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Results From a New Run 1 $WH \to \ell\nu b\bar{b}$ Search

Christopher Neu, Richard Hughes, Phillip Koehn, Evelyn Thomson, Brian Winer
The Ohio State University

Abstract

This note details the results of a new Run 1 $WH \to \ell\nu b\bar{b}$ search. A two stage event selection was utilized. Standard selection criteria were applied in order to assemble the W+2jet+$\geq$ 1 SECVTX tag data sample that has been the focus of several previous Run 1 analyses. An advanced selection was imposed that was designed to identify events consistent with $WH \to \ell\nu b\bar{b}$ production. We see an excess of events in our W+2 jet sample after advanced selection over the expectation from background. The 95% CL limit on σ_{WH} was measured as a function of M_H and was determined to be 18-22 pb in the range $M_H < 130\ GeV$. An event-by-event comparison with two other lepton+jets analyses is also performed.

1 Changes in Version 3.0

One change: cosmetic updates to Figures 1–6.

2 Changes in Version 2.0

Several changes were incorporated into v2.0 of this document:

- Correction of typographical errors in the overall uncertainty on signal and background in Tables 5 and 7; no changes to results
- Updated data plots, for mostly cosmetic reasons
- Updated VH cross section versus M_H plot

3 Introduction

We are performing a Run 1 search for WH production in the $\ell\nu b\bar{b}$ final state. We have utilized a baseline event selection [1] and an advanced selection [2] that are sensitive to the $\ell\nu b\bar{b}$ final state. The selection employed attempts to balance the need for high signal efficiency with the need for large background rejection. The baseline event selection chosen for this analysis attempts to isolate the $\ell\nu b\bar{b}$ channel:

- have at least one E_T (p_T) $> 20\ GeV$ central electron (muon)
- have $\not\!\!E_T > 20\ GeV$
- pass Z boson removal
- pass standard+extended dilepton $t\bar{t}$ removal
- have exactly two $E_T > 15\ GeV$, $\mid \eta \mid < 2.0$ jets
- have one or more SECVTX tags among the two required jets

Events are also required to have satisfied the high p_T lepton trigger and have a z vertex within $60cm$ of the center of the detector. A discussion of the effect of this event selection on signal and background samples is available elsewhere [1]. This baseline event selection matches that of other Run 1 lepton+jets analyses, for example [4]. Table 2 contains the Run and Event Numbers for 42 events from the Run 1 data set that satisfy this baseline criteria.

An advanced event selection was employed that imposed two further requirements on these W+2jet events:

- the events were required to pass a neural network(NN) selection, described in detail in [2]
- the events were required to have a reconstructed di-jet mass within some window

It was shown [3] that the same 8-12-5 NN could be utilized for all relevant M_H values without suffering considerable signal inefficiency. The optimal $M_{j_1 j_2}$ window was determined via scan, and varies as a function of M_H hypothesis one is considering. The $M_{j_1 j_2}$ window as a function of M_H is listed in Table 1.

M_H	$M_{j_1j_2}$ Window
100	$60 < M_{j_1j_2} < 130$
110	$70 < M_{j_1j_2} < 140$
120	$80 < M_{j_1j_2} < 150$
130	$90 < M_{j_1j_2} < 160$
140	$100 < M_{j_1j_2} < 170$
150	$110 < M_{j_1j_2} < 180$

Table 1: Optimized $M_{j_1j_2}$ requirements for each M_H value considered in this analysis.

	Run	Event	Trigger	# of SECVTX tags	Pass NN	Pass $M_{j_1 j_2}$ (for M_H= 120)
Run 1a	40190	98182	e	1	Y	N
	41627	87219	e	1	Y	Y
	45776	386857	e	1	N	N
	46357	511399	μ	1	Y	Y
	46935	266805	e	1	Y	Y
	47439	128290	e	1	Y	Y
	47689	80060	μ	2	N	N
Run 1b	60705	93795	μ	1	Y	Y
	60766	299452	e	1	Y	N
	61167	368226	e	2	N	N
	61377	114526	μ	1	N	N
	63603	4029	μ	1	Y	Y
	63883	935	e	1	Y	Y
	63946	43019	μ	1	N	N
	64126	52063	e	1	Y	Y
	64916	499208	e	2	Y	N
	64997	46557	e	1	Y	Y
	65022	34157	e	1	N	N
	65298	907072	e	1	Y	Y
	65384	266051	e	1	N	N
	65470	4390	e	1	N	N
	65741	654870	μ	2	Y	Y
	65750	106257	μ	1	Y	Y
	66103	190513	e	1	Y	N
	66103	563542	e	1	Y	Y
	66103	743101	μ	1	Y	N
	66412	121506	e	1	Y	Y
	66518	203555	μ	1	N	N
	67692	420568	e	1	Y	Y
	68044	53510	e	1	Y	N
	68231	157759	μ	1	Y	N
	68374	364586	e	1	Y	N
	68423	3326	μ	1	N	N
	68464	275644	e	1	Y	N
	68593	37659	μ	1	Y	Y
	68637	225974	μ	1	Y	Y
	68774	150313	μ	1	Y	Y
	69498	36574	μ	1	Y	Y
	69520	136405	e	1	N	N
	69683	21986	e	1	Y	Y
	69709	173294	e	1	Y	Y
	69761	157205	μ	2	Y	N

