CDF note 10212

Search for the Standard Model Higgs boson in the $\not\!\!E_T$ plus jets sample

The CDF Collaboration

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We search for the Higgs boson produced in association with a Z or W boson. We consider a scenario where $Z \to \nu\nu$, or $W \to l\nu$ and the lepton escapes detection; the Higgs boson decays into a $b\bar{b}$ pair. This analysis uses 5.7 fb^{-1} of CDF data. It implements a NN to remove the huge backgrounds. We check the goodness of our background modeling by comparing data against backgrounds in many control regions, and find good agreement. An additional NN is used to discriminate the Higgs signal from the remaining background. Observing no significant excess in the data we place 95% confidence level upper limits on the Higgs boson production cross section. For a mass of 115 GeV/c^2 the expected (observed) limit is $4^{+1.6}_{-1.2}$ (2.3) times the standard model prediction. This result is one of the most sensitive at the Tevatron.

Preliminary Results for Summer 2010 Conferences

I. INTRODUCTION

The search for the Higgs boson is one of the most active areas of research at the Tevatron. The electroweak fits to SM parameters, performed including the latest Tevatron top mass averaged measurements [1], point to the value $m_H = 87^{+36}_{-27}\, GeV/c^2$, or $m_H < 160\, GeV/c^2$ [2]. In the mass region above $\sim 135\, GeV/c^2$ the searches focus on $gg \to H$ where $H \to WW$, because of the high cross section and the "low" backgrounds when the W's decay leptonically. At low mass the searches focus on the production of H associated with either a Z or a W boson. It has to be noted that while both CDF and DZero have excluded the presence of the Higgs boson in the high mass region around 165 GeV[3], the low mass searches are lagging behind. In fact, none of the searches in the various low mass channels are reaching sensitivity to the Standard Model Higgs cross section. Nonetheless by combining these searches from CDF and DZero, the collaborations might have a chance to exclude or find a low mass Higgs boson.

This note describes a search for Higgs boson production in association with a Z or W boson in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV with the CDF detector at the Fermilab Tevatron. We consider a scenario where $Z \to \nu\nu$, or $W \to l\nu$ and the electron or muon escape detection; the Higgs boson decays into a $b\bar{b}$ pair.

We split the data-sample into various control regions and a signal region. To avoid potential bias in the search, we test our understanding of the sample in control regions. The observed data in signal region is analyzed after all background predictions and final event selection is determined.

The tools used in this analysis were used to measure the single top production cross-section for the first time in this channel [4]. This result was part of the recent observation of the single top quark by CDF[5]. We thus are at the stage where even the smallest backgrounds in this channel have been measured, apart from diboson production, which is as challenging as finding the Higgs boson due to the low invariant mass and the low branching ratio ; $\mathcal{B}(Z \to b\bar{b}) = 0.2$ while $\mathcal{B}(H \to bb) = 0.75$. Moreover, these tools, especially the QCD removing neural network, make this channel one of the most sensitive at low mass, and as sensitive as analyses requiring the presence of leptons.

The CDF detector is described in detail elsewhere [6].

II. DATA SAMPLE & EVENT SELECTION

This analysis is based on an integrated luminosity of 5.7 fb^{-1} collected with the CDFII detector. The data are collected with two $\not\!\!E_T$ plus two jets triggers [7]. The original trigger path used in the previous iterations has been kept for the first 2.1 fb^{-1} while we use an new trigger for the more recent data. The new trigger collects 10% more data with the current selections.

Jets are reconstructed from energy depositions in the calorimeter towers using a jet clustering cone algorithm with a cone size of radius $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$. Jet energies are corrected to account for effects that cause mismeasurements in the jet energy such as non-linear calorimeter response, multiple beam interactions, or displacement of the event vertex from the nominal position. We further correct jet emergies by reconstructing their four-momenta according to the H1 prescription [8]. Both the magnitude and the direction of $\not\!\!E_T$ are recalculated after correcting the energies of jets.

