

Searching for $H \rightarrow WW^*$ and Other Diboson Final States at CDF

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We report searches for standard model (SM) Higgs production decaying to $WW^{(*)}$ and continuum ZZ production in the two charged lepton and two neutrino final states. The data were collected with the CDF II detector at the Fermilab Tevatron and correspond to an integrated luminosity of 1.1 fb^{-1} . In order to separate the processes contributing to the final state, event probabilities calculated using the leading order differential cross-sections were used to construct a likelihood ratio discriminant. The observed (median expected) 95% C.L. upper limit for $\sigma(H \rightarrow WW^{(*)})$ with $160 \text{ GeV}/c^2$ mass hypothesis is $1.3(1.8) \text{ pb}$ which corresponds to $3.4(4.8)$ times the SM prediction at next-to-next-to-leading logarithmic level (NNLL) calculation.¹ The significance of the observed ZZ signal is 1.9σ and the 95% C.L. upper limit is 3.4 pb^{-1} which is consistent with the next-to-leading order (NLO) calculation of $1.4 \pm 0.1 \text{ pb}^{-1}$.

1 Introduction

The Higgs boson is introduced into the standard model (SM) to explain electroweak symmetry breaking and the origins of particle mass. Precision electroweak measurements and direct searches have constrained the Higgs mass to lie between 114 and $182 \text{ GeV}/c^2$ at the 95% C.L.² We search for the Higgs boson through the gluon fusion production and decay channel, $gg \rightarrow H \rightarrow WW^*$, which is the dominant channel for a Higgs with $m_H > 135 \text{ GeV}/c^2$. The maximum Higgs cross-section times branching fraction for the $p\bar{p} \rightarrow H \rightarrow WW^*$ process is 0.388 pb^{-1} at NNLL and occurs at the mass $m_H = 160 \text{ GeV}/c^2$. This is a small signal compared to continuum WW production which has a cross-section of 12.4 pb^{-1} at NLO³. A good understanding of the SM diboson production is essential for this search. To get a good signal to background ratio sample, we search for fully leptonic decay of $WW^* \rightarrow l^+l^-\nu\bar{\nu}$, where $l^\pm = e, \mu$ or τ and τ decays to e or μ . Pair production of Z bosons also decays to the same final state

and has not yet been seen at a hadron collider. The analysis strategy is to maximize the signal acceptance by loosening selection cuts and use the likelihood ratio discriminator (LR) calculated by Matrix Element methods to set the limits for 10 different Higgs mass hypotheses and to search for ZZ production.

2 Selection

The $l^+l^-\nu\bar{\nu}$ candidates are selected from two opposite-sign leptons from the same vertex and high missing transverse energy \cancel{E}_T . At least one lepton is required to satisfy the trigger and have $p_T > 20$ GeV/c. The other lepton has looser requirement $p_T > 10$ GeV/c to increase the kinematic acceptance. This sample receives contributions from continuum $WW, WZ, ZZ, t\bar{t}$, Drell-Yan, and $W\gamma$ and W +jets where the γ or jet is misidentified as a lepton. To suppress the W +jets background, we require leptons to be both track and calorimeter isolated such that the sum of the $E_T(p_T)$ for the calorimeter towers (tracks) in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ around the lepton is less than 10% of the E_T for electrons or p_T for muons and track lepton candidates. To suppress the Drell-Yan background, we require $\min \cancel{E}_{T,\text{rel}} > 25$ GeV, where $\min \cancel{E}_{T,\text{rel}}$ is defined to be:

$$\min \cancel{E}_{T,\text{rel}} \equiv \begin{cases} \cancel{E}_T & \text{if } \Delta\phi(\cancel{E}_T, \text{lepton}, \text{jet}) > \frac{\pi}{2} \\ \cancel{E}_T \sin(\Delta\phi(\cancel{E}_T, \text{lepton}, \text{jet})) & \text{if } \Delta\phi(\cancel{E}_T, \text{lepton}, \text{jet}) < \frac{\pi}{2} \end{cases} \quad (1)$$

This definition will reject events whose observed \cancel{E}_T is consistent with the mis-measurement of a single jet or lepton in the event. We further require the candidates to have less than 2 jets with $p_T > 15$ GeV and $|\eta| < 2.5$, in order to suppress $t\bar{t}$ backgrounds, $M_{\ell^+\ell^-} > 25$ GeV in order to suppress heavy flavor contributions, and exactly 2 leptons to suppress WZ contributions with a third lepton.

For the ZZ analysis, the $e\mu$ channel is not used and one additional cut, $\cancel{E}_{T,\text{sig}} \equiv \cancel{E}_T / \sqrt{\sum E_T} > 2.5$ GeV $^{\frac{1}{2}}$, where $\sum E_T$ is the scalar sum of calorimeter transverse energy, is applied to further suppress the effect of mis-measurement of unclustered energy.