Table 2: List of 42 Run 1 events that pass the baseline event selection. Also listed for each event is whether the event passed the NN and M_H= 120 $M_{j_1 j_2}$ selection.

A priori studies were done to determine the ultimate reach of our analysis [3]; Table 3 lists our *a priori* limit as a function of M_H. Table 4 lists the 95% CL limit on WH production as a function of N_{Obs}, the possible outcomes of this analysis.

	A priori Limit (pb)	
M_H	No Systematics	With Systematics
100	9.5	11.3
110	8.4	9.9
120	8.4	10.0
130	9.3	10.9
140	13.5	15.6
150	24.3	28.5

Table 3: *A priori* limit as a function of M_H before and after the inclusion of systematic effects.

4 Results

The 42 events listed in Table 2 that pass our baseline event selection were first sent through the 5-output NN. The output distributions for data and the four background classes from MC are shown in Figures 1- 2. One of the motivations for using a multiple output NN is that by having an output node for each class of events, then the values of each output node represent event-by-event Bayesian *a posteriori* class probabilities. Thus one should verify that, in the data, the output values behave like probabilities. Figure 3 shows the sum of the output values for each data event; we see that the data in general exhibit the property

$$\sum_{i=1}^{5} NNOut_i(data) = 1$$

as one would expect if the Bayesian *a posteriori* class probabilities argument is valid. The NN selection was not imposed directly in the NN output value for any of the output nodes; instead, as described in [2], the distance,d, in the 5D output space for each event from the traget output vector associated with signal is the variable in which the cut is performed($d < 0.95$ was shown to be optimal). Figure 4

N_{Obs}	σ_{WH} Limit (pb) M_H=100 GeV	110	120	130	140	150
0	3.3	3.0	3.2	3.8	6.0	11.7
1	3.6	3.2	3.5	4.2	6.8	13.5
2	3.9	3.6	3.9	4.7	7.7	15.5
3	4.3	3.9	4.3	5.2	8.8	18.0
4	4.7	4.3	4.8	5.8	10.0	20.8
5	5.2	4.7	5.3	6.5	11.4	24.0
6	5.7	5.2	5.8	7.3	13.0	27.7
7	6.3	5.7	6.5	8.2	14.7	31.5
8	6.9	6.3	7.2	9.2	16.6	35.8
9	7.6	7.0	8.0	10.3	18.8	40.5
10	8.4	7.7	8.9	11.5	21.0	45.3
11	9.2	8.4	9.8	12.7	23.4	50.4
12	10.1	9.2	10.8	14.1	25.8	55.2
13	11.0	10.1	11.9	15.4	28.2	60.2
14	12.1	11.1	13.1	16.9	30.9	65.1
15	13.2	12.1	14.2	18.4	33.3	70.1
16	14.3	13.1	15.3	19.8	35.6	74.4
17	15.4	14.2	16.6	21.4	38.4	78.4
18	16.6	15.2	17.8	22.9	40.9	81.9
19	17.8	16.3	19.2	24.5	43.4	85.1
20	19.0	17.5	20.4	26.0	46.1	87.5
21	20.4	18.7	21.8	27.6	48.6	90.0
22	21.7	19.9	23.1	29.2	51.3	91.9
23	22.9	21.0	24.4	30.7	53.7	93.2
24	24.2	22.1	25.9	32.5	56.7	94.3
25	25.4	23.2	27.0	33.9	58.9	95.2
26	27.0	24.6	28.3	35.4	61.3	96.0
27	28.1	25.7	29.6	37.0	63.9	96.5
28	29.5	26.9	30.9	38.5	66.3	97.0
29	30.9	28.1	32.2	40.0	68.8	97.4
30	32.1	29.2	33.4	41.4	70.9	97.7

Table 4: The 95% CL limit on σ_{WH} for values of N_{Obs} $\leq$30.

contains the distribution of d for the 42 W+2jet events. The cut $d < 0.95$ is 74% efficient on our data sample, and thus eliminates 11 events.