The trigger efficiency is obtained from data and is used to scale the Monte-Carlo based signal and background samples to correct for event loss during data taking. The overall efficiency of the online event selection is parametrized by the offline corrected $\not\!\!E_T$ and applied on the Monte Carlo samples providing a proper scaling for the simulated events.

From this inclusive dataset we select events offline with the following requirements:

- $\not\!\!E_T > 50\ GeV$ to avoid trigger inefficiencies

- leading and the second leading jets are within $|\eta| < 2.0$, at least one jet is central $|\eta| < 0.9$
- leading jet $E_T > 35GeV$, second jet $E_T > 25GeV$
- $\Delta R(1^{st}\ jet, 2^{nd}\ jet) > 1.0$
- reject events with 4 or more jets with $E_T > 15GeV$ in $\eta < 2.4$ region.

Events passing all of the above selections are referred to as the *pretag sample*.

We accept events with three jets in this channel. The main motivation is to accept events where one of the b quarks coming from the Higgs radiates a gluon. In addition to that, we also accept WH events where the charged lepton coming from the W is reconstructed as a jet. The latter case happens when the W decays to $e\nu$ and the electron fails the CDF electron identification algorithm, but is reconstructed as a jet; or when the W decays to $\tau\nu$ and $\tau \rightarrow hadrons$. Table I shows the contributions in Signal region from WH processes in 2 and 3 jet events.

Process	All events		e, τ matched jet	
	2 jet	3 jet	2 jet	3 jet
$W \rightarrow \tau\nu$	44%	61%	2.8%	33%
$W \rightarrow e\nu$	38%	25%	0.6%	4%
$W \rightarrow \mu\nu$	18%	14%	–	–

TABLE I: Contributions to 2/3jet events from different decay modes of the W-boson in WH events

The major drawback of accepting three-jet events lies in the increase of QCD multi-jet production and pair produced top background; the latter background is a secondary one at this point and can be dealt with at later stages in the analysis.

As a way to get a better estimate of the event true missing energy we calculate the $\not{p}_T$, which is defined as negative vector sum of charged particle track p_T's. For true $\not{E}_T$ events $\not{p}_T$ is highly correlated with calorimeter $\not{E}_T$, while for QCD events with mismeasured jets it is not. Thus, $\not{p}_T$ would provide an additional handle to separate mismeasurements from real $\not{E}_T$ events.

A. Tagging Algorithms

In order to improve the signal to background further, we need to identify jets originating from a b quark. We do so by employing both the SECVTX [9] and JETPROB [10] b-tagging algorithms. We subdivide the sample into three orthogonal tagging categories:

- both jets are tagged by SECVTX at the "tight" operating point
- one jet is tagged by "tight" SECVTX and the other jet by JETPROB tagger with $< 5\%$ probablity
- exactly one jet is tagged by "tight"SECVTX.

The double-tagged samples provide the most sensitivity in this analysis. In addition to that the single-tagged sample adds $\sim 10\%$ to the overall sensitivity.

B. Neural network to remove QCD

The main background in this search is the QCD production of two or three jets. We investigated the dynamic of the events in the sample, using a QCD heavy flavor Monte-Carlo simulation. Looking at a large set of variables, we keep here only the ones for which QCD has a very different behaviour with respect to the signal and the remaining backgrounds; the idea is that we will *remove* events very much not signal-like with a NN, and then use a second NN to *discriminate* the surviving, more signal-like backgrounds. The NN presented here is an improved version with that from the previous iteration, rejecting more background globally while still rejecting most of the QCD multi-jet and keeping high signal acceptance. This approach to remove QCD backgrounds has been successful used in the search for other signals, such as single top [4].

We train a mixture of 50% WH events and 50% ZH events ($m_H = 115\,\mathrm{GeV}$) against pre-tagged data weighted by our Tag-Rate-Function. The latter is the first step of our data driven technique (described below) to estimate this type of background.

