Searches for the SM Higgs Boson at the Tevatron

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We report on the searches of the CDF and DØ collaborations for Standard Model Higgs production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron. The results are based on data corresponding to 0.9-4.2 fb^{-1}. No significant excess of events above the expected backgrounds was observed in the mass range m_H=100-200 GeV. The combined CDF and DØ results exclude Standard Model Higgs with mass between 160 and 170 GeV at 95% CL.

1 Introduction

High-energy physics has made a lot of progress in building a consistent picture of the properties and interactions of the fundamental particles. Nevertheless, there are still some central hypotheses that await conclusive experimental results that can either confirm or rule them out. A high-profile example is the Higgs mechanism of electroweak symmetry breaking. In its simplest form, it postulates the existence of a new self-interacting complex doublet of scalar fields that are incorporated in the Standard Model (SM). Apart of explaining the origin of Z, W, and fermion masses, this mechanism also predicts the existence of a new fundamental scalar particle - the Higgs boson. The mass of the Higgs boson is a free parameter of the theory. Searches by the LEP experiments exclude Higgs bosons with mass $m_H > 114.4$ GeV at 95% CL [1]. Constraints on the mass are also obtained from electroweak precision measurements, which combined with the LEP results set a limit of $m_H < 191$ GeV at 95% CL [2]. These results indicate, that **if** a Higgs boson with properties predicted by the SM exists, it must be fairly light.

2 Searches for the SM Higgs in Run 2 of the Tevatron

Although the favored Higgs mass range is within the energy reach of the Tevatron the searches are very challenging due to the small expected signal and large competing backgrounds. The most important Higgs production mechanisms at the Tevatron are gluon fusion $gg \rightarrow H$, associated production with a vector boson $qq \rightarrow VH$ $(V = Z, W)$, and to some extend, vector boson fusion (VBF) $qq \rightarrow qqH$. The searches for SM Higgs are performed in the mass region $100 < m_H < 200$ GeV and can be divided into "low-mass" and "high-mass" searches, based on the dominant Higgs decay modes. The decay $H \rightarrow b\bar{b}$ dominates in the region $m_H < 135$ GeV, while for higher masses Higgs decays predominantly to WW^*, where one of the W's can be off mass-shell.

The vast majority of Higgs searches at CDF and DØ use multivariate techniques such as Matrix Element (ME) methods, artificial Neural Networks (NN), and Boosted Decision Trees (BDT). They combine a number of input parameters to form a more powerful single discriminator that provides a better signal/background separation that leads to improved sensitivity to Higgs signal.

Due to the large number of explored channels we provide only brief descriptions of the analyses. All quoted limits are set at 95% CL. For each investigated channel, the limits are obtained for a certain Higgs mass range. In the descriptions below we quote limits only for representative mass points. Detailed information on the results can be found in the provided references.

2.1 Low-mass region

The searches for $H \to b\bar{b}$ rely on identification (tagging) of the b-quarks and reconstruction of the di-jet invariant mass. The overwhelming backgrounds from QCD multi-jet production do not allow inclusive searches, and the best strategy is to consider Higgs production in association with a vector boson.

2.1.1 $WH \to l\nu b\bar{b},\ l = e, \mu$

The search for $WH \to l\nu b\bar{b},\ l = e, \mu$ is one of the most efficient channels in the low-mass region. The requirement of an isolated lepton with high transverse momentum ($p_T > 15-20$ GeV) and large missing transverse energy in the event ($\not{E}_T > 20$ GeV) efficiently reduce QCD backgrounds. Further sample clean-up is achieved by requiring one or both jets to be b-tagged.

The search at DØ [3] uses 2.7 fb^{-1} of data and divides the sample into four categories depending on the number of jets in the event and the number of identified b-jets. The signal extraction is performed using a NN optimized for each sub-sample and Higgs mass point. The inputs include various kinematic variables and a discriminant based on ME calculations. No signal evidence was found and upper limits on Higgs production were set for $m_H = 100 - 150$ GeV. For $m_H = 115$ GeV the observed (expected) limit corresponds to 6.7 (6.4) times the SM model prediction.