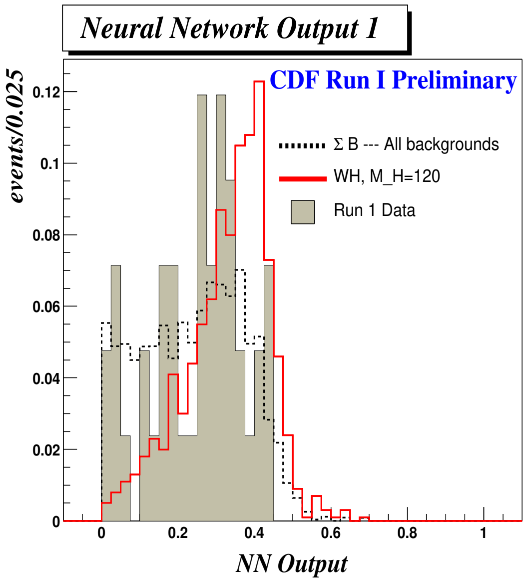

Figure 1: Data distribution for values from NN output node 1, the node associated with signal. Overlayed are the expected shapes from signal and summed background. All distributions are normalized to equal area.

The advanced selection is completed by a cut in the reconstructed di-jet mass, $M_{j_1 j_2}$. Care was taken in the construction of the NN to avoid choosing input variables that would sculpt the $M_{j_1 j_2}$ distribution of the selected sample. It was hoped that via fit one could extract the contribution from signal. Given the low expected number of signal events from MC studies and the overwhelming amount of expected background, fitting of the $M_{j_1 j_2}$ distribution was abandoned in favor of a windowed cut in the di-jet mass value after the imposition of the NN cut. Recall that the $M_{j_1 j_2}$ cut varies for different values of M_H (as listed in Table 1). Figure 5 shows the data $M_{j_1 j_2}$ distribution (overlayed with the background expectation) for events prior to the NN cut(a), for those events passing the NN cut(b), and for events failing the NN selection(c).

The results of our counting experiment are listed in Table 5. We see, for example, that for the hypothesis M_H=120 GeV, we expect 10.6 $\pm$ 2.1 events from background, and we see 21, a $\sim$3 σ excess considering the statistical uncertainty on the expected 10.6 events. Given these observation outcomes, we can use the values in Table 4 to determine the 95% CL limit on the WH production cross section as