We use the Multi Layer Perceptron (MLP) which is a simple feed-forward network, as implemented inside the TMVA [11] package. We will refer to the output of this NN as NN_{QCD}.

The variables used in the training are shown in table II.

Variable
Magnitude of $\vec{\not{E}}_T$
Magnitude of $\vec{\not{p}}_T$
$\not{E}_T/\sqrt{\sum E_T}$
$\not{E}_T/H_T$
$\not{H}_T$ / $\not{E}_T$
$M(\vec{\not{E}}_T, \vec{j_1}, \vec{j_2})$
$\Delta\phi$ between $\vec{\not{E}}_T$ and $\vec{\not{p}}_T$
Maximum of $\Delta\phi$ between any two jets
Maximum of ΔR between any two jets
Minimum of $\Delta\phi$ between the $\vec{\not{E}}_T$ and $\vec{j_i}$
Minimum of $\Delta\phi$ between the $\vec{\not{p}}_T$ and $\vec{j_i}$
$\Delta\phi(\vec{j_1}, \vec{j_2})$ in the 2-jet rest frame
Sphericity
$\sum {p_T}^{chgd}/{p_T}^{j^1}$
$\sum {p_T}^{chgd}/{p_T}^{j^2}$

TABLE II: Input variables to the neural network devised to suppress the QCD background, and the background coming from production of light flavor jets.

We use the output of this NN to define the final signal region. This cut reduces QCD by about one order of magnitude while keeping the signal efficiency between 90 and 95% (table III).

Cat.	Sig. Acc.	Bkg. Rej.	QCD Rej.
1S	90.0%	72.6%	89.1%
SS	94.9%	48.2%	87.0%
SJ	93.6%	64.8%	87.4%

TABLE III: Performance of the NN_{QCD} when discarding events with $NN_{QCD} \leq -0.3$.

III. SIGNAL AND BACKGROUND MODELING

A. Signal Modeling

The signal Monte Carlo samples are generated with PYTHIA [12]. The ZH/WH processes were generated for Higgs boson masses ranging from 100 GeV to 150 GeV in 5 GeV steps. The cross-sections are corrected for NNLO effects by a k-Factor of 0.99 in case of ZH production and 0.96 for WH production [13]. In these samples the Higgs is forced to decay into b-jet pairs, the Z boson to neutrinos or a pair of charged leptons, and the W decays to leptons. We use $\mathrm{Br}(Z \to \nu\nu) = 0.200$ $\mathrm{Br}(Z \to ll) = 0.03$ and $\mathrm{Br}(W \to l\nu) = 0.324$.

B. Background Modeling

In the signal events the Higgs decays into two b-jets, the Z boson into two neutrinos, and the W to leptons. The most important characteristics of these events are the large intrinsic missing transverse energy, relatively low jet multiplicity, and the lack of (detectable) isolated leptons. There are numerous Standard Model processes that can produce this signature.

The most significant background at the first stage of the analysis is the QCD multi-jet processes. QCD jet production has a large cross-section ($\sim \mu$b), which is about 9 orders of magnitude greater than the signal before requiring the first b-tag. Although, these processes generally do not have intrinsic $\not\!\!E_T$, mis-measured jets do cause imbalance in the total transverse energy by which the QCD events can pass the basic selection cuts if one of the jets is mis-tagged. Furthermore, QCD b-quark pair production yields taggable jets and if one b undergoes a semi-leptonic decay large $\not\!\!E_T$. In both cases, the missing transverse energy tends to be aligned parallel or anti-parallel to the first or second most energetic jet. This topology provides us one of the most effective devices against the QCD background.