The search at CDF [4] consists of two efforts that apply different analysis techniques to the same sample of 2.7 fb^{-1}. The first one combines kinematic variables in a NN to separate the signal from the backgrounds. The other one relies on a BDT that combines kinematic variables with event probability densities from ME calculations, and flavor separating NN information. The results of the two analyses are combined with a NN to produce a super-discriminant used to set upper limits on Higgs production. The observed (expected) limit for $m_H = 115$ GeV corresponds to 5.6 (4.8) times the SM prediction.

2.1.2 $ZH \to llb\bar{b},\ l = e, \mu$

The production cross section of ZH is smaller but the presence of two leptons in the final state translates to lower backgrounds compared to WH. These channels allow full event reconstruction that is used to set constraints and sharpen the resolution of jet energies and the reconstructed di-jet mass.

CDF uses a NN to correct jet energies to parton level and improve the di-jet mass resolution. Signal selection is done with a 2D NN discrimination against $t\bar{t}$ and Z+jets events. Six sub-samples based on loose/tight lepton identification and b-tagging requirements are treated separately to take advantage of the different background compositions. No signal is found in the analyzed data sample of 2.7 fb^{-1}. The observed (expected) upper limit on Higgs production at $m_H = 115$ GeV is 7.1 (9.9) times the prediction of the SM.

The search at DØ [6] uses 4.2 fb^{-1} of data and relies on a kinematic fit to improve jet energy estimates. Signal significance is maximized through combining kinematic variables in a single discriminator provided by a BDT. Training is done separately for different lepton selections, b-tagging requirements, and Higgs masses. The observed (expected) limit at $m_H = 115$ GeV corresponds to 9.1 (8.0) times the SM prediction.

2.1.3 $\not{E}_T + b\bar{b}$

This topological state mirrors the expected signature for $ZH \to \nu\bar{\nu}b\bar{b}$ of two b-jets and missing transverse energy from the two neutrinos. However, some $WH \to l\nu b\bar{b}$ events will be reconstructed in the same way if the lepton is not detected due to limited detector coverage or identification inefficiency. Because of the larger WH cross section, the contribution from such events can be comparable to $ZH \to \nu\bar{\nu}b\bar{b}$. Therefore, the search is defined in topological terms and both processes are included in the estimation of signal detection efficiency.

One of the challenges in this search mode is the modeling and suppression of backgrounds from multi-jet events, where large $\not{E}_T$ can appear due to energy mismeasurements. Data-driven techniques and multiple control regions ensure that these backgrounds are well understood. Other major backgrounds in this search are $t\bar{t}$ and W/Z+jets events.

The discrimination between signal and backgrounds at DØ [7] is done with a BDT. For a sample of 2.1 fb^{-1}, the observed (expected) limit at $m_H = 115$ GeV is 7.5 (8.4) times the SM prediction. The corresponding search at CDF [8] uses a data sample of 2.1 fb^{-1} that is split into three sub-samples based on b-tagging requirements. NN discriminators are used to maximize signal significance. The observed (expected) limit in the CDF search corresponds to 6.9 (5.6) times the SM prediction for Higgs production.

2.1.4 Other low-mass searches

Besides the thee major low-mass Higgs search modes at the Tevatron, there are a number of other channels that are explored by CDF and DØ. Although less powerful, they add to the overall sensitivity in this region and help to push the combined results closer to the SM predictions. Some of these channels are going to play very prominent roles at the LHC.

A list of resent result includes the searches with two taus in the final state by CDF [9] and DØ [10], the searches by DØ for $H \to \gamma\gamma$ [11] and $t\bar{t}H$ production [12]. CDF has also extended the search for VH production to include hadronic Z/W decays [13].

2.2 High-mass region

The region $m_H > 135$ GeV is dominated by the decay $H \to WW^*$. If both W's are required to decay leptonically to final states with electrons or muons the detector signature of the signal is very clean and one can take advantage of the dominant production mode - gluon fusion [a]. The analyses require two opposite sign isolated leptons ($l = e, \mu$) above certain p_T threshold. The invariant mass of the lepton pair is required to be above ~15 GeV to suppress heavy-flavor decays. These basic cuts suppress most of the backgrounds, leaving Drell-Yan (DY) production of lepton pairs, and di-boson production as the main background sources. The most sensitive discriminator between lepton pairs from Higgs decays and the

[a] The searches at CDF and DØ use the latest theoretical results [14] and the MSTW2008 parton distribution functions [15].

backgrounds is the azimuthal opening angle $\Delta\phi_{ll}$ between the two leptons. Due to spin correlations, $\Delta\phi_{ll}$ tends to be small for leptons coming from Higgs decays, while for the mix of backgrounds the leptons tend to have larger opening angles.

