CDF Note 9248

Search for the Standard Model Higgs Boson in H$\rightarrow \tau\tau$ Channel at CDF Run II

$\sim$ Simultaneous Search for WH/ZH/VBF/H Processes $\sim$

The CDF Collaboration
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We report the results of a search for the Standard Model (SM) Higgs Boson using τ decay mode in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV . Signal processes under considerations are $W(\rightarrow q\bar{q'})H(\rightarrow \tau\tau)$, $Z(\rightarrow q\bar{q})H(\rightarrow \tau\tau)$, Vector Boson Fusion(VBF) $H \rightarrow \tau\tau$ and $gg \rightarrow H(\rightarrow \tau\tau)$. Candidate events are first selected by requiring one isolated lepton (e or μ) from leptonic τ decay (τ_{lep}), one hadronic τ (τ_{had}) and at least 2 jets in an event. In order to further improve search sensitivity, a technique we employ is a multivariate artificial neural network (NN). After optimizing a capability to discriminate signal against various backgrounds, four SM Higgs processes are simultaneously searched with the final NN shape. Using 2.0 fb^{-1} data accumulated by CDF II detector at the Tevatron collider at Fermilab, there was no clear excess in search region. Therefore we set a 95% confidence level upper limit on the cross section times branching ratio ($\sigma \times BR(H \rightarrow \tau\tau)$) relative to the SM prediction. The observed limit ($\sigma(limit)/\sigma(SM)$) is from 30 to 159 for Higgs mass (M_H) from 110 to 150 GeV/c^2 while the expected limit ranges from 24 to 112.

Preliminary Results for Winter 2008 Conferences

I. INTRODUCTION

One of the biggest challenge and immediate task in high energy particle physics is to search for the Standard Model (SM) Higgs boson that is undiscovered yet as of 2008, but its existence is strongly predicted to explain a mechanism of electroweak symmetry breaking. Although the mass (M_H) is not directly predicted by theory, the direct search from LEP2 experiment indicates that the Higgs mass has to be greater than 114.4 GeV/c^2 at 95% confidence level while current electroweak global fits provide the upper bound of $M_H <$ 182(144) GeV/c^2 when the LEP limit is (not) taken into account. Considering great success of the SM with those constraints, it is natural to focus on searching for the Higgs boson in this mass region. At the Fermilab Tevatron, providing $\bar{p}p$ collisions at $\sqrt{s}$ = 1.96 TeV, the CDF/DØ experiments have performed the search with various production processes depending of M_H. In low mass range ($M_H = 110 \sim 135$ GeV/c^2) all analyzes so far have looked for only V$H \to b\bar{b}$ decay mode. (Note that both CDF and DØ have implemented MSSM Higgs search with $H \to \tau\tau$ decay[1, 2], but no analysis has been optimized for the SM Higgs to $\tau\tau$ channel specifically). In order to obtain further sensitivity as well as to investigate different Higgs decay mode, we optimize the SM Higgs search in $\tau\tau$ decay mode and describe the first results with 2.0 fb^{-1} data accumulated in CDF RunII.

Four independent signal processes listed below are simultaneously searched.

- W($\to q\bar{q}'$)H($\to \tau\tau$) : $\tau\tau$ + 2 jets
- Z($\to q\bar{q}$)H($\to \tau\tau$) : $\tau\tau$ + 2 jets
- VBF H($\to \tau\tau$)qq' : $\tau\tau$ + 2 jets
- $gg \to$H($\to \tau\tau$) : $\tau\tau$ + njets (in this analysis, n$\geq$2 is required)

Feynman diagram of each signal process is shown in Figure 1. In this note, we focus on detecting 2τ's + 2jets in an event. (It is of course possible to add 0jet and 1jet events from gluon fusion process but we just ignore them now because of much worse S/B). Within the SM framework, the branching ratio (BR) of $H \to \tau\tau$ is smaller than that of $b\bar{b}$ by roughly 10%. However this disadvantage can be significantly recovered by looking at W/Z boson decaying to 2jets (BR:67/70%) and adding the Vector Boson Fusion (VBF) and gluon fusion (ggH) processes. Moreover, in LHC, VBF $H \to \tau\tau$ *i.e.* $\tau\tau$+2jets process is one of the main channel for Higgs discovery in this mass range (if exist). Therefore, detailed studies and understandings of this event signature would be useful and commonly shared beyond the experiments (Tevatron to LHC).