To estimate the QCD background from data we have developed a Tag-Rate-Matrix (TRM) method. This allows us to estimate not only heavy flavor QCD production, but also processes with a light flavor jet falsely tagged as a b-quark. Both of these backgrounds are treated together in the following and are referred to as "multi-jet". In order to estimate the multi-jet background in the single-tagged sample we measure the probability to tag one jet from the "pre-tag" sample (Sec. II). The tag rate probabilities are parameterized as a function of:

- transverse energy of the jet
- pseudorapidity of the jet $|\eta|$
- event H_T, which is defined as a scalar sum of all jets in the event
- $\sum {p_T}^{chgd}/{p_T}^{j^{1(2)}}$, which provides a handle to separate light flavor jets from heavy flavor jets.

The matrix is measured in subsample of $\not\!\!E_T$+jets dataset, which is orthogonal to the final signal sample, and is defined with the following selections:

- QCD sample
  - All leptons are vetoed using loose lepton identifications
  - Azimuthal angular separation $\varphi(2^{nd}jet, \not\!\!E_T)$ $\leq$0.4
  - 50 GeV< $\not\!\!E_T$ <70 GeV

Two classes of top-production are considered in this analysis: the pair-production (PYTHIA) and the single top-production in the t- and s-channels (MADEVENT). They both yield a significant contribution to the background in the signal region. Due to the large mass and the semi-leptonic decay of the top, these events are energetic, bear large $\not{E}_T$ and high jet multiplicity. In the di-boson samples (PYTHIA), the bosons' decays are inclusive. In the W/Z + jets samples (ALPGEN), the bosons are forced to decay into leptons, or b-quarks. The parton showering is done by PYTHIA.

We check our modeling of the data-sample for all tagging categories in 3 control regions which are defined below.

C. Multi-jet Background Normalization

In order to estimate the backgrounds originating from QCD heavy flavor multi-jet production, as well as falsely tagged light flavor jet production, we use the TRM method described above. This method provides an excellent model to describe the shapes of the background. However, the normalization of the background is not well predicted and a scaling factor must be determined.

In order to constrain the expected rates of these backgrounds we utilize the intermediate region of our NN_{QCD} output ($-0.8 \leq NN_{QCD} \leq -0.3$). This region has the advantage to yield a ratio of QCD+HF to mis-tags which is closer to that found in our signal region and yet have enough statistics to allow for a reasonable uncertainty.

Once we are confident that the shapes are well reproduced by the matrix, we extract the normalization factor as described above, and use this SF in the final measurement.

IV. CONTROL REGIONS

In order to test our ability to predict the multi-jet backgrounds we check the performance of the method in two control regions. QCD Control Region 1 is a high statistics region where we check the data-based model and evaluate the systematic uncertainties on the shapes of various kinematic variables.

Since in the Signal Region we expect backgrounds originating from events with real high $\not{E}_T$, such as W/Z+jets, $t\bar{t}$, single top production and di-boson production, we test our ability to predict this types of backgrounds in another Control Region. In order to remain unbiased to our final region, we test Electroweak/Top backgrounds in the kinematic region similar to Signal Region, with the exception of requiring at least one lepton in the event (all events with leptons are vetoed in the Signal Region).

In order to test the data-driven estimation of QCD plus mis-tags in a more signal-like region, we define a QCD Control Region 2. This region intends to test multi-jet data-based modeling in a kinematic region which is very similar to Signal Region. This region is defined by reversing the NN_{QCD} cut to remain blind to the signal region. In summary:

- Control Region 1 (QCD Control Region 1)
  - All leptons are vetoed using the loose lepton identifications
  - Azimuthal angular separation $\varphi(2^{nd} jet, \not{E}_T) \leq 0.4$
  - $\not{E}_T > 70$GeV (*50 GeV< $\not{E}_T$ <70 GeV region is used to build the Tag-Rate-Matrix for the data-based model*)
- Control Region 2 (EWK/Top processes)
  - Minimum 1 loose lepton is required

