Search for $W H \rightarrow \ell \nu b \bar{b}$ Final States at the Tevatron

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Latest results are presented in the search for low mass standard model Higgs production in association with a $W$ boson, based on large luminosity data samples collected at the CDF and D0 Experiments at the Fermilab Tevatron $p\bar{p}$ collider. The selection of event samples containing an isolated lepton, an imbalance in transverse energy in the events, and either one or two reconstructed jets consistent with having evolved from a $b$-quark, provides statistically independent data samples to search for $q\bar{q} \rightarrow W H$ candidates. Expected and observed upper limits are derived for the product of the $W H$ production cross section and branching ratios and are reported in units of the standard model prediction. The observed (expected) upper limits for a Higgs mass $M_H = 115$ GeV are factors 2.65 (2.6) and 4.6 (3.5) above the standard model prediction for the CDF and D0 searches, respectively.

1. Introduction

In the Standard Model (SM) of particle physics the explanation for the finite masses of the weakly interacting $W$ and $Z$ bosons is the process of electroweak symmetry breaking yielding a single Higgs particle state. The finite masses of fermions are then accounted for via their Yukawa couplings to the Higgs field. At Tevatron $p\bar{p}$ collider energies, searches for SM Higgs production using $\ell \nu b \bar{b}$ final states are expected to be among the most sensitive to SM Higgs production, most notably in the Higgs mass range $100 < m_H < 135$ GeV. The requirement of a $W$ Boson reconstructed in association with jets serves to reduce experimental backgrounds from QCD jet production processes, and improves sensitivity to signal.

The searches presented here are based on large luminosity data samples collected at the CDF and D0 experiments at the Tevatron $p\bar{p}$ collider. [3, 4] Candidate $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ events are selected by requiring a single isolated lepton together with an associated imbalance in transverse energy in the events. The Higgs decay mode $H \rightarrow b\bar{b}$ is used since it has the largest expected branching fraction in the studied mass regime. Statistically independent (orthogonal) data samples are selected via the application of $b$-tagging. Multivariate techniques are then applied to suppress remaining search backgrounds in each sample. Finally, upper limits are derived for the product of the $W H$ production cross section and branching ratios and reported in units of the SM prediction.

Direct searches for the process $e^+e^- \rightarrow ZH$ at CERN $e^+e^-$ LEP collider experiments already constrain the minimum SM Higgs mass to $m_H > 114.4$ GeV at 95% confidence level. In addition, a fit to precision electroweak measurements of the top-quark and $W$ boson masses, from both Tevatron $p\bar{p}$ and CERN $e^+e^-$ Collider experiments, infer an upper limit of $m_H < 161$ GeV at 95% CL [1, 2] and more recently searches at the CERN LHC $pp$ collider experiments yield preliminary exclusions at larger Higgs masses. [3, 4]

2. Event Selections

Candidate $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ events are selected by requiring a single isolated lepton together with an associated imbalance in transverse energy in the events. Jets are reconstructed using iterative cone algorithms which make use of midpoints as additional seeds. Figure 1(a) shows the $p_T$ distribution of $W$ candidates selected in events with two large-$p_T$ centrally reconstructed leptons by the CDF Collaboration. [3] The search is based on a total integrated luminosity of $L = 7.5$ fb$^{-1}$. Prior to the application of $b$-tagging, a total of four samples are selected using different leptonic angular and reconstruction criteria, each requiring two reconstructed large-$p_T$ jets. The recently added fourth search sample is based on loose lepton selection criteria.

Figure 1(b) shows the transverse energy imbalance in the $W$ candidate events in $L = 7.5$ fb$^{-1}$ of data selected by the D0 Collaboration. [4] Four samples are selected prior to the application of $b$-tagging, by requiring either two or three reconstructed jets for each leptonic channel. The three-jet selected sample is included to allow for additional gluon radiation in the collision hard subprocess. Loose lepton selection criteria are used for both the electron and muon channel searches.
Figure 1: (a) The transverse momentum $p_T$ distribution of $W$ boson candidates in the central lepton selected sample of the CDF experiment and (b) the transverse energy imbalance ($\text{MET}$) in the two-jet selected sample of the D0 experiment. (c) The dijet mass distribution in two-jet selected events from the D0 search, after application of a new multivariate discriminant to suppress multijet background and (d) the dijet mass distribution after correcting for dijet mass resolution effects in loose lepton selected events by the CDF experiment. Both the CDF and D0 collaborations select four initial search samples and make use of loose lepton selection criteria. The candidate $W \to e\nu$ and $W \to \mu\nu$ events are shown combined in the figures.

The background contributions in each sample are normalized according to their theoretical predictions and/or modeled in separately selected control samples. The PYTHIA [7], ALPGEN [8] or COMPHEP [9, 10] event generators are used, with ALPGEN and COMPHEP interfaced to PYTHIA to account for subsequent hadronization according to the MLM factorization (“matching”) scheme. Both the CDF and D0 selections include additional smaller sensitivities to $W \to \tau\nu$ decays, in which the $\tau$ subsequently decays into an electron or a muon. In addition, candidate $ZH \to \ell\ell b\bar{b}$ events in which one decay lepton passes and one fails the isolated lepton selection criteria used in $ZH \to \ell\ell$ searches are also selected.