3 Event Probability Calculation

In order to use all the kinematic information available in the event to distinguish the modes contributing to the selected sample, we use an event-by-event calculation of the probability density function $P_m(x_{\text{obs}})$ for a mode m which is either Higgs, WW , ZZ , $W\gamma$ or W +parton:

$$P_m(x_{\text{obs}}) = \frac{1}{\langle \sigma_m \rangle} \int \frac{d\sigma_m^{\text{th}}(y)}{dy} \epsilon(y) G(x_{\text{obs}}, y) dy \quad (2)$$

where x_{obs} are the observed lepton four-vectors and \vec{E}_T, y are the true lepton four-vectors (include neutrinos), σ_m^{th} is the MCFM³ 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 $\frac{1}{\langle \sigma_m \rangle}$ is the normalization. The function $\epsilon(y)$ describes the probabilities of a parton level object (e, μ, γ or parton) to be reconstructed as an observed lepton and is extracted from a combination of Monte Carlo and data. The event probability density functions are used to construct a dimensional discriminator:

$$LR(x_{\text{obs}}) \equiv \frac{P_H(x_{\text{obs}})}{P_H(x_{\text{obs}}) + \sum_i k_i P_i(x_{\text{obs}})}, \quad (3)$$

where H is Higgs, k_i is the expected fraction for each background and $\sum_i k_i = 1$. For SM ZZ search, we just use ZZ and WW to construct the discriminator $P_{ZZ}/(P_{ZZ} + P_{WW})$.

4 Systematics

The trigger efficiency uncertainty (0.3%–0.6%) is measured from data. The E_T resolution modeling uncertainty (1%–20%) and lepton identification uncertainty (1.4%–1.8%) are determined from comparisons of the data and the Monte Carlo simulation in a sample of dilepton events. For the $W\gamma$ background contribution, there is an additional uncertainty of 20% from the detector material description and conversion veto efficiency. The higher order effects in WW (4.5%) is assigned to be a half of the difference between the Pythia and MC@NLO⁴ acceptance. The theoretical cross-section uncertainties (10%–15%) are assigned from NLO calculation. The Parton Density Function uncertainties (1.9%–2.7%) are the quadrature sum of variations between CTEQ5L and CTEQ6M. The systematic uncertainty of the W +jets background estimate is determined to be 26.8% from the dependence on the sample selection in the measurement of the rate at which a jet is misidentified as a lepton. An additional 6% uncertainty originating from the luminosity measurement is assigned to both signal and background except W +jets.

5 $H \rightarrow WW^*$ Results

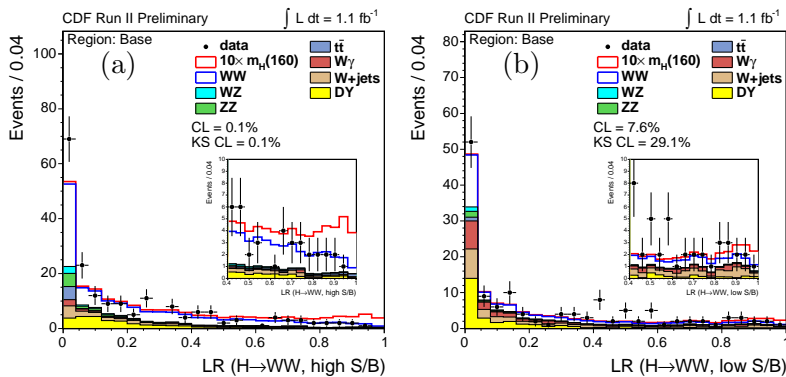


Figure 1: The LR distributions of Higgs mass 160 GeV/ c^2 for (a) High S/B channel and (b) Low S/B channel.

| | Expected |
|------------|------------------|
| WW | 132.9 |
| WZ | 9.5 |
| ZZ | 11.7 |
| $t\bar{t}$ | 9.6 |
| DY | 55.4 |
| $W\gamma$ | 24.7 |
| W +jets | 42.4 |
| Total | 286.1 ± 23.3 |
| Data | 323 |

Table 1: Expected and observed yields for $H \rightarrow WW$ selection.

The expected yield from each of the contributing backgrounds and the observed total are shown in Table 1 while the expected yield due to an SM Higgs is shown as a function of mass in Table 2. In order to maximize the sensitivity, the sample is divided into two parts based on the expected signal to background (S/B) ratio for lepton identification categories. The corresponding LR distributions are shown in Figure 1. The limit of Higgs production cross section is evaluated by performing a Bayesian binned maximum likelihood fit. All of the background normalizations are free parameters in the fit but constrained to their expectations with a set of Gaussian constraints considering all of the assumed correlations between the systematics uncertainties. The limits of Higgs production cross section times $WW^{(*)}$ decay branching ratio and their ratios to NNLL calculations (σ_{SM}) are shown in Table 2 and Figure 2.

