Seeking the Brout-Englert-Higgs Boson: New Results from Tevatron Experiments

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We combine results from CDF and D0 on direct searches for the standard model (SM) Higgs boson (H) in $p\bar{p}$ collisions at the Fermilab Tevatron at $\sqrt{s} = 1.96$ TeV. With up to 10 fb^{-1} of luminosity analyzed, the 95% C.L. median expected upper limits on Higgs boson production are factors of 0.94, 1.10, and 0.49 times the values of the SM cross section for Higgs bosons of mass m_H =115 GeV/c^2, 125 GeV/c^2, and 165 GeV/c^2, respectively. We exclude, at the 95% C.L., two regions: $100 < m_H < 106$ GeV/c^2, and $147 < m_H < 179$ GeV/c^2. We expect to exclude the regions $100 < m_H < 119$ GeV/c^2 and $141 < m_H < 184$ GeV/c^2. There is an excess of data events with respect to the background estimation in the mass range $115 < m_H <$ 135 GeV/c^2 which causes our limits to not be as stringent as expected. At $m_H = 120$ GeV/c^2, the p-value for a background fluctuation to produce this excess is $\sim 3.5\times10^{-3}$, corresponding to a local significance of 2.7 standard deviations. The global significance for such an excess anywhere in the full mass range is approximately 2.2 standard deviations.

1 Introduction

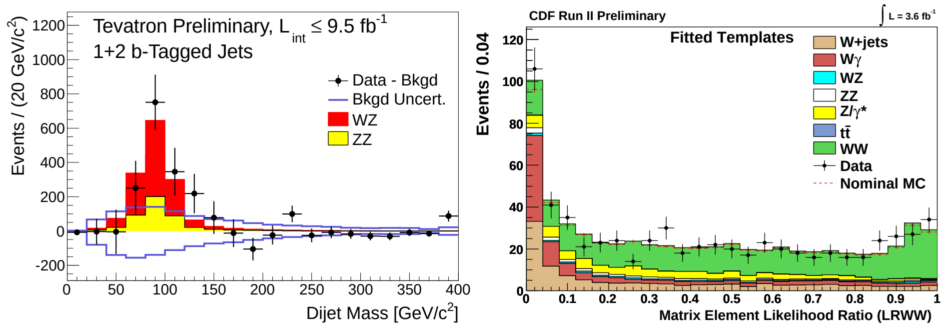
Understanding the mechanism for electroweak symmetry breaking, specifically by testing for the presence or absence of the standard model (SM) Higgs boson, has been a major goal of particle physics for many years, and is a central part of the Fermilab Tevatron physics program. Both the CDF and D0 collaborations have performed new combinations [1,2] of multiple direct searches for the SM Higgs boson. The new searches include more data, additional channels, and improved analysis techniques compared to previous analyses. Precision electroweak data, including the recently updated measurements of the W-boson mass from the CDF and D0 Collaborations [3], yield an indirect constraint on the allowed mass of the Higgs boson, $m_H < 152$ GeV/c^2 [4], at 95% confidence level (C.L.). The Large Electron Positron Collider (LEP) has excluded Higgs boson masses below 114.4 GeV/c^2 [5], and the LHC experiments, ATLAS and CMS, now limit the SM Higgs boson to have a mass between 115.5 and 127 GeV/c^2 [6,7] at the 95% C.L. Both LHC experiments report local ~ 3 standard deviation (s.d.) excesses at approximately 125 GeV/c^2. The sensitivities of the new combinations presented here significantly exceeds those of previous Tevatron combinations [8], providing sensitivity within the allowed Higgs boson mass range.