Background from multijet (QCD) production processes is studied separately using the data. Figure (c) shows the dijet invariant mass distribution of the D0 Collaboration after application of a multivariate discriminant technique to further improve suppression of multijet background. The CDF experiment employs a similar approach based on the super vector machine technique. Figure (d) shows the dijet invariant mass distribution for the loose selected lepton sample by the CDF experiment after applying recent improvements to improve dijet mass resolution. The improvements, which are from 15% to 11%, have a direct impact in the procedure to set upper limits and are described in detail in [11]. A good description of the data by the sum of the expected search backgrounds is obtained in all cases.
Figure 2: Data samples divided into statistically independent samples using \(b\)-tagging. (a) The dijet invariant mass distribution in two-jet, two \(b\)-tagged jets events from the D0 collaboration and (b) the dijet mass distribution in two-jet events containing a single \(b\)-tagged jet. The expected signal contribution for a Higgs mass \(M_H = 115\) GeV is shown scaled in the figures and the electron and muon leptonic search samples are combined.

3. Application of \(b\)-tagging

The events are further subdivided into statistically independent (orthogonal) samples through the application of \(b\)-tagging. The obtained samples are of different sensitivities due to the different background contributions which remain in each sample.

The D0 Collaboration uses a Neural Network approach to tag \(b\)-jets which is based on a total of seven input discriminating variables.[12] Two samples are selected from each of the previously selected two-jet and three-jet samples. The first sample is selected by requiring two jets to be consistent with having been initiated by \(b\)-quarks. Events that fail the first condition are used to select a second sample requiring a single \(b\)-tagged jet. Figure 2(a) shows the D0 dijet invariant mass distribution in the two-jet, two \(b\)-tagged sample (the electron and muon leptonic channels are shown combined in the figure). Figure 2(b) shows the dijet invariant mass distribution in two-jet events that fail the two \(b\)-tag requirement and contain a single \(b\)-tagged jet. The expected signal contribution for a Higgs mass \(M_H = 115\) GeV is shown scaled by factors of 50 and 100 in each figure, respectively.

The CDF Collaboration tag \(b\)-jets using a combination of three separate techniques; (1) a neural network algorithm (NN), (2) secondary vertex tagging (ST) and (3) requiring that the probability for a jet to have originated from the primary vertex (JP) to be small. Four independent samples are selected, three of which require two \(b\)-tagged jets and one of which requires a single \(b\)-tagged jet. The two-jet samples are selected using different combinations (ST-ST, ST-JP and ST-NN) of the \(b\)-tagging requirements.
4. Multivariate Discrimination

The remaining backgrounds in each b-tagged sample are suppressed through the application of multivariate techniques. The CDF Collaboration use a Bayesian Neural Network (BNN) approach which is based on eight discriminating input variables. The eight input event variables are studied and optimized separately for each of the orthogonally selected b-tagged samples. Figures 3(a) and (b) show the output distributions obtained after applying the BNN to the CDF ST-NN and ST-JP b-tagged samples, respectively. In each distribution, the $q\bar{q} \rightarrow WH$ signal peaks at large discriminant output values, whereas the sample backgrounds are shifted towards small discriminant output values. The four leptonic selections are shown combined in each figure and the expected $WH$ signal contribution is shown scaled by a factor 5.

The D0 Collaboration use a Boosted Decision Tree (BDT) approach, which is applied multiple times to each b-tagged sample to generate a random forest. A total of 13 input variables are used for each decision tree. These are randomly assigned from a total of 20 event input variables, which are studied and optimized in separate studies. Since the approach is able to discriminate against multiple background sources, the same 20 input event variables are used as discriminants for each of the orthogonally selected b-tagged samples.

5. Cross Section Upper Limits

Upper limits are derived for product of the $WH$ production cross section and branching ratios and reported in units of the SM prediction. The output multivariate distributions described in the previous section are used as discriminating inputs in the limit derivation procedure.

Figure 4 shows the observed and expected upper limits of the CDF collaboration search. The results are shown combined with an independent search based on a three-jet event selection by the CDF Collaboration which uses a matrix method approach for backgrounds. The observed limits are derived for 11 discrete values of Higgs mass $M_H$. The expected limits are shown by the dashed line and the bands incorporate the effect of the systematic and Poisson statistical uncertainties. The observed (expected) upper limits for a Higgs mass $M_H = 115$ GeV are 2.65 (2.6), respectively, and represent a 17% improvement in total sensitivity.

The observed and expected upper limits of the D0 Collaboration search are shown in Fig. 5. The results are combined with a previously published D0 result, which is based on 1 fb$^{-1}$ of analyzed data. The bands incorporate the effect of the systematic and Poisson statistical uncertainties and the observed limits are again
Figure 4: CDF observed (solid line) and expected (dashed line) upper limits for the $WH$ cross section times branching ratio in units of the SM prediction. The two-jet search is combined with the independent CDF three-jet search of $[13]$. The bands incorporate the effect of the systematic and Poisson statistical uncertainties derived for 11 discrete values of Higgs mass. The observed (expected) upper limits for a Higgs mass of $M_H = 115$ GeV are 4.6 (3.5), respectively, and the results represent an 11% improvement beyond those expected from the increase in analyzed luminosity alone.

6. Summary

Searches for $WH \to \ell\nu b\bar{b}$ final states are particularly sensitive to SM Higgs production at Tevatron $p\bar{p}$ Collider energies. The selection of event samples containing an isolated lepton, an imbalance in transverse energy in the events, and either one or two reconstructed jets consistent with having evolved from a $b$-quark, provides statistically independent data samples to search for $q\bar{q} \to WH$ candidates. The observed (expected) limits for a Higgs mass of $M_H = 115$ GeV are 2.65 (2.6) and 4.6 (3.5) for the CDF and D0 searches, respectively, and the results, which are based on large luminosity data samples collected by the CDF and D0 collaborations, continue to gain in sensitivity.
Figure 5: D0 observed (solid line) and expected (dashed line) upper limits for the $WH$ cross section times branching ratio in units of the SM prediction. The search is combined with the 1 fb$^{-1}$ D0 result previously reported in [14]. The bands incorporate the effect of the systematic and Poisson statistical uncertainties.

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