IL NUOVO CIMENTO Vol. 35 C, N. 6 Novembre-Dicembre 2012
DOI 10.1393/ncc/i2012-11383-5

Colloquia: LaThuile12

Low-mass Higgs searches at the Tevatron

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ricevuto il 7 Settembre 2012

Summary. — We report on recent searches for a low-mass Higgs boson at the Tevatron $p\bar{p}$ collider. Sensitivity to a Higgs boson with a mass less than $\sim 135\,\text{GeV}$ arises dominantly from the production of a Higgs boson decaying to $b\bar{b}$, in association with a W or Z boson decaying leptonically. However additional sensitivity is gained by searching in other final states such as diphotons, or final states with τ leptons. Both the CDF and D0 collaborations have conducted searches in up to $10\,\text{fb}^{-1}$ of $p\bar{p}$ collisions collected at $\sqrt{s} = 1.96\,\text{TeV}$. The results from the two experiments are combined to set 95% confidence level limits on the Higgs production cross section. At a Higgs mass of 115 GeV, the observed (expected) limit is 1.17 (1.16) times the standard model cross section.

PACS 14.80.Bn – Standard-model Higgs bosons.
PACS 13.85.Rm – Limits on production of particles.

1. – Introduction

One of the most important unresolved problems in particle physics is the nature of electroweak symmetry breaking. The standard model (SM) addresses this problem through the Higgs mechanism. In addition to generating masses for the W and Z boson, this mechanism produces a heavy spin-0 particle: the Higgs boson (H).

Precision electroweak data, including the latest W boson mass measurements from CDF [1] and D0 [2], constrain the mass of a SM Higgs boson to $M_H < 152\,\text{GeV}$ [3] at 95% CL. Searches at the CERN LEP e^+e^- collider have excluded a SM Higgs boson with $M_H < 114\,\text{GeV}$ [4]. Previous searches at the Fermilab Tevatron $p\bar{p}$ collider [5] and by the CMS and ATLAS collaborations at the LHC using pp collisions have restricted the allowed range of M_H to 117–127 GeV [6, 7].

For $M_H \lesssim 135\,\text{GeV}$, the decay $H \to b\bar{b}$ dominates, and observation of this decay mode will be critical to the interpretation of any potential signal. At the Tevatron, Higgs bosons are produced primarily by gluon fusion through a top-quark loop: $gg \to H$. The large multijet background makes searches for $gg \to H \to b\bar{b}$ impractical. Instead, searches for $H \to b\bar{b}$ are focused on the associated production modes, in which the Higgs boson is produced with a W or Z boson that decays leptonically. The sensitivity of the Tevatron $p\bar{p}$ collider to the $H \to b\bar{b}$ mode complements searches at the LHC pp collider, where the sensitivity to a Higgs boson is driven by the $\gamma\gamma$, ZZ and WW decay modes.

Although the Tevatron reach is driven by the associated production modes, we adopt a strategy of searching for a Higgs signal in many different final states. Here, we also discuss searches for $gg \to H \to \gamma\gamma$; and for final states involving τ leptons that are sensitive to gluon fusion production, associated production, and vector boson fusion production: $q\bar{q} \to W(Z)qW(Z)\bar{q} \to Hq\bar{q}$. Moreover, searches that are traditionally used for $M_H \gtrsim 135\,\text{GeV}$ also contribute significant sensitivity in the low mass region, and are discussed elsewhere in these proceedings [8].

2. – Searches for $H \to b\bar{b}$

In the narrow range of M_H that has not yet been excluded, sensitivity to a Higgs boson at the Tevatron is dominated by the searches for WH and ZH production in which the Higgs boson decays to $b\bar{b}$, and the W or Z decays leptonically. Both CDF and D0 have conducted searches in the resulting $\nu\nu b\bar{b}$ [9, 10], $\ell\nu b\bar{b}$ [11, 12], and $\ell\ell b\bar{b}$ [13, 14] final states, using integrated luminosities from 7.5–8.6 fb^{-1}.