In this note, we combine the most recent results of all such searches in $p\bar{p}$ collisions at $\sqrt{s} =$ 1.96 TeV in the Higgs boson mass range from 100–200 GeV/c^2. The analyses combined here seek signals of Higgs bosons produced in association with a vector boson ($q\bar{q} \rightarrow W/ZH$), through gluon-gluon fusion ($gg \rightarrow H$), and through vector boson fusion (VBF) ($q\bar{q} \rightarrow q'\bar{q}'H$) corresponding to integrated luminosities up to 10.0 fb^{-1} at CDF and up to 9.7 fb^{-1} at D0. The Higgs boson decay modes studied are $H \to b\bar{b}$, $H \to W^+W^-$, $H \to ZZ$, $H \to \tau^+\tau^-$ and $H \to \gamma\gamma$. For Higgs boson masses greater than 125 GeV/c^2, $H \to W^+W^-$ modes with leptonic decay provide the greatest sensitivity, while below 125 GeV/c^2 sensitivity comes mainly from ($q\bar{q} \to W/ZH$) where H decays to $b\bar{b}$ and the W or Z decays leptonically. The dominant decay mode for a low mass Higgs boson is $H \to b\bar{b}$, and thus measurements of this process provide constraints on possible Higgs boson phenomenology that are complementary to those provided by the LHC. These new results from the Tevatron experiments are described below in this note. More details and a greater historical record are made available by the Tevatron Higgs Working Group [9].

The CDF and D0 collaborations each evaluate upper limits on the production rate of Higgs bosons by combining search results from each experiment. These search channels are designed to be sensitive to Higgs production via a broad combination of production mechanisms and decays. For hypothesized Higgs bosons with masses less than roughly 135 GeV/c^2, the dominant Higgs decay mode is to two bottom quarks ($H \to b\bar{b}$) with smaller contributions from pairs of tau leptons, charm quarks and photons, in order of decreasing frequency. For Higgs boson masses larger than 135 GeV/c^2, the dominant Higgs decay modes are to weak boson pairs ($H \to WW$, $H \to ZZ$). The dominant Higgs boson production mechanism at the Tevatron is via the fusion of gluons ($gg \to H+X$), with subdominant contributions from associated production ($W/Z+H$) and the fusion of vector bosons $WW/ZZ \to H$. Final state leptons are used as a primary means for event triggering and background reduction, thus the production and decay mechanisms are chosen to maximize this benefit. The largest contributions to Higgs search strength at the Tevatron thus arise from the pairing of associated production with $H \to b\bar{b}$ decays for Higgs mass (m_H) less than 135 GeV/c^2 ($WH \to \ell\nu b\bar{b}$, $ZH \to \nu\bar{\nu}b\bar{b}$, $ZH \to \ell^+\ell^- b\bar{b}$) and from the pairing of gluon fusion production with $H \to WW$ decays for $m_H < 135$ GeV/c^2. In both cases one or both weak bosons in the final state are required to decay to leptons. Additional contributions come from tau lepton and photon final states, but have smaller contributions to total search strength. Specific details on these Tevatron Higgs searches were presented by Joseph Haley (D0 results) and Homer Wolf (CDF results) at the same conference session.

Before evaluating upper limits on Higgs production cross sections, the CDF and D0 collaborations use known processes within the SM to calibrate their search techniques. Specifically, the simultaneous production of two vector bosons (dibosons) produces final states that closely mimic the signature of the primary Higgs searches. The final states of $W/Z + Z \to \ell\nu/\ell\ell/\nu\nu + b\bar{b}$ and $WW \to \ell\nu\ell\nu$ are analogs to the $H \to b\bar{b}$ and $H \to WW$ searches. By performing a measurement of both the production rate and kinematic features of these processes, the Tevatron experiments are able to gauge their ability to properly determine event selection efficencies and their ability to model the kinematic phase space of the background processes of the Higgs searches. Examples of these measurements are shown in Figure 1. In both the $W/Z + Z \to \ell\nu/\ell\ell/\nu\nu + b\bar{b}$ and $WW \to \ell\nu\ell\nu$ measurements, the observed production rates agree well with the predictions of the SM: $(1.01 \pm 0.21) \times \sigma_{\mathrm{SM}}$ for $W/Z + Z \to \ell\nu/\ell\ell/\nu\nu + b\bar{b}$ [10] and $(1.07 \pm 0.16) \times \sigma_{\mathrm{SM}}$ for $WW \to \ell\nu\ell\nu$ [11].