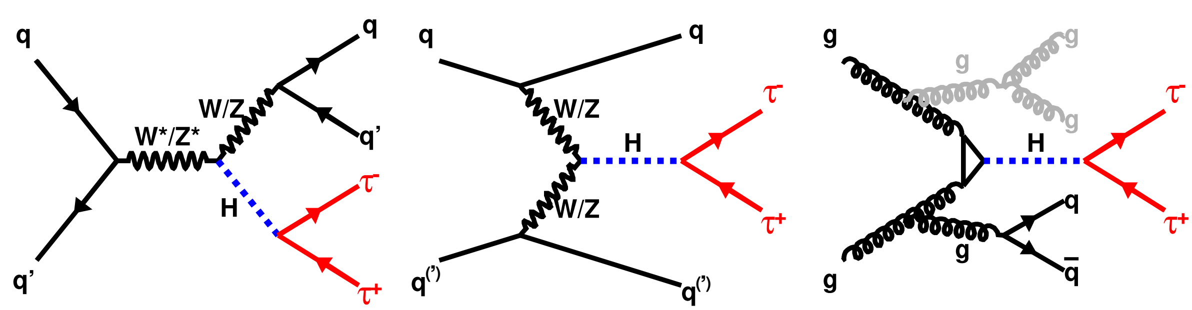

FIG. 1: Feynman diagrams for V(V:W or Z)H, VBF and ggH, result in 2τ+2jets event topology.

τ lepton can be only detected after its decay, either leptonically ($\tau \to e+\nu_e+\nu_\tau$, $\tau \to \mu+\nu_\mu+\nu_\tau$) at $\sim$ 17% for each lepton type, or hadronically ($\tau \to \nu_\tau + h$ or $\tau \to \nu_\tau + hhh$) at 65% (with $\geq$0 assoicated π° production). Therefore, depending on τ decay mode, there are three channels we could possibly use: $\tau_{lep}\tau_{lep}$(BR=12%), $\tau_{lep}\tau_{had}$(BR=45%), $\tau_{had}\tau_{had}$(BR=43%). We only use $\tau_{lep}\tau_{had}$ mode which is *"golden mode"* because of the highest BR and also due to the fact that a large QCD rejection is expected by having one good isolated lepton.

II. DATA SAMPLE & EVENT SELECTION

This analysis is based on an integrated luminosity of 2.0 fb^{-1} collected with the CDF II detector from March 2002 through May 2007. The details on CDF II detector can be found in [3].

The $\tau_{lep}\tau_{had}$ candidate events are pre-selected with *lepton plus track* triggers that require one central ($|\eta| <\sim 1.0$) lepton (e or μ from τ_{lep}) and an isolated track associated with τ_{had} candidate, both pointing central detector. These two objects have to be well separated by $\Delta\phi > 10°$. The overall trigger efficiency is a product of lepton and τ_{had} efficiency which is greater than 90%. From this dataset we select events offline by identifying a reconstructed electron E_T (muon P_T) greater than 10 GeV. To ensure that leptons come from leptonic τ decay they must be isolated. Also a τ_{had} candidate must satisfy the following requirements: We start with a (triggered) charged track with $P_T > 6$ GeV/c as a *seed track*. The direction of the seed track is used as the axis of a signal cone (α^{sig}) and an isolation (α^{iso}) annulus. The size of the signal cone α^{sig} is determined by taking a minimum of 10° and (5 GeV)/E^{calo} where E^{calo} is the calorimeter cluster energy associated with τ candidate. The minimum of α^{sig} is set to 0.05 rad driven by resolution effects. The isolation annulus extends from α^{sig} to $\alpha^{iso} = 30°$. The τ decay mode is classified by the number of *prongs* defined as the number of tracks with $P_T > 1$ GeV/c inside the signal cone. We accept 1 or 3 prongs and impose no track in the isolation annulus. The contributing π° candidates with $E_T > 1$ GeV inside the signal cone of 0.17 rad are treated as decay products of τ_{had}. The four-momentum of τ_{had} candidate then is calculated as $P^{vis} = \sum P^{track} + \sum P^{\pi^\circ}$. Based on this definition, we require $P_T^{vis} > 15$ GeV/c and invariant mass of τ_{had} to be less than 1.8 GeV/c^2. The $e/\mu \to \tau_{had}$ fake is significantly suppressed by imposing $E_{had}/P^{track} > 0.2$ cut where E_{had} is the energy deposit in the hadronic calorimeter. Jets are reconstructed using a fixed-cone algorithm with $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$. At least 2 jets with E_T >15 GeV and $|\eta|$ <2.5 are required. Missing transverse energy ($\not{E}_T$) is corrected by event vertex, muon candidate, and jet energy correction accordingly but no cut is made in the event selection. We further require that lepton and τ_{had} candidates to be the opposite sign (OS) due to the charge conservation of Higgs decay. The Drell Yan (DY) contributions($Z \to ee/\mu\mu$) are further suppressed by rejecting events if the invariant mass of $lepton + \tau_{had}$ lies in 80 to 110 GeV/c^2 and $E_{had}/P < 0.4$ in τ_{had} candidate. The veto is only applied to 1-prong τ_{had} events and rejects roughly 70% of DY events while only 1∼2% for Higgs signal is lost. The contribution of $Z \to ee/\mu\mu$ to overall background in the signal region becomes less than 5% due to this veto cut.