The DØ search [16] uses integrated luminosity of 3.0-4.2 fb^{-1} and looks at ee, $\mu\mu$, and $e\mu$ final states. A requirement of large $\not\!\!E_T$ in the event is applied to suppress DY backgrounds. The final signal/background separation is done with a NN using 14 inputs, characterizing the leptons, the event as a whole, and various angular correlations. No signal evidence was found and upper limits on the production cross section of SM Higgs bosons were set. For $m_H = 160$ GeV the observed (expected) limit corresponds to 1.7 (1.8) times the SM prediction.

The sensitivity of the searches for $H \to WW^*$ can be increased by considering final states with two like-sign leptons. Such signatures arise mainly from the process $WH \to WWW^* \to l^{\pm}l^{\pm} + X$. Using 3.6 fb^{-1} of data DØ [17] observed a limit corresponding to 18 times the SM prediction for $m_H = 160$ GeV.

The $H \to WW^*$ search at CDF [18] is performed with 3.6 fb^{-1} of data and considers the ee, $\mu\mu$, and $e\mu$ final states. The sample is split into three sub-samples based on jet multiplicity in the event. NN's are trained to separate the signal from the backgrounds for each of them. The sub-samples not only have different background compositions but are expected to contain Higgs produced in different processes. The sub-sample with zero jets almost exclusively selects Higgs produced in gluon fusion. About 20% of the signal in the sub-sample with one jet comes from VH or VBF, while in the sub-sample with two or more jets this contribution reaches ~60%. In the absence of signal, the results are combined to set upper limits on Higgs production. The addition of final states with like-sign leptons increases the sensitivity by about ~5%. The observed (expected) combined limit for $m_H = 160$ GeV is 1.4 (1.5) times the SM prediction.

3 Combined results

The strategy for Higgs searches at the Tevatron is to have CDF and DØ perform independent analyses in all viable modes, and then combine the channels from both collaboration to get a single result for each Higgs mass hypothesis. The current combination [19] shows no signal evidence and the results are interpreted as 95% exclusion limits on SM Higgs production. Figure 1 shows the combined limits normalized to the SM predictions. The results exclude SM Higgs bosons with mass between 160 and 170 GeV. This is the first mass region exclusion from direct searches since the LEP 2 results.

4 Conclusions

CDF and DØ are pursuing comprehensive SM Higgs search programs and the latest round of data analyses has produced the first constraints on the SM Higgs mass from direct searches at the Tevatron. With more data on tape and constant improvements in the analysis techniques we expect to have more exiting news in near future.

References

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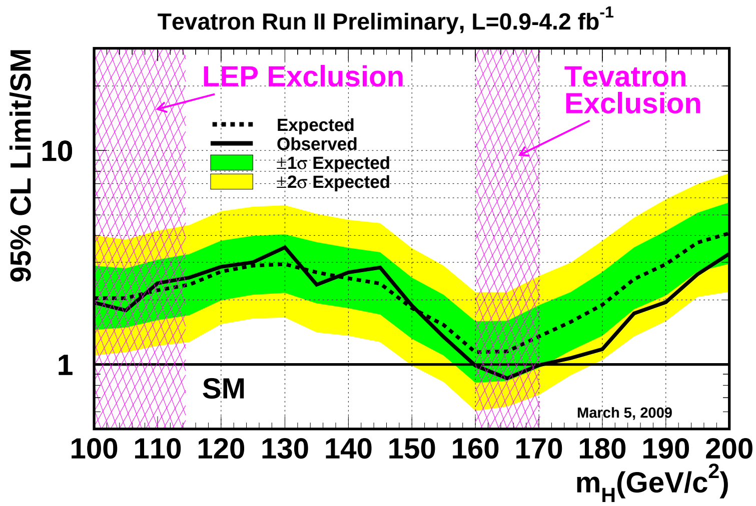

Figure 1: Combined CDF and DØ upper limits on SM Higgs production at 95% CL. The limits are expressed as ratios to the SM predictions. The solid (dotted) line shows the observed (expected) limits. The color bands represent the 68% and 95% probability regions for the background only hypothesis.

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