The combination of the CDF and D0 Higgs search results is performed by the Tevatron New Phenomena/Higgs Working Group, wherein the search results are evaluated using two independent statistical methods to check for potential errors in the exchange of results between experiments. The exchanged results are first inspected by combining all contributing Higgs search data as a function of $\log_{10}(s/b)$, where s and b are the predicted numbers of signal and background events per histogram bin, respectively. This distribution can then be integrated from large to small $\log_{10}(s/b)$ to discern the general trend of the data, determining whether it agrees with a model that includes a Higgs signal or one that does not. The same $\log_{10}(s/b)$ distribution can be fit to the data, within systematic uncertainties, and compared to the predicted Higgs signal by subtracting the background predictions from the data. These three distributions are illustrated in Figure 2 for a Higgs mass of $m_H = 125$ GeV/c^2.

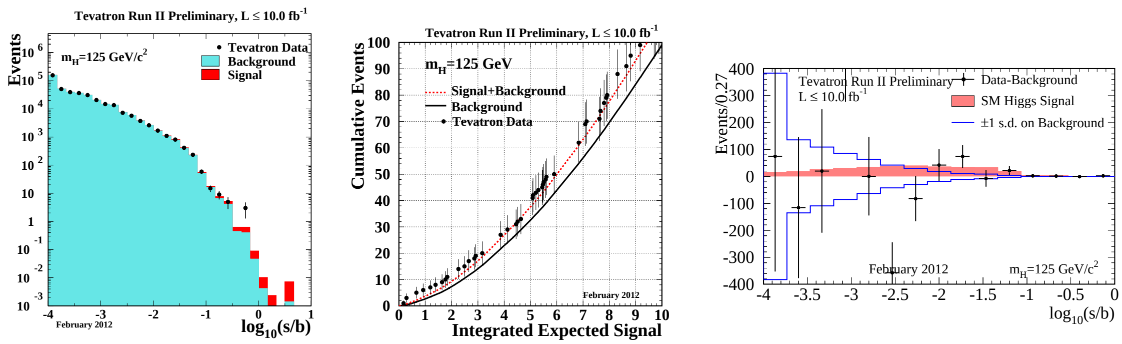


(a) (b)

Figure 1: (a) Background-subtracted data distributions for the dijet invariant mass in a measurement of $W/Z + Z \to \ell\nu/\ell\ell/\nu\nu + b\bar{b}$. The background has been fit, within its systematic uncertainties, to the data. The points with error bars indicate the background-subtracted data. The unshaded (blue-outline) histogram shows the systematic uncertainty on the best-fit background model. (b) Observed data and the predictions for the events in 3.6 fb^{-1} of CDF data compatible with $WW \to \ell\nu\ell\nu$ decays, as a function of a Matrix Element likelihood ratio with WW diboson production as the signal model.

Using all Higgs search results from the CDF and D0 collaboration, the significance of the combined search can be visualized the negative log-likelihood ratio (between the hypotheses which do and do not include a Higgs boson) as a function of Higgs mass. These results are summarized in Figure 3(a) and show a general agreement between the observed data and the background-only hypothesis (no Higgs boson) except for test masses in the range of 115-135 GeV/c^2. These search results can also be expressed as an upper limit on Higgs boson production cross section as a function of m_H, as illustrated in Figure 3(b). These upper limits are evaluated at the 95% confidence level (C.L.) and are expressed as a ratio to the SM prediction. Thus, a ratio greater than unity represents a failure to exclude the predicted rate for SM Higgs production, and a ratio smaller than unity represents exclusion of the predicted SM Higgs rate for that test Higgs mass. With up to 10 fb^{-1} of luminosity analyzed, the 95% C.L. median expected upper limits on Higgs boson production are factors of 0.94, 1.10, and 0.49 times the values of the SM cross section for Higgs bosons of mass m_H =115 GeV/c^2, 125 GeV/c^2, and 165 GeV/c^2, respectively. We exclude, at the 95% C.L., two regions: $100 < m_H < 106$ GeV/c^2, and $147 < m_H < 179$ GeV/c^2. We expect to exclude the regions $100 < m_H < 119$ GeV/c^2 and $141 < m_H < 184$ GeV/c^2. There is an excess of data events with respect to the background estimation in the mass range $115 < m_H < 135$ GeV/c^2 which causes our limits to not be as stringent as expected.