III. SIGNAL ACCEPTANCE & EXPECTATION

All signal Monte Carlo samples have been generated by PYTHIA (v6.216) with run-dependent detector simulation and overlayed minimum bias appropriately. For each of four processes, there are different Higgs mass samples in a range of 110 GeV/c^2 to 150 GeV/c^2. Acceptance and the number of expected event are summarized in Table I for each Higgs mass point. The numbers in the table are after all selection cuts including two or more jets. There are small mass dependence in acceptance and the total expectation ranges from 0.83 to 0.12 events for M_H=110 to 150 GeV/c^2.

L=2fb^{-1}	M_H=110	M_H=115	M_H=120	M_H=130	M_H=140	M_H=150
WH	0.25(1.5%)	0.21(1.5%)	0.18(1.6%)	0.11(1.7%)	0.06(1.8%)	0.025(1.9%)
ZH	0.16(1.5%)	0.14(1.6%)	0.11(1.6%)	0.07(1.8%)	0.04(1.9%)	0.017(2.0%)
VBF	0.14(1.4%)	0.13(1.4%)	0.12(1.5%)	0.09(1.6%)	0.05(1.7%)	0.024(1.9%)
ggH	0.28(0.18%)	0.28(0.21%)	0.26(0.24%)	0.18(0.26%)	0.11(0.3%)	0.052(0.33%)
Total	0.83±0.01	0.76±0.01	0.67±0.01	0.45±0.004	0.26±0.002	0.12±0.001

TABLE I: The expected number of events (acceptance in %) for each signal process with various Higgs mass. The numbers are after all event selection including N^{jet} ≥2 at $2fb^{-1}$ requirement. Quoted errors are statistical only.

IV. BACKGROUNDS

We rely on Monte Carlo simulation for Z+jets, $t\bar{t}$, diboson(WW/WZ/ZZ) and (a portion of) W+jets productions. ALPGEN (v2.10) with MLM matching (followed by PYTHIA v6.325 parton showering) has been used for Z+jets modeling (and for Add-on Wjets which will be described later). $t\bar{t}$ and diboson processes are generated with PYTHIA(v6.216). The expected number of events is obtained by

$$N^{ik} = \sigma^i \times A^{ik} \times \epsilon^k_{trig} \times \epsilon^k_{ID} \times \int Ldt \quad (1)$$

where i denotes each background process and k corresponds to each lepton type (e or μ). σ^i represents the production cross section for a process i. A^{ik} is an acceptance for i-th process and k-th lepton type, estimated by

Monte Carlo simulation. ϵ^k_{trig} and ϵ^k_{ID} are trigger efficiency and ID scale factor that depend on lepton type k. We properly calculate the number of events for each lepton type separately and obtain the total expectation by summing all lepton types. Systematic uncertainties related to this calculation will be all summarized in Table IV.