- Azimuthal angular separation $\varphi(2^{nd} jet, \not{E}_T)$ >0.4

- Control Region 3 (QCD Control Region 2, Signal like) and Control Region 4 (SF Control Region 2, Signal like)
  - All leptons are vetoed using the loose lepton identifications
  - Angular separation $\varphi(1^{st} jet, \not{E}_T) \geq 1.5$, $\varphi(2^{nd} jet, \not{E}_T) \geq 0.4$, $\varphi(3^{rd} jet, \not{E}_T) \geq 0.4$
  - $-0.8 \leq NN_{QCD} \leq -0.3$ to have a sample with good statistics where to check the data modeling and to extract the multi-jet normalization scale factor

The region with $NN_{QCD} < -0.8$ is kept to serve as a (high statistics) cross check of the multi-jet normalization.

- Signal Region
  - All leptons are vetoed using the loose lepton identifications
  - Azimuthal angular separation $\varphi(1^{st} jet, \not{E}_T) \geq 1.5$, $\varphi(2^{nd} jet, \not{E}_T) \geq 0.4$, $\varphi(3^{rd} jet, \not{E}_T) \geq 0.4$
  - $NN_{QCD} > -0.3$

With respect to the previous iteration, the lepton identification cuts have been tightened a bit as to consider as identified leptons candidates with either a E_T (electrons) or p_T (muons) above 20 GeV. Even with this addition, the cuts are considered loose, to avoid overlap with other searches. This change in the cut increases signal acceptance by approximatively 5%.

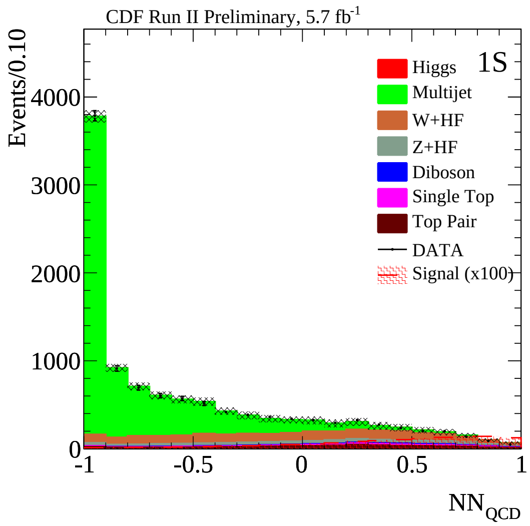
Comparisons of kinematic distributions in all Control Regions and in the Signal Region in all tagging categories are shown at CDF public web-page, accessible from:
http://www-cdf.fnal.gov/physics/new/hdg/hdg.html

Table IV lists the expected and observed event yields in Signal Region.