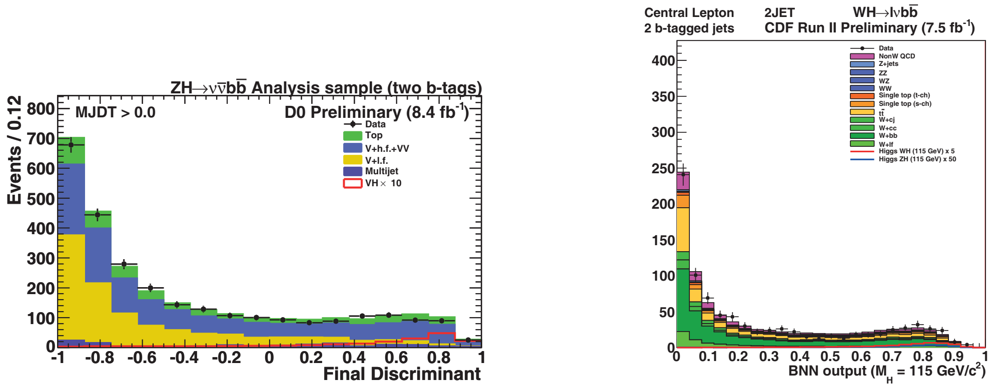
2˙1. *Event selection.* – Both experiments select events with two electrons or two muons; exactly one electron or muon; or no charged leptons. Neutrinos are inferred through the presence of an imbalance of the total transverse momentum in the event ($\not{E}_{\mathrm{T}}$). Events are also required to contain a Higgs boson candidate, consisting of two high-energy jets.

The backgrounds to these searches include the production of W or Z boson with jets, and $t\bar{t}$ and diboson (WW, WZ and ZZ) production. These backgrounds are estimated with Monte Carlo (MC) simulations. There is also a contribution from multijet events with non-prompt muons, or with jets that are misidentified as electrons. Such events can have a large apparent $\not{E}_{\mathrm{T}}$ from the mismeasurement of jet energies. This background is estimated from control samples in the data. In the $\nu\nu b\bar{b}$ searches, multivariate discriminants provide a powerful tool to reduce the initially overwhelming multijet background.

At least one of the jets in the selected events must be identified as likely to originate from a b-quark (b-tagged). CDF uses two algorithms, one based on the reconstruction of displaced decay vertices within the jet, and one that uses high impact parameter tracks associated with the jet. D0 combines this information into a single neural network discriminant. The b-tagging efficiency for b-jets is typically 50–70%, whereas the the misidentfication rate for light jets is 0.5–5%, depending on the precise criterion applied. To maximize sensitivity, both experiments consider events with exactly one tagged jet, or with at least two tagged jets in independent samples.

2˙2. *Statistical analysis.* – After the final event selection, both experiments employ multivariate discriminants, based on neural networks or boosted decision trees, to separate the Higgs signal from the remaining backgrounds. Example distributions of the final discriminants from the D0 $\nu\nu b\bar{b}$ and CDF $\ell\nu b\bar{b}$ searches are shown in fig. 1. We obtain limits on the Higgs production cross section using a Bayesian technique [15].

The calculation compares the predicted background-only and signal-plus-background distributions of the multivariate discriminants to the corresponding distributions in the data. This is accomplished through the construction of a Poisson likelihood function in which the signal prediction is multiplied by an arbitrary scale factor, R; and both the signal and background predictions are functions of nuisance parameters with Gaussian



(a) (b)

Fig. 1. – Distributions of the final discriminants in events with two b-tagged jets from (a) the D0 $ZH \to \nu\nu b\bar{b}$ analysis, and (b) the CDF $WH \to \ell\nu b\bar{b}$ analysis.

distributions that account for systematic uncertainties. We integrate the likelihood function over the nuisance parameters, resulting in a one-dimensional function of R. The value of R that corresponds to 95% of the area of this distribution is the 95% CL upper limit on R. We check this calculation with a modified frequentist technique (CL_S) [16,17] that is found to yield consistent results.