The same sign ($Q^{lep} \times Q^{\tau} > 0$) data is directly used for the estimate and model of QCD, γ+jets and (a portion) of W+jets events. In principle, those backgrounds can contribute into the signal region only when $jet \rightarrow \tau_{had}$ (also $jet \rightarrow lepton$ in QCD). In QCD and γ+jets fake, there is no charge correlation between lepton and τ_{had} candidates so the amount of SS and OS is expected to be equal. This assumption has been verified by checking lepton isolation distributions as in left four plots in Figure 2 in which OS observed data is well modeled by SS data especially in high tail (QCD dominant) region. In W+jets production however, when W decays either to e or μ and jet faking τ_{had}, there is a charge correlation between lepton (from W) and outgoing quark that causes more events into OS category, and so $N_{OS} > N_{SS}$. Therefore an extra W+jets contribution ($=N_{OS} - N_{SS}$ as Add-on Wjets) has to be added. This correction is done by two steps. The first step is to evaluate SS W+jets K-factor(Data/MC). The second is to obtain a scale factor of OS/SS ratio between data and Monte Carlo. Using loose τ_{had} ID sample (in which some ID cuts e.g. visible mass cut are released) which is exclusive to signal samples of tight τ_{had} ID , we evaluated SS K-factor to be 1.4±0.2 and the scale factor of OS/SS ratio is 1.04±0.04. Based on those scale factors, "Add-on Wjets" contribution is properly included. Right four plots in Figure 2 show distributions of transverse mass of lepton and $\not\!\!E_T$. Also in Drell Yan ($Z/\gamma^* \rightarrow ee, \mu\mu$) events, there are two possibilities that mimic our signal events - the hadronic τ object originates from either $e, \mu \rightarrow \tau_{had}$ or $jet \rightarrow \tau_{had}$ where jets are produced by initial state radiation activity. In the first case, (*i.e.* if a lepton fakes τ_{had}), we expect lepton and τ_{had} candidates are OS at almost 100% of the time. In second case however since there is no charge correlation between lepton and jet($\rightarrow \tau_{had}$), the same ratio of OS and SS events can be expected. Thus we drop such events from Monte Carlo sample by looking at generator information (by matching $\Delta R < 0.4$) to avoid double counting between SS data and Monte Carlo simulations. After those careful corrections, the expected number of background and observed data are summarized in Table II. The predictions and observed data are consistent within uncertainties.