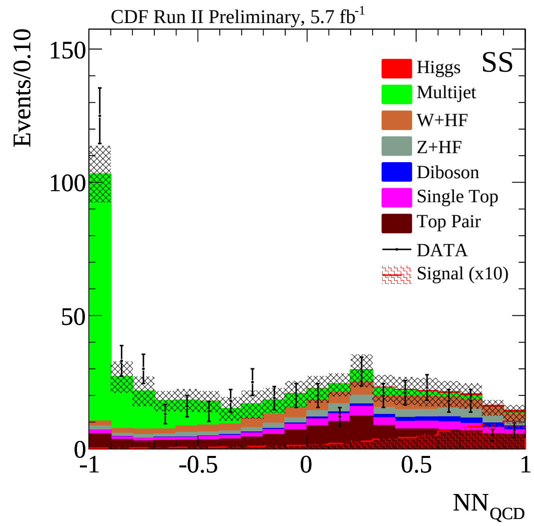
CDF Run II Preliminary, 5.7 fb^{-1}

Process	Excl. ST	ST+ST	ST+JP
Top Pair	381.1 ± 46.4	89.7 ± 13.0	76.7 ± 13.0
Single Top	136.4 ± 24.5	32.3 ± 6.3	24.6 ± 5.3
Diboson	106.5 ± 17.3	14.2 ± 2.6	12.4 ± 2.5
Z+HF	399.7 ± 129.6	32.7 ± 11.1	35.0 ± 12.3
W+HF	1065.2 ± 356.0	49.7 ± 17.4	68.5 ± 24.9
Multi-jet	1108.0 ± 113.8	43.5 ± 9.7	120.3 ± 13.3
Exp. Background	3196.9 ± 501.8	262.2 ± 33.5	337.7 ± 42.0
Observed	3220	237	301
$ZH \to llb\bar{b}$ ($m_H = 115$ GeV)	0.3 ± 0.02	0.2 ± 0.02	0.1 ± 0.02
$WH \to l\nu b\bar{b}$ ($m_H = 115$ GeV)	5.9 ± 0.3	2.8 ± 0.2	2.1 ± 0.3
$ZH \to \nu\nu b\bar{b}$ ($m_H = 115$ GeV)	5.6 ± 0.2	2.8 ± 0.2	2.0 ± 0.2
Exp. Signal	11.8 ± 0.5	5.7 ± 0.5	4.3 ± 0.5

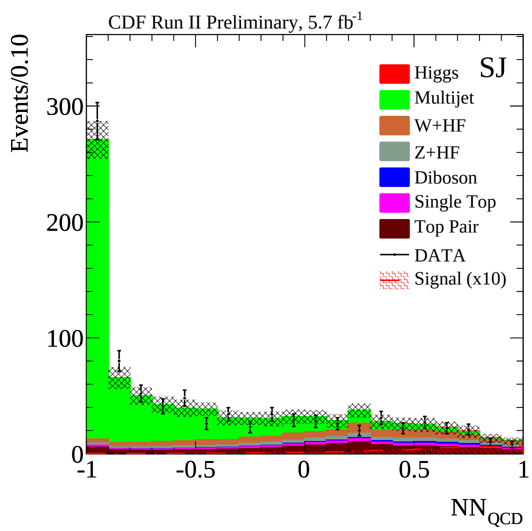
TABLE IV: Number of expected and observed events in the Signal Region in all tagging categories.



(a)QCD Rejection NN output, Exclusive Single Tag



(b)QCD Rejection NN output, ST+ST



(c)QCD Rejection NN output, ST+JP

FIG. 1: QCD Rejection Neural Network output

V. THE SEARCH FOR THE SIGNAL

As mentioned above, we selected the Signal Region to maximize signal significance keeping high signal efficiency. The biggest background rejected is QCD events faking high $\not{E}_T$. The dominating backgrounds at this point are QCD, mis-tags, W/Z+jets and $t\bar{t}$ in similar proportions. We study the dynamic of those events to develop a NN with the goal of discriminating the surviving backgrounds from the interesting signal.

A. A second NN to discriminate the signal from the backgrounds

Since the background composition is different in events with 2 or 3 jets, we train separate Neural Networks in each category. The outputs of these networks are combined in the end, when searching for the signal. For the NN training of 2-jet events we use a background sample made of 75% of MET+JETS untagged data (none of the jets in the event are tagged) and 25% of $t\bar{t}$ events ($50\% - 50\%$ mixture is used for the 3-jet NN training). The Higgs signal used for the training is a mixture of 50% WH events and 50% ZH events with $M_H = 115\,GeV/c^2$.

In order to increase the separating power of the NN, we implement the Track-based Discriminant (*trackMet* Neural Network), which was trained to optimize the separation of both ZH and WH events from QCD and $t\bar{t}$ backgrounds. A detailed description of the method can be found in [15].