2·3. *Results.* – Figure 2 shows the limits for WH/ZH production, with $H \to b\bar{b}$ as a ratio to the predicted SM rate. These searches exclude a SM Higgs boson with $100 < M_H < 108$ GeV. For $M_H = 115$ GeV, the observed (expected) limit is a factor of 1.18 (1.26) greater than the SM prediction. To validate the analysis techniques, we have also searched for diboson production in which one weak boson decays leptonically, and one hadronically, yielding cross section times branching ratio measurements that are in agreement with the SM. This test is discussed elsewhere in these proceedings [18].

3. – Searches in final states with τ leptons

Searches in final states with τ leptons are sensitive to $gg \to H$ as well as the associated and vector boson fusion production mechanisms. In the associated production mechanism, the τ lepton can originate from either the Higgs boson decay or from the decay of a W or Z boson. Because of the diversity of signal production modes, searches in this final state offer a sensitivity that depends only weakly on the mass of the Higgs boson.

D0 has conducted a search using a data set of 7.0 fb^{-1} in a final state with a muon and two hadronically decaying τ leptons [20]. This result is reported here for the first time. Because of the presence of a third lepton, this analysis is primarily sensitive to the associated production mechanisms. Selected events are categorized according to the number of jets present in the event, to take advantage of the different signal-to-background ratios for different jet multiplicities. The final discriminant used to extract results is H_T, the scalar sum of the $\not{E}_T$ and the transverse momenta of the leptons and jets, shown for zero-jet events in fig. 3a. For $M_H = 115$ GeV, the limit on the cross section is 11 times the SM prediction, with an expected limit equal to 14 times the SM prediction.

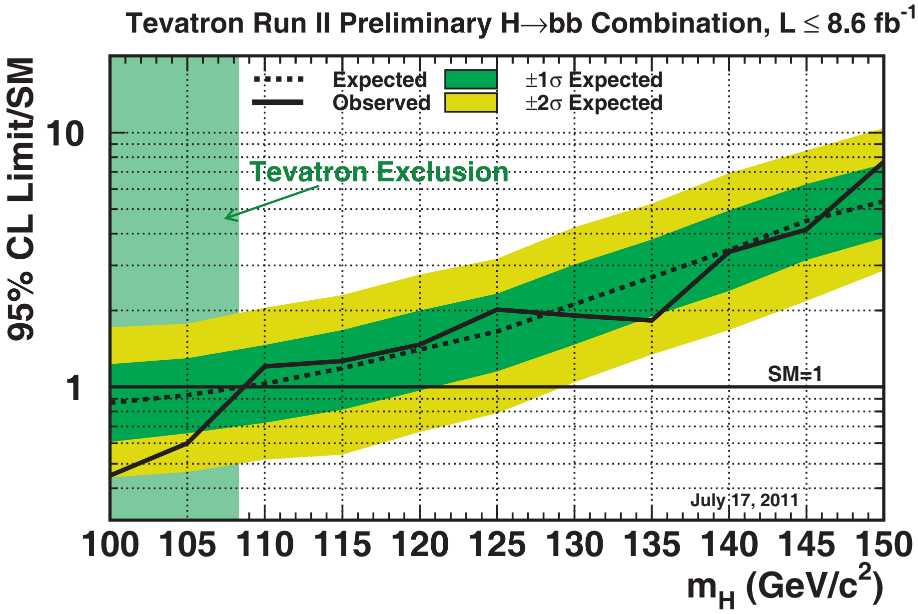


Fig. 2. – Expected and observed 95% CL cross section upper limits, from the combination of all Tevatron searches for WH/ZH production, with $H \to b\bar{b}$. Limits are expressed as a ratio to the SM production rate. Also shown are the one (green) and two (yellow) standard deviation variations about the expected limits.