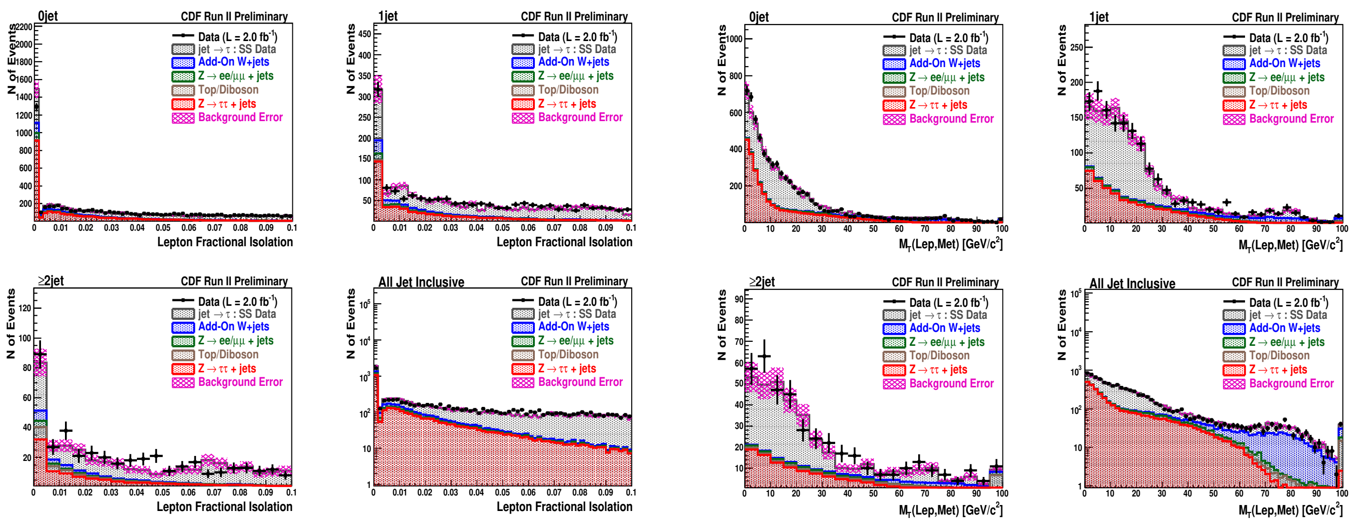

FIG. 2: Left four plots are lepton fractional isolation distributions and right four plots are distributions of transverse mass of lepton and $\not\!\!E_T$. In each four plots, upper left(right) are 0jet(1jet) events and lower left(right) are $\geq 2jets$(all jets inclusive) events.

V. ARTIFICIAL NEURAL NETWORK

In order to further improve search sensitivity, in this analysis a neural net technique is employed. We use the Root-Jetnet interface to the Jetnet neural net program package with standard back-propagation method. After comparing sensitivities from possible configurations, the following procedure is selected to be performed:

1. Train NN for Mixed signal vs $Z \rightarrow \tau\tau$ (NN$^{MixS}_Z$)

Source	Model	$e/\mu+\tau_h+$ 0jet	$e/\mu+\tau_h+$ 1jet	$e/\mu+\tau_h+\geq$2jet
Z$\to\tau\tau+jets$	ALPGEN	2746.8±260.7	465.1±108.3	99.1±25.9
Z$\to ll+jets$	ALPGEN	216.9±23.0	48.3±7.8	11.7±2.2
$t\bar{t}$	PYTHIA	0.10±0.02	2.2±0.4	16.9±2.7
Diboson	PTYHIA	21.9±3.0	7.6±1.1	4.6±0.8
$jet\to\tau_{had}$	SS data	3269±57.2	876±29.6	220±14.8
Add-on $W+jets$	ALPGEN	414.9±61.7	99.6±14.9	21.5±3.2
Total Background		6669.6±290.8	1498.8±116.8	373.8±32.4
		Control Region	Control Region	Signal Region
Observed (2 fb^{-1})		6653	1571	410

TABLE II: The predicted number of background events and observed events with 2 fb^{-1}. Quoted errors include both statistical and systematic uncertainties listed in Table IV.

2. Train NN for Mixed signal vs $t\bar{t}$ (NN$_{t\bar{t}}^{MixS}$)
3. Train NN for Mixed signal vs QCD (NN$_{QCD}^{MixS}$)
4. For a given event, calculate 3 NN scores above and choose minimum NN score.
5. Use minimum NN score (1D) to fit signal and background.

As training samples, Monte Carlo events are used for $Z\to\tau\tau$ and $t\bar{t}$. Training samples are always exclusive to the samples to be used for the final template. For QCD, non-isolation lepton sideband events are used. Typically we have 2000 events for each training. Each signal mixing rate is chosen to be the same for WH/ZH/VBF/ggH.

For the choice of input variables, we perform an iterative procedure. First the best variable (from 16 kinematic variables) are determined. This variable is kept as the first input. Then again, we loop over all other variables to select the second best variable. We repeat this procedure until performance error becomes plateau. For the training for Mixed Signal vs Z$\to\tau\tau$ (NN$_Z^{MixS}$), error gets plateau at N=5 and no gain above that point. Thus we stop at N=5. For $t\bar{t}$ and QCD, this happens at N=7 and N=4, respectively. Variables selected in this procedure are summarized in Table III.

Signal Background	Mixed Signal $Z(\tau\tau)$	Mixed Signal $t\bar{t}$	Mixed Signal QCD
τ_{had} visible P_T		$\surd$	
τ_{had} seedtrack P_T		$\surd$	
Mass(jet1,jet2)	$\surd$		
Transverse Mass(l,$\not\!\!E_T$)		$\surd$	
H_T	$\surd$		$\surd$
dϕ(l,$\not\!\!E_T$)		$\surd$	$\surd$
dϕ(l,τ)	$\surd$	$\surd$	
Mass(l,τ,$\not\!\!E_T$)	$\surd$	$\surd$	$\surd$
Full Mass(τ,τ)	$\surd$	$\surd$	$\surd$
N$_{input}$($\surd$)	5	7	4

TABLE III: A summary of NN input variable choice for each NN training.