The neural net chosen here is the Multi Layer Perceptron (MLP). The 6 input variables are:

- Invariant mass of all jets in the event: m_{jj}.
- Invariant transverse mass of all jets and $\not\!\!E_T$ in the event: $m_{T,jets,\not\!\!E_T}$
- Difference between the scalar sum of transverse energy of the jets and $\not\!\!E_T$: $H_T - \not\!\!E_T$;
- Difference between the vector sum of transverse energy of the jets and $\not\!\!E_T$: $\not\!\!H_T - \not\!\!E_T$;
- The output of the trackMet Neural Network
- Maximum of the difference in the R space between the directions of two jets, taking two jets at the time;

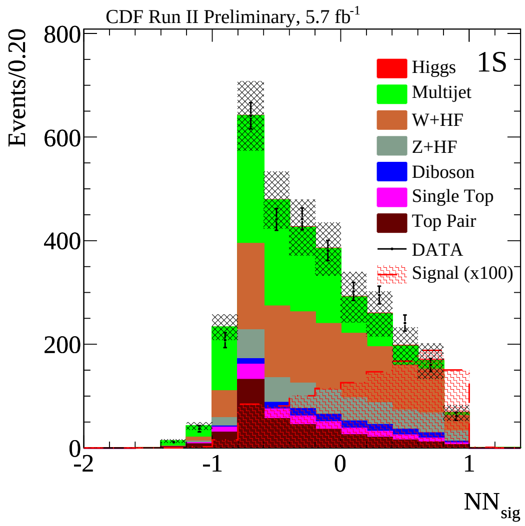
Fig. 2 shows the NN output which we will use to scan for the presence of a signal.

B. Systematic Uncertainties

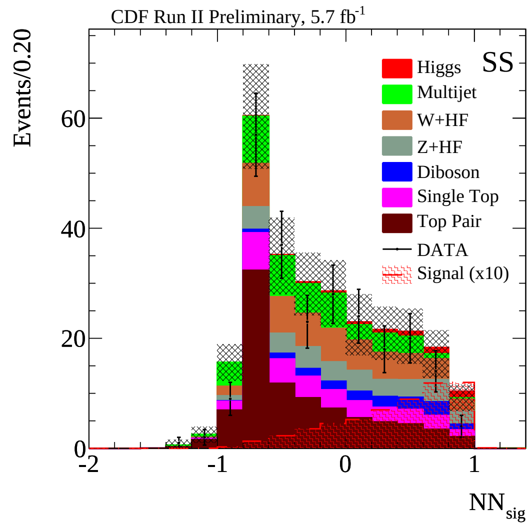
The systematic uncertainties are classified as correlated and uncorrelated errors considering the relations between the signal and the background processes. The correlated errors are taken into account separately for each processes in the limit calculation. The uncorrelated systematic uncertainties are: QCD multi-jet normalization (10% in single tagged, 21% in SECVTX+SECVTX, 11% in SECVTX+JETPROB samples), MC statistical fluctuations. Additionally, the statistical variations in TRM, which is used to estimate the multi-jet background, can also modify the distributions. It is taken into account by varying the TRM probability in each bin of the matrix by $\pm 1\sigma$, and the alternative shapes are used in the limit calculation. The correlated systematics are: luminosity (6.0%), b-tagging efficiency scale factor between data and Monte Carlo (5.2% for single and 10.4% for SECVTX+SECVTX, 11.6% for SECVTX+JETPROB samples), trigger efficiency (<3%), lepton veto efficiency (2%), PDF uncertainty (2%) and Jet Energy Scale. ISR/FSR systematic uncertainties (between 1% and 5%) are applied on the signal.

C. Results

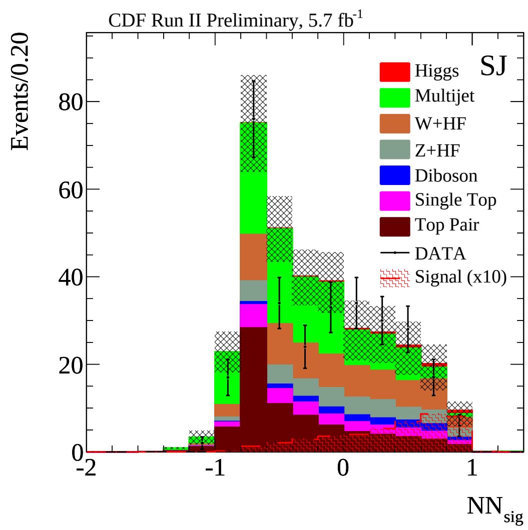
Considering the systematic uncertainties listed above, we computed the expected limit for the Higgs cross-section when the Higgs is produced with a Z/W boson and decays to two b-quarks where Z decays to neutrinos and W to leptons. We use Bayesian method for deriving the limits[16]. Table V shows the final result. All the cross-sections are ratios with respect to the Standard Model cross-section.