This excess of events in the mass range $115 < m_H < 135$ GeV/c^2 can be studied using the values of CL_{s+b} and $1 - CL_b$, which correspond to the p-value for the signal hypothesis and the p-value for the background-only hypothesis, respectively. Figure 4(a) shows the p-value $\mathrm{CL_{s+b}}$ as a function of m_H as well as the expected distributions in the absence of a Higgs boson signal. Figure 4(b) shows the p-value 1-$\mathrm{CL_b}$ as a function of m_H, i.e., the probability that an upward fluctuation of the background can give an outcome as signal-like as the data or more. In the absence of a Higgs boson signal, the observed p-value is expected to be uniformly distributed between 0 and 1. A small p-value indicates that the data are not easily explained by the background-only hypothesis, and that the data prefer the signal-plus-background prediction. Our sensitivity to a Higgs boson with a mass of 165 GeV/c^2 is such that we would expect to see a p-value corresponding to ~ 4 s.d. in half of the experimental outcomes. The smallest observed p-value corresponds to a Higgs boson mass of 120 GeV/c^2. The fluctuations seen in the observed p-value as a function of the tested m_H result from excesses seen in different search channels, as well as from point-to-point fluctuations due to the separate discriminants at each m_H, and are discussed in more detail below. The width of the dip in the p-values from 115 to 135 GeV/c^2



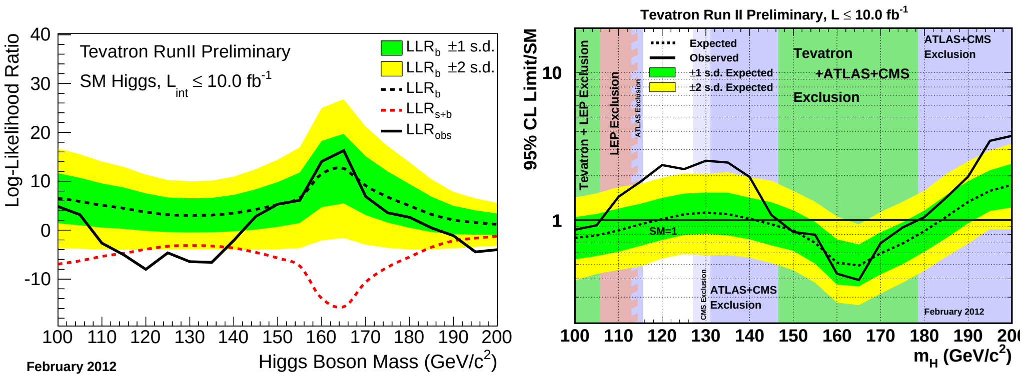
(a) (b) (c)

Figure 2: (a) Distributions of $\log_{10}(s/b)$, for the data from all contributing channels from CDF and D0, for Higgs boson masses of 125 GeV/c^2. The data are shown with points, and the expected signal is shown stacked on top of the backgrounds. (b) Integrated distributions of s/b, starting at the high s/b side, for a Higgs boson mass of 125 GeV/c^2. The total signal+background and background-only integrals are shown separately, along with the data sums. (c) Background-subtracted data distributions for all channels, summed in bins of s/b, for a Higgs boson mass of 125 GeV/c^2. The background has been fit, within its systematic uncertainties and assuming no Higgs boson signal is present, to the data. The points with error bars indicate the background-subtracted data. The unshaded (blue-outline) histogram shows the systematic uncertainty on the best-fit background model, and the shaded histogram shows the expected signal for a Standard Model Higgs boson.