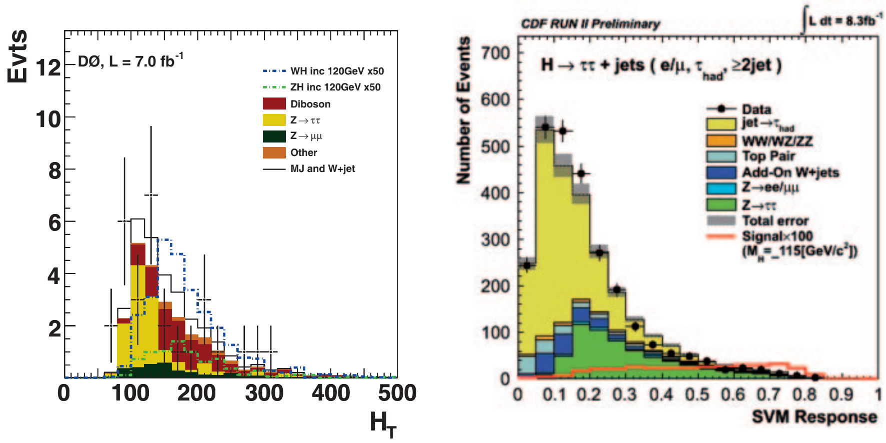
The CDF $\tau\tau$+jets analysis [21] is divided into two independent samples: the $e\mu$ sample which contains events with one electron and one muon; and the $e/\mu + \tau$ sample, which contains events with one electron or muon and a hadronically decaying τ. Selected events in each sample must also contain at least one jet, and are further categorized according to jet mutliplicity.

Support vector machines (SVMs) are used as final discriminants to search for a signal. An independently trained SVM is used for each subsample. Figure 3b displays the resulting distribution for the $e/\mu + 2$ jet sample. For $M_H = 115\,\text{GeV}$, CDF observes a limit of 12 times the predicted SM rate, and expects a limit of 13 times the SM rate.

4. – Searches for $H \to \gamma\gamma$ production

Both D0 [22] and CDF [23] search for a Higgs boson decaying to the diphoton final state. Both have been updated to use the full Tevatron dataset since the most recent Tevatron combined Higgs search [19], and have achieved improvements in sensitivity of 15–25% beyond the expectation from the additional data.

The D0 search uses a Monte Carlo simulation to estimate the background from $Z/\gamma^* \to e^+e^-$, in which electrons are misidentified as photons. Other backgrounds include direct production of diphoton events as well as photon plus jet and dijet events, in which one or more jets is misidentified as a photon. These backgrounds are estimated from control samples in the data. D0 then uses boosted decision trees (BDTs) to search for the presence of a Higgs boson. The BDT distribution for $M_H = 120\,\text{GeV}$ is shown in fig. 4a. The observed upper limit on the cross section times branching ratio

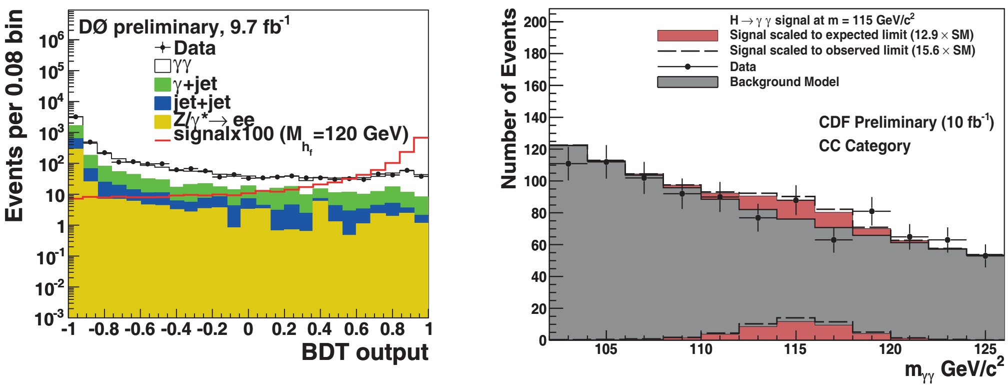


(a) (b)

Fig. 3. – Distributions of the final discriminants (a) in D0 $\tau\tau\mu$ search in events with no jets, and (b) in the CDF $\tau\tau$+jets search in events with one electron or muon, one hadronically decaying τ and at least two jets.

at $M_H = 115\,\text{GeV}$ is a factor of 8.4 larger than the SM prediction, with an expected sensitivity of 12 times the SM prediction.