(a)Final NN output in Signal Region, Exclusive Single Tag



(b)Final NN output in Signal Region, ST+ST



(c)Final NN output in Signal Region, ST+JP

FIG. 2: NNoutput distribution in Signal Region

CDF Run II Preliminary, 5.7 fb^{-1}

Higgs mass (GeV)	VH limit, combined	
	Predicted	Observed
100	$3.1\ ^{+1.4}_{-0.9}$	2.3
105	$3.2\ ^{+1.4}_{-0.9}$	2.2
110	$3.5\ ^{+1.4}_{-1}$	2.3
115	$4\ ^{+1.6}_{-1.2}$	2.3
120	$4.8\ ^{+2}_{-1.4}$	2.8
125	$5.4\ ^{+2.5}_{-1.5}$	3.8
130	$6.7\ ^{+3.2}_{-1.9}$	4.7
135	$9.3\ ^{+3.6}_{-2.8}$	5.4
140	$11.9\ ^{+4.9}_{-3.4}$	7
145	$18\ ^{+7.2}_{-5.4}$	10.4
150	$32.5\ ^{+13.8}_{-9.5}$	19.4

TABLE V: The predicted and observed cross-section limits of the ZH and WH processes combined when $H \to b\bar{b}$ divided by the SM cross-section

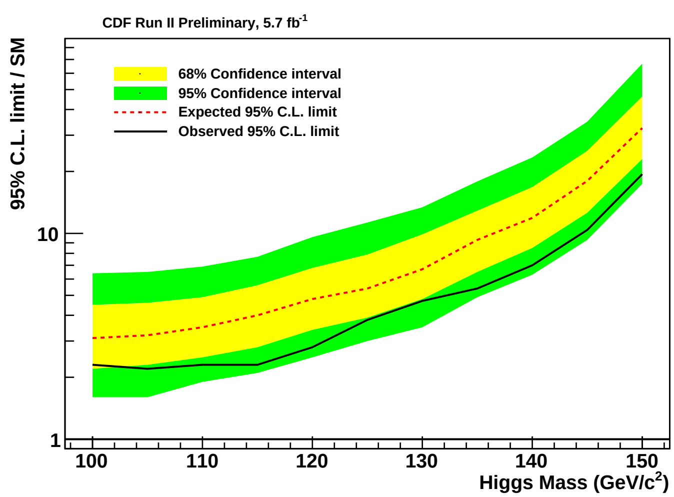


FIG. 3: 95% C.L. exclusion limits in the $VH \to \not{E}_T b\bar{b}$ channel divided by the SM cross-section

VI. SUMMARY

We have presented an updated search of the Standard Model Higgs boson in events $VH \rightarrow \not\!\!E_T + b\bar{b}$ using 5.7 fb^{-1} of CDF data. We use a NN to suppress the dominant QCD background. An additional NN is used to discriminate the signal from the surviving backgrounds. We have improved our background modeling and have analyzed additional data using a new trigger path. We expect to set a limit on the Standard Model Higgs cross section times the branching ratio of 4 in the hypothesis of $m_H = 115\,\text{GeV}$. In absence of a significant signal excess, we proceed to put an observed limit of 2.3, in the hypothesis of $m_H = 115\,\text{GeV}$. This result is one of the most sensitive at the Tevatron.

Acknowledgments

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