is consistent with the resolution of the combination of the $H \to b\bar{b}$ and $H \to W^+W^-$ channels. The effective resolution of this search comes from two independent sources of information. The reconstructed candidate masses help constrain m_H, but more importantly, the expected cross sections times the relevant branching ratios for the $H \to b\bar{b}$ and $H \to W^+W^-$ channels are strong functions of m_H in the SM. The observed excesses in the $H \to b\bar{b}$ channels coupled with a more background-like outcome in the $H \to W^+W^-$ channels determines the shape of the observed p-value as a function of m_H. At $m_H = 120$ GeV/c^2, the p-value for a background fluctuation to produce this excess is $\sim 3.5\times 10^{-3}$, corresponding to a local significance of 2.7 standard deviations. The global significance for such an excess anywhere in the full mass range is approximately 2.2 standard deviations, after accounting for the look-elsewhere effect.

We also perform a fit of the signal-plus-background hypothesis to the observed data, allowing the signal strength to vary as a function of m_H. The resulting best-fit signal strength is shown in Figure 5(a), normalized to the SM prediction. The signal strength is within 1 s.d. of the SM expectation with a Higgs boson signal in the range $110 < m_H < 140$ GeV/c^2. The largest signal fit in this range, normalized to the SM prediction, is obtained at 130 GeV/c^2. The reason the highest signal strength is at 130 GeV/c^2 while the smallest p-value from Figure 4(b) is at 120 GeV/c^2 is because a signal at 120 GeV/c^2 would have a higher cross section than a signal at 130 GeV/c^2, and since the resolution of the discriminants cannot distinguish very well such a small mass difference, a signal at 120 GeV/c^2 would be similar to a signal at 130 GeV/c^2 with a larger scale factor for the predicted cross section. Figure 5(b) shows $\Delta\chi^2 = \mathrm{LLR_{obs}} - \mathrm{LLR_b}$, which is an estimate of how discrepant the observed data are with the median expectation from the prediction of the background-only hypothesis, as a function of m_H. Significantly negative values of $\Delta\chi^2$ indicate a preference in the data for the signature of Higgs boson production.

In summary, we combine all available CDF and D0 results on SM Higgs boson searches, based on luminosities ranging from 4.3 to 10.0 fb^{-1}. Compared to our previous combination, more data have been added to the existing channels, additional channels have been included, and analyses have been further optimized to gain sensitivity. The results presented here significantly extend the individual limits of each collaboration and those obtained in our previous combination. The sensitivity of our combined search is sufficient to exclude a Higgs boson at high mass and is, in



(a) (b)

Figure 3: (a) Distributions of the log-likelihood ratio (LLR) as a function of Higgs boson mass obtained with the CL$_s$ method for the combination of all CDF and D0 Higgs search analyses. The green and yellow bands correspond to the regions enclosing 1 s.d. and 2 s.d. fluctuations around the median expected value assuming only background is present, respectively. The red dashed curve shows the median expected value assuming a Higgs boson signal is present, separately at each m_H. (b) Observed and expected (median, for the background-only hypothesis) 95% C.L. upper limits on the ratios to the SM cross section, as functions of the Higgs boson mass for the combined CDF and D0 analyses. The limits are expressed as a multiple of the SM prediction for test masses (every 5 GeV/c^2) for which both experiments have performed dedicated searches in different channels. The points are joined by straight lines for better readability. The bands indicate the 68% and 95% probability regions where the limits can fluctuate, in the absence of signal.

the absence of signal, expected to grow in the future as further improvements are made to our analysis techniques. There is an excess of data events with respect to the background estimation in the mass range $115 < m_H < 135$ GeV/c^2 which causes our limits to not be as stringent as expected. At $m_H = 120$ GeV/c^2, the p-value for a background fluctuation to produce this excess is $\sim 3.5 \times 10^{-3}$, corresponding to a local significance of 2.7 standard deviations. The global significance for such an excess anywhere in the full mass range is approximately 2.2 standard deviations, after accounting for the look-elsewhere effect.