VI. SYSTEMATIC UNCERTAINTIES

Several sources of systematic uncertainties are taken into account in this analysis and described below.
6% and 0.5% are assigned for luminoisty calculation and Z vertex cut uncertainties. Uncertainties on trigger efficiency and lepton ID scale factor depend on lepton type. We take 0.3%, 1.0% and 3.0% as trigger efficiency errors for electron, muon and tau objects and also assign 2.4%, 2.6% and 3.0% for electron, muon τ ID and reconstruction uncertainties respectively. These errors are accounted for all MC based sources including signal events. Uncertainties on cross section or normalization depend on each process. For Drell Yan process, we take 2.2% based on CDF measurement[4]. For $t\bar{t}$ and diboson processes, 13.4% and 10.0% are assgined respectively. For Add-on W+jets, since the normalization

factor is extracted completely from data, we don't assign any MC related systematics but K-factor has its own error of 14.8% (1.4±0.2). For Higgs signal errors on theory calculation are typically 10% or less [5]. As uncertainties of Monte Carlo modeling, we checked that the difference between Monte Carlo and data in $Z \to ee/\mu\mu$ events are orders of 10% to 20% in $\geq$ 2jet bin. Therefore we take conservative errors of 20%(10%) for $Z \to \tau\tau (Z \to ll)$. Uncertainty from parton distribution function (PDF) is taken into account for Higgs signal. We produced weight functions for each of 20 eigen-vector ($\pm 1\sigma$) in CTEQ6M and also for MRST72 and MRST75 (different α_s value). Then these two are added in quadrature. Uncertainties on initial state radiation(ISR) and final state radiation(FSR) for signal processes are typically very small except for ggH process (12.3%). This is because gluons are more affected by parameter tuning and jets in ggH are basically all coming from the initial state radiations. Finally we take into account both rate and shape uncertainties from jet energy scale uncertainties.

The systematic uncertainties are summarized in Table IV.

	Systematic Uncertainties (%)									
Source	$Z \to \tau\tau$	$Z \to ll$	$t\bar{t}$	Diboson	$jet \to \tau$	Add. Wjet	WH	ZH	VBF	ggH
	ALPGEN	ALPGEN	PYTHIA	PYTHIA	SS Data	ALP+Data	PYTHIA	PYTHIA	PYTHIA	PYTHIA
Luminosity	6.0	6.0	6.0	6.0	-	-	6.0	6.0	6.0	6.0
$\lvert Z_{vtx} \rvert$	0.5	0.5	0.5	0.5	-	-	0.5	0.5	0.5	0.5
e Trig.	0.3	0.3	0.3	0.3	-	-	0.3	0.3	0.3	0.3
μ Trig.	1.0	1.0	1.0	1.0	-	-	1.0	1.0	1.0	1.0
τ Trig.	3.0	3.0	3.0	3.0	-	-	3.0	3.0	3.0	3.0
e ID	2.4	2.4	2.4	2.4	-	-	2.4	2.4	2.4	2.4
μ ID	2.6	2.6	2.6	2.6	-	-	2.6	2.6	2.6	2.6
τ ID	3.0	3.0	3.0	3.0	-	-	3.0	3.0	3.0	3.0
JES(Shape)	15.6	13.0	2.0	9.5	-	-	3.4	3.1	4.1	13.5
MC Stat.	0.5	4.0	1.0	1.0	-	(1.0)	1.0	1.0	1.0	2.0
σ or Norm.	2.2	2.2	13.4	10.0	SS Stat.	14.8(KF)	5.0(NNLO)	5.0(NNLO)	10.0(NLO)	10.0(NNLO)
MC Model	20	10	-	-	-	-	-	-	-	-
PDF	-	-	-	-	-	-	1.2	0.9	2.2	4.9
ISR/FSR	-	-	-	-	-	-	2.0/0.3	0.9/0.5	2.5/1.2	12.3/1.3

TABLE IV: A Summary of systematic uncertainties in $\tau_{lep}\tau_{had} + \geq 2jets$.

