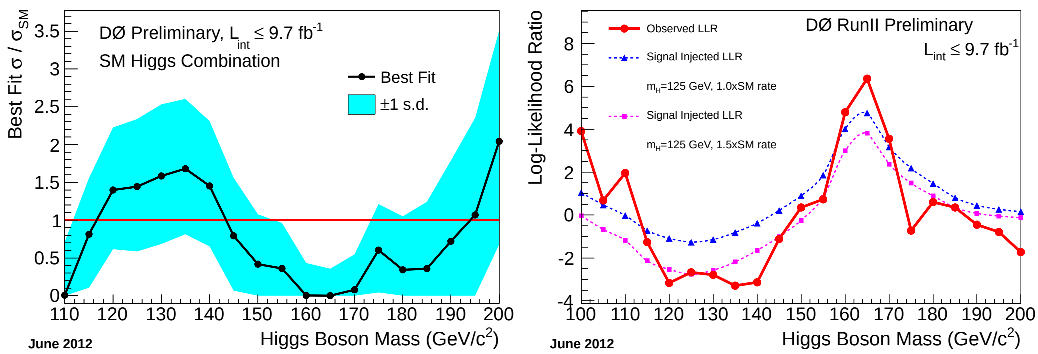


Figure 3: The expected and observed 95% C.L. upper limits on the SM Higgs boson production cross section expressed as a ratio to the SM. The green and yellow shaded regions are the 1 and 2 s.d. envelopes around the expected limit.

sum of a 125 GeV Higgs boson signal and the SM backgrounds, and generate a LLR curve for a signal a 1.0 and 1.5 times the SM rate. We compare this test to our observed result in Fig. 5b and find that the observed excess is consistent with the expectation from SM Higgs boson production.

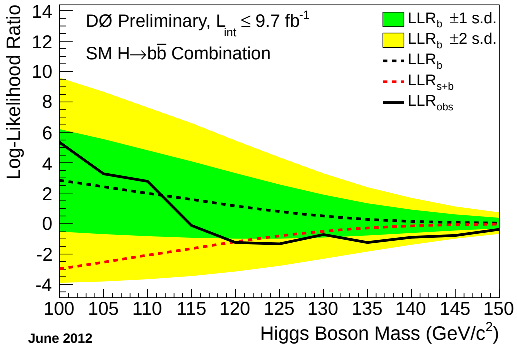


(a) (b)

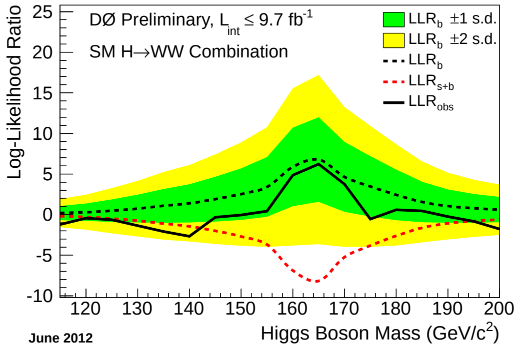
Figure 4: (a) The LLR distribution for the combined $H \to b\bar{b}$ searches. (b) The LLR distributions for the combined $H \to WW^*$ searches.

4. Conclusions

We have presented the combination of searches for the SM Higgs boson with the D0 experiment at the Fermilab Tevatron collider in integrated luminosities of up to 9.7 fb^{-1}. The searches are sensitive to Higgs boson production via gluon fusion, associated production with a vector boson, and vector boson fusion. We set an observed (expected) upper limit of 2.94 (1.70) times the SM prediction on SM Higgs boson production for $M_H = 125$ GeV. In the mass range 120 – 140 GeV we observe a modest excess with a maximum local significance of approximately two Gaussian standard deviatons.



(a)



(b)

Figure 5: (a) The best fit SM Higgs boson production cross section to data expressed as a ratio to the SM. (b) The LLR including curves representing the expected value of background plus a 125 GeV Higgs boson signal at 1.0 and 1.5 times the SM rate at all mass points.

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