6 ZZ Results

The expected and observed yields for the ZZ selection are shown in Table 3. To avoid binning away information, the variable $\log_{10}(1 - LR)$ (shown in Figure 3) is used to set an upper limit. The frequentist approach is used by performing background-only Monte Carlo experiments based on the expected yields varied within the assigned systematics. For each experiment a test statistic is formed from the difference in the log likelihood value with the background-only model and

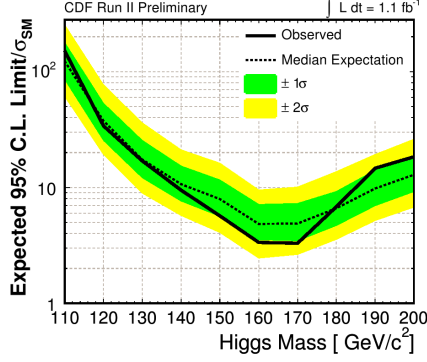


Figure 2: The ratio of 95% C.L. upper limit of $H \rightarrow WW^{(*)}$ production to NNLL calculation as a function of m_H .

| | N_{exp} | $\sigma_{95\%}$ (pb) | $\sigma_{95\%}/\sigma_{SM}$ |
|-----|-----------|-----------------------|-----------------------------|
| 110 | 0.2 | 8.9(7.1) | 151.2(122.6) |
| 120 | 0.6 | 4.7(4.9) | 33.9(37.4) |
| 130 | 1.4 | 4.0(3.8) | 17.0(17.4) |
| 140 | 2.4 | 3.0(3.4) | 9.5(10.7) |
| 150 | 3.2 | 2.1(2.9) | 5.7(8.0) |
| 160 | 3.9 | 1.3(1.8) | 3.4(4.8) |
| 170 | 3.9 | 1.2(1.7) | 3.3(4.9) |
| 180 | 3.3 | 1.9(1.8) | 6.8(6.6) |
| 190 | 2.4 | 2.8(1.9) | 14.6(9.8) |
| 200 | 2.0 | 2.8(2.0) | 18.4(12.9) |

Table 2: The expected yields, N_{exp} , and the observed (median expected) 95% C.L. upper limit $\sigma_{95\%}$, for the $H \rightarrow WW^{(*)}$ search.

with the signal yield at the best fit value. The observed significance is 1.9σ and we set the 95% CL upper limit of 3.4 pb, which is consistent with the SM NLO cross section of 1.4 ± 0.1 pb. This result has been combined with a search in the four charged lepton final state to yield a total significance of $3.0 \sigma^5$.

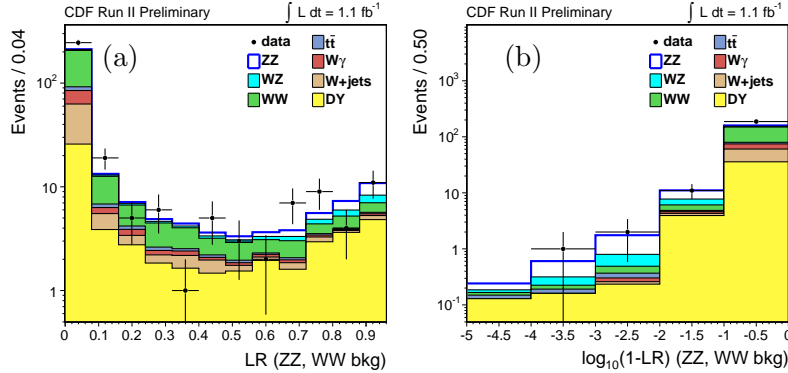


Figure 3: Distributions of (a) $LR = \frac{P_{ZZ}}{P_{ZZ}+P_{WW}}$ (b) $\log_{10}(1-LR)$

| | Expected |
|-------------|------------------|
| WW | 69.2 |
| WZ | 7.1 |
| ZZ | 10.7 |
| t \bar{t} | 5.1 |
| DY | 24.0 |
| W γ | 13.6 |
| W+jets | 23.2 |
| Total | 152.9 ± 11.6 |
| Data | 182 |

Table 3: Expected and observed yields for ZZ selection.

7 Summary

We have searched for a SM Higgs boson in the $l^+l^-E_T$ final state with the Matrix Element method. The observed 95% CL upper limit compares well with the expected upper limit as shown in Fig 2. We see no sign of a significant excess or deficit at any Higgs mass. The 95% CL upper limit for SM ZZ production is 3.4 pb and consistent with the SM NLO calculation.

References

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