VII. RESULTS

The resulting NN distributions with 2fb^{-1} data are shown in Figure 3 for NN_Z^{MixS}, NN_{Top}^{MixS} and NN_{QCD}^{MixS} outputs. The final NN shape after minimum selection of those three NN scores is shown in Figure 4.

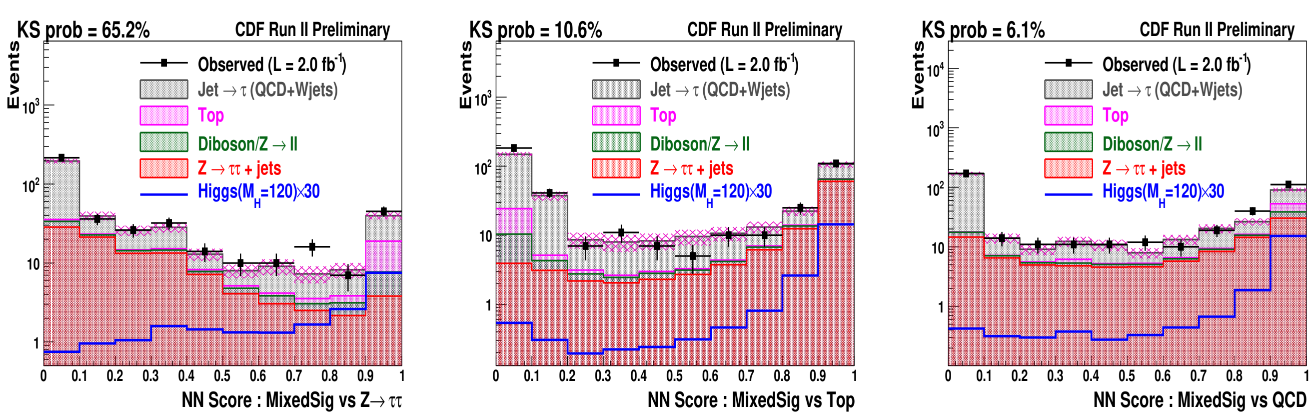

FIG. 3: From left to right: NN$_Z^{MixS}$, NN$_{TOP}^{MixS}$, NN$_{QCD}^{MixS}$ for observed data and predictions. Signal×30 is also shown for shape comparisons.

Since background predictions are consistent with data with reasonable Kolmogorov-Smirnov (KS) probabilities and there is no clear excess found in signal region, we set an upper limit on the SM production cross section times

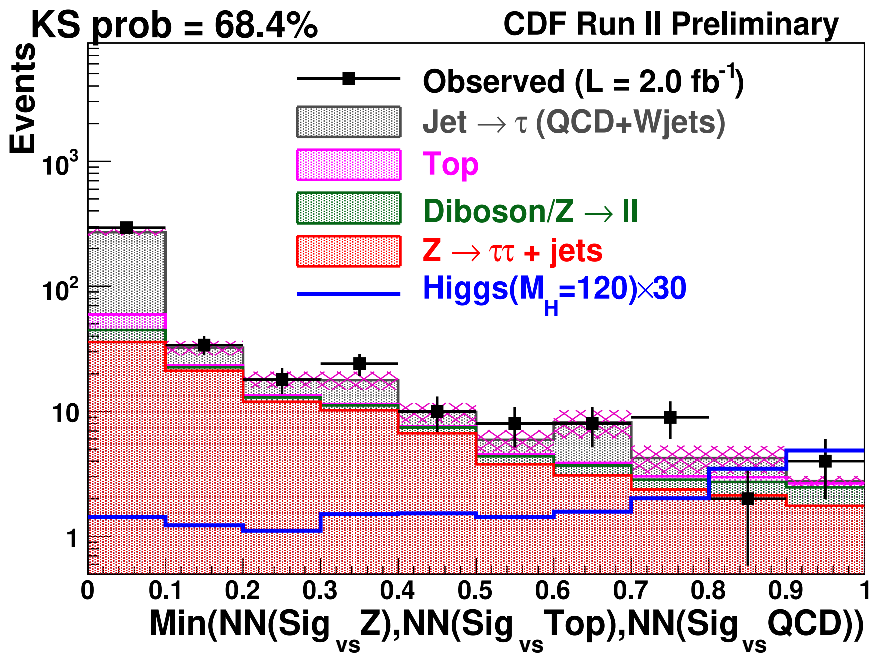

FIG. 4: The Final NN distribution after selecting minimum of 3 NN outputs.