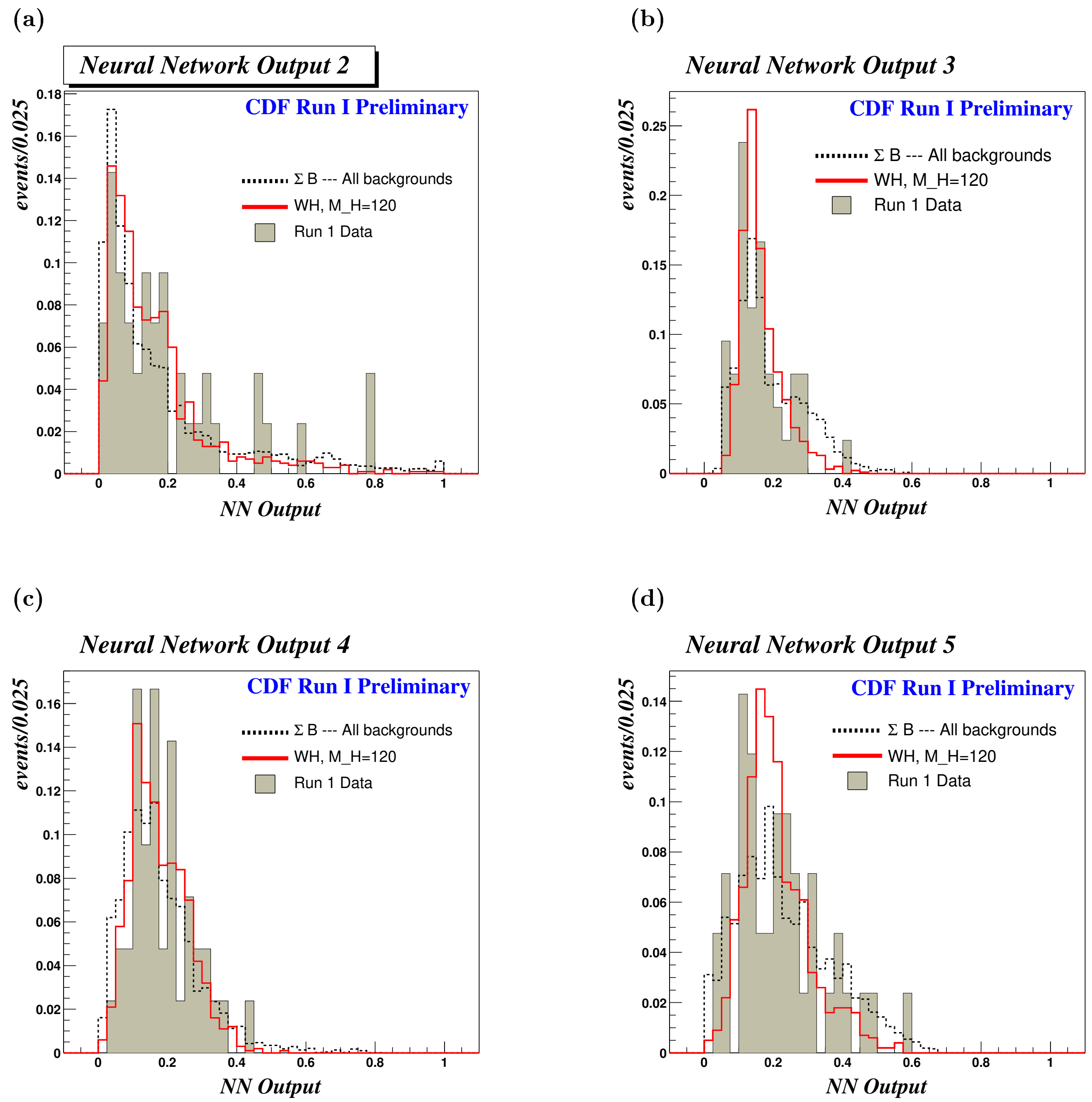

Figure 2: Data distribution for values from NN output nodes 2–5, the nodes associated with background. Overlayed are the expected shapes from signal and summed background. All distributions are normalized to equal area.

a function of M_H, which is contained in Table 6 and Figure 6.

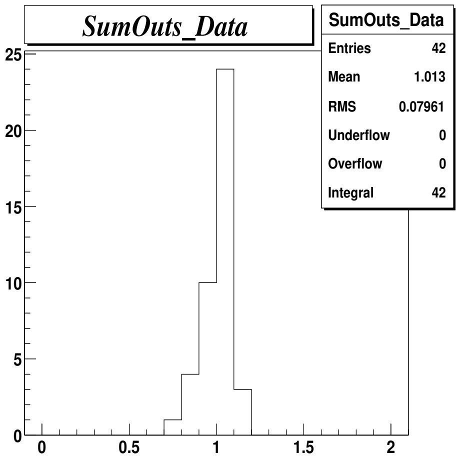

Figure 3: Sum of the values returned by the 5 NN output nodes for 41 data events. It is encouraging that the sum is centered about one, lending credence to the outputs-as-probabilities argument.

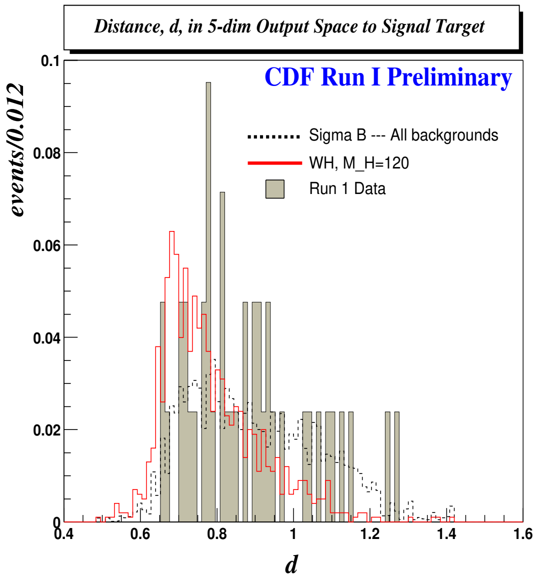

Figure 4: Data distribution for d, the parameter in which the NN selection is imposed. The cut $d < 0.95$ is 73% efficient in the 41 event Run 1 data sample. Overlayed are the distributions for signal and summed background, normalized to equal area.

