Searching for a Higgs Boson Decaying to $WW^*$ at CDF using Multivariate Techniques

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Abstract. The process $gg \rightarrow H \rightarrow WW^* \rightarrow ll\nu\nu$ is one of the most sensitive and challenging Higgs search channels at hadron colliders. This channel is also sensitive to a variety of new physics scenarios. This paper describes two searches using multivariate techniques to separate a potential Higgs signal from the much larger continuum $q\bar{q} \rightarrow WW$ production using 1.1 $fb^{-1}$ of 1.96 TeV $pp$ collisions recorded with the CDF detector.

1. Introduction
Discovering or ruling a low mass standard model Higgs boson is critical to understanding the origin of electroweak symmetry breaking and has become the focus of several large experimental efforts. From a Higgs mass of $\approx 135$ GeV up to twice the top mass, $WW^*$ is the dominant branching fraction. In addition, the leptonic branching fraction of $WW^*$ is $\approx 10$ times larger than $ZZ^*$. The combination of these two branching fractions makes the process $gg \rightarrow H$ with $H \rightarrow WW^* \rightarrow ll\nu\nu$ the most sensitive channel at the Tevatron for the intermediate mass range.

It is difficult to differentiate $gg \rightarrow H \rightarrow WW^* \rightarrow ll\nu\nu$ from the continuum process $q\bar{q} \rightarrow WW \rightarrow ll\nu\nu$, because of the two neutrinos in the final state. There are however several effects which can be used to differentiate these processes. These effects can be classified as polarization effects observable in the kinematics of the $W$ daughters, effects on the lepton kinematics due the the Higgs mass constraint, and hadronization and rapidity differences due to the differences between a $gg$ system in the initial state versus a $q\bar{q}$ system.

Spin correlations are particularly important, because the Higgs is a scalar particle, so the final state $W$s are produced with their polarizations opposite each other. Since the $W^-$ decays to a left-handed charged lepton and a right-handed neutrino, the $l^-$ tends point away from the $W^-$ spin and conversely the $l^+$ tends to point along the $W^+$ spin. These correlations produce a $ll\nu\nu$ final state in which the angle between the charged-leptons is on average smaller than in continuum $q\bar{q} \rightarrow WW$ production. Also the $t$-channel process in $q\bar{q} \rightarrow WW$ produces W's polarized along the beam direction and similarly produces leptons directed along the beam line.

This paper presents two multivariate analyses designed to exploit these differences to separate the $H \rightarrow WW^*$ candidates from the $WW$ continuum using 1.1 $fb^{-1}$ of 1.96 TeV $pp$ collisions recorded with the CDF detector [1]. A matrix element (ME) method calculates probabilities using the charged and neutral lepton kinematics alone, while a neural network (NN) method also uses variables that include the hadronic system. For both analyses a sample of candidate events is selected, described in Section 2, and then the multi-dimensional parameter spaces is
reduced to a one-dimension discriminant using either the matrix element or the neural network method, described in Sections 3 and 4, respectively.

2. Sample Selection and Modeling
Both analyses start from a sample of events that is aimed at separating $WW$ events from the far more common $Z/\gamma^* \rightarrow ll$ events. The ME analysis uses a set of cuts on the missing transverse energy $E_T$, a variable which quantifies the lack of momentum conservation in the plane transverse to the beamline. The NN analysis uses a neural network which is separate from the one used for the final discriminant, but uses the same set of variables listed in Section 4.

The resulting sample of events was modeled using a Monte Carlo calculation of the collision followed by a GEANT3-based [2] simulation of the CDF II detector response. The event generator used for $WW$ events is MC@NLO [3], for $WZ$, $ZZ$, and $t\bar{t}$ it is PYTHIA [4], for $W$ it is the generator described in [5]. A correction of up to 10% per lepton is applied to the simulation based on measurements of the lepton reconstruction and identification efficiencies in data using $Z$ decays. The $W+\text{jets}$ background is modeled using a data-driven method similar to that described in Reference [6]. The resulting sample is about half $WW$ events with 3.9(2.4) events expected for the ME(NN) analysis.

3. Matrix Element Technique
In order to separate the $H \rightarrow WW$ from $WW$, we use an event-by-event calculation of the probability $P_m(x_{\text{obs}})$ for mode $m$ to produce an event with the measured kinematics $x_{\text{obs}}$ (charged lepton momenta and $E_T$):

$$P_m(x_{\text{obs}}) = \frac{1}{\langle \sigma_m \rangle} \int \frac{d\sigma^\text{th}_m(y)}{dy} \epsilon(y)G(x_{\text{obs}}, y)dy$$

where $y$ are the true lepton four-vectors (include neutrinos), $\sigma^\text{th}_m$ is leading-order theoretical calculation of the cross-section for mode $m$, $\epsilon(y)$ is total event efficiency $\times$ acceptance, $G(x_{\text{obs}}, y)$ is an analytic model of resolution effects, and $\langle \sigma_m \rangle$ is the normalization. The modes considered in the calculation are restricted to $H \rightarrow WW$, $WW$, $ZZ$, $W+\text{jets}$, and $W\gamma$. Because of the missing neutrinos in the final state, the integral in this equation integrates out the unobserved degrees of freedom (DOF) reducing the 12 DOF in $y$ to the eight measured DOF. These probabilities are used to construct a discriminant $LR(x_{\text{obs}}) = \frac{P_H \rightarrow WW(x_{\text{obs}})}{P_H \rightarrow WW(x_{\text{obs}}) + \sum_m \text{bkg}_m P_m(x_{\text{obs}})}$ where bkg includes all of the background modes (listed above) for which $P_m$ is calculated and $f_m$ is the expected fraction of background $m$ in that sum. The one-dimensional $LR(x_{\text{obs}})$ distribution (divided into high and low signal to background based on the lepton identification categories) is then used to set a Bayesian 95% upper credibility limit on ratio of the cross-section of $gg \rightarrow H \rightarrow WW$ to the standard model expectation. A sample LR distribution and the limit as a function of Higgs mass are shown in Figures 1 and 2, respectively.

4. Neural Network Technique
The NN analysis used a the TMVA package [7] to implement a neural network to differentiate between the $q\bar{q} \rightarrow WW$ background and the $H \rightarrow WW^*$ signal. The input variables used can be classified as

- lepton kinematics: dilepton mass, leading and subleading lepton $p_T$, lepton angular separation, lepton azimuthal separation, and $E_T$.
- global event: total transverse and azimuthal between $E_T$ and nearest lepton or jet,
- jet structure: number of jets and leading and subleading jet $E_T$.

Cross-section limits derived from the one-dimensional NN output are shown in Figure 4.
5. Conclusion

Two searches for the process $gg \rightarrow H \rightarrow WW$ have been presented. At this time the two analyses use different lepton selections, minimum dilepton mass requirements, and systematics evaluations, so a quantitative comparison cannot be done. Work to unify these analyses is ongoing so the effect of the information used in the multivariate techniques can be quantified.

Both analyses show sensitivities approaching the standard model and rule out some parameter space of new physics. Figures 2 and 4 show the expected increase in the $gg \rightarrow H$ cross-section for a heavy fourth generation. Also shown in Figure 2 is the potential effect of an additional loop induced term in the Lagrangian with its scale set by dimensional analysis which could enhance the cross-section by a factor of 3 or more (or suppress it completely) [8].

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