branching ratio of $H \to \tau\tau$ with the assumption that the data is consistent with our predictions. Based on the final NN shape, we perform 1 dimensional binned maximum likelihood method to obtain 95% confidence level limits relative to the SM predictions($\sigma(limit)/\sigma(SM)$). Results are summarized in Table V and also in Figure 5 with the expectations.

Mass	Expected Limit (Median)	Observed Limit
110	$25.8^{+11.5}_{-7.5}$	32.5
115	$24.8^{+10.5}_{-7.5}$	30.5
120	$24.2^{+10.0}_{-7.0}$	30.0
130	$32.3^{+13.1}_{-9.5}$	39.5
140	$52.8^{+22.5}_{-13.5}$	67.5
150	$111.7^{+49.5}_{-33.0}$	159.0

TABLE V: Expected and observed 95% confidence level Limit relative to SM prediction for each mass point.

VIII. CONCLUSIONS

We performed a simultaneous search for four SM Higgs processes, WH, ZH, VBF and ggH into $2\tau + 2jets$ events with 2.0 fb^{-1} data accumulated at the CDF. Since there was no clear excess in our search region unfortunately, we set a 95% confidence level upper limit. The expected limit on the SM cross section times branching ratio relative to the SM prediction ranges from 24 to 112 for 110 GeV/c^2 to 150 GeV/c^2 Higgs Mass. This is about 30∼50% sensitivity compared to other single analysis ($WH \to l\nu b\bar{b}$, $ZH \to llb\bar{b}$, $ZH \to \nu\nu b\bar{b}$). The observed limit ($\sigma(limit)/\sigma(SM)$) is from 30 to 159. By itself, an impact might not be so strong, but this analysis can contribute to improve overall sensitivity in combination roughly 5-10%[6]. This is because this analysis is statistically independent and also most of the systematic uncertainties are uncorrelated to $H \to b\bar{b}$ analyzes.

On the other hand, this is not only the first result for the SM Higgs search using τ decay mode at Tevatron but also the first approach to look for four different Higgs production processes simultaneously with final state basis. Thus this analysis could be a great break-through for the SM Higgs search using τ mode and strongly connected to LHC Higgs searches where $2\tau + 2jets$ event becomes more important channel for low mass Higgs discovery.

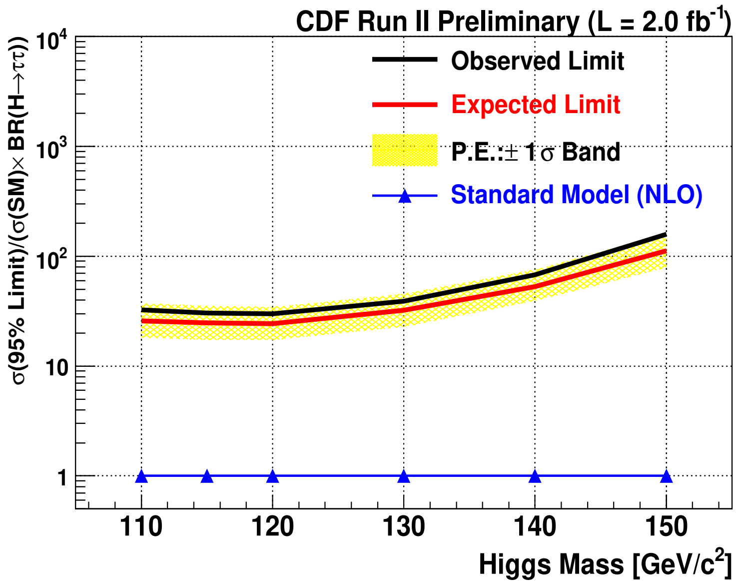

FIG. 5: Observed and expected 95% CL upper limit relative to the SM prediction. Expected line is based on Median of pseudo-experiments.

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