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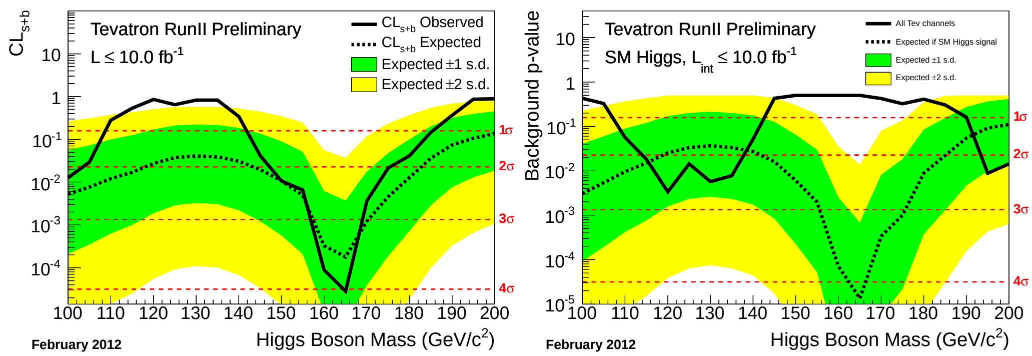
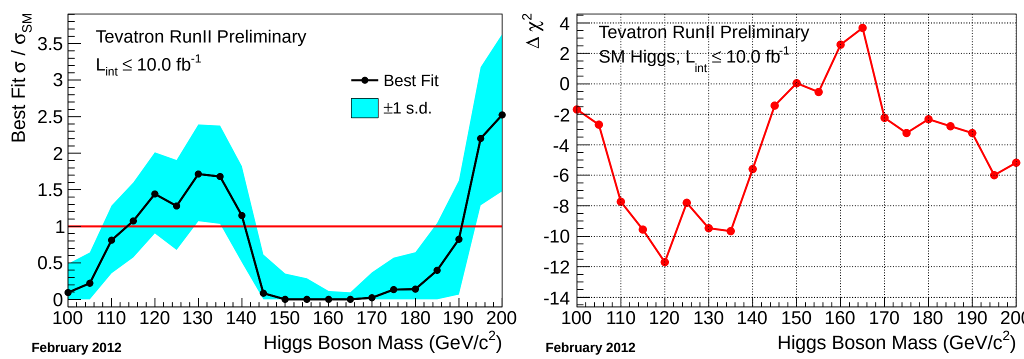


(a) (b)

Figure 4: Described in this figure are (a) the signal p-values CL_{s+b} as a function of the Higgs boson mass and (b) the background p-values 1-CL_b as a function of the Higgs boson mass, all for the combination of the CDF and D0 analyses (in steps of 5 GeV/c^2) . The green and yellow bands correspond to the regions enclosing 1 s.d. and 2 s.d. fluctuations around the median predicted value in the background-only hypothesis, respectively.



(a) (b)

Figure 5: (a) The best fit signal cross section of all CDF and D0 search channels combined shown as a ratio to the standard model cross section as a function of the tested Higgs boson mass. The horizontal line at 1 represents the signal strength expected for a standard model Higgs boson hypothesis. The blue band shows the 1 s.d. uncertainty on the signal fit. (b) The curve shows $\Delta\chi^2 = \mathrm{LLR_{obs}} - \mathrm{LLR_b}$, an estimate of how discrepant the observed data are with the median expectation from the prediction of the background-only hypothesis, as a function of m_H. Significantly negative values of $\Delta\chi^2$ indicate a preference in the data for the signature of Higgs boson production.

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