The CDF analysis extends the selection of two photons to include events in the forward calorimeter. A specialized reconstruction is used to identify photons that have converted to e^+e^- pairs. The diphoton mass spectrum, shown in fig. 4b is used as the final discriminant. The background is estimated using a sideband fit. For $M_H = 115\,\text{GeV}$, the observed upper limit on the cross section times branching ratio is a factor of 11 larger than the SM prediction, with an expected sensitivity of 13 times the SM prediction.



(a) (b)

Fig. 4. – Distributions of (a) the BDT trained to identify SM Higgs with $M_H = 120\,\text{GeV}$ in diphoton events from D0, and (b) the diphoton mass spectrum from CDF in events with two central photons.

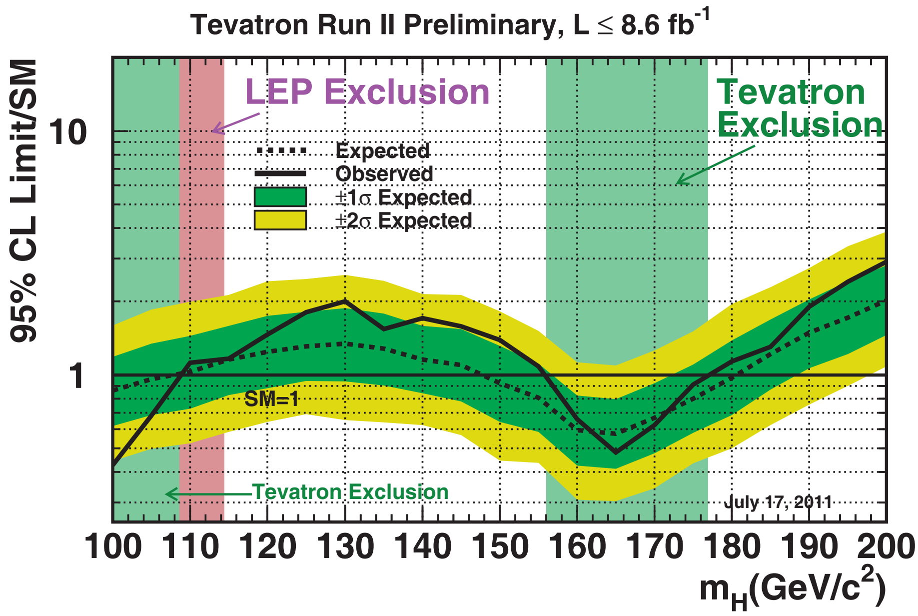


Fig. 5. – Expected and observed 95% CL cross section upper limits, from the combination of all Tevatron searches. Limits are expressed as a ratio to the SM production rate. Also shown are the one (green) and two (yellow) standard deviation variations about the expected limits.

5. – Combined Higgs search results

For a wide range of M_H there is no single search channel that is sensitive to the presence of a SM Higgs boson. Therefore the CDF and D0 collaborations have combined the results of all SM Higgs searches conducted at the Tevatron [19], although several of the searches presented here were not included in this combination. Figure 5 shows the expected and observed limits as a function of M_H, expressed as ratio to the rate predicted by the SM. For $M_H = 115\,\text{GeV}$, the observed (expected) limit is 1.17 (1.16) times the SM rate.

6. – Summary

In the summer of 2011, the CDF and D0 collaborations released a combined search for the Higgs boson that approaches sensitivity to the SM prediction across the entire range of allowed masses. At $M_H = 115\,\text{GeV}$, the observed (expected) limit is a factor of 1.17 (1.16) larger than the SM expectation. The combination of the Tevatron $H \to b\bar{b}$ searches results in an observed (expected) limit on Higgs boson production is a factor of 1.18 (1.26) larger than the SM prediction. The Tevatron sensitivity in this primary decay mode complements the LHC sensitivity in other decay modes, and will provide important insights into the nature of electroweak symmetry breaking.

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The author would like to thank the organizers for a stimulating conference with many interesting presentations.

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