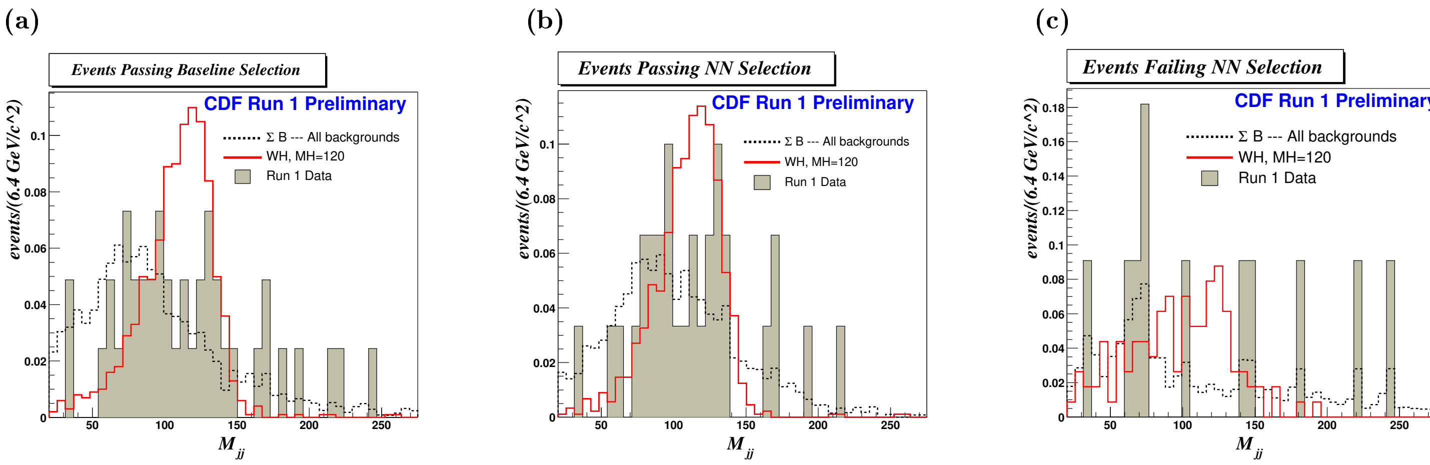

Figure 5: $M_{j_1 j_2}$ distribution for 42 data events before NN cut, the surviving 31 events after the NN cut, and the $M_{j_1 j_2}$ for the 11 events that do not satisfy our NN selection.

CDF Run I Preliminary

	Signal	Background					Data	
M_H (GeV)	(theoretical)	$t\bar{t}$	W+$b\ \bar{b}$,W+$c\ \bar{c}$, W+c ,non-W, W+mistags	Single top (W-*gluon* and $W*$)	WZ,WW, ZZ, Z+$b\ \bar{b}$, Z+$c\ \bar{c}$, $Z \to \tau\tau$	Bkgd Total	Events	Prob
100	0.25 ± 0.05	1.4 ± 0.4	8.8 ± 2.5	0.9 ± 0.2	1.5 ± 0.4	12.6 ± 2.6	19	0.0899
110	0.20 ± 0.04	1.4 ± 0.4	8.3 ± 2.3	0.9 ± 0.2	1.4 ± 0.4	12.0 ± 2.4	22	0.0183
120	0.15 ± 0.03	1.3 ± 0.4	7.2 ± 2.0	0.9 ± 0.2	1.2 ± 0.3	10.6 ± 2.1	21	0.0092
130	0.09 ± 0.02	1.3 ± 0.4	6.1 ± 1.7	0.9 ± 0.2	0.9 ± 0.2	9.2 ± 1.8	17	0.0255
140	0.04 ± 0.01	1.2 ± 0.4	4.6 ± 1.3	0.8 ± 0.2	0.6 ± 0.2	7.2 ± 1.4	15	0.0141
150	0.02 ± 0.005	1.0 ± 0.3	3.9 ± 1.1	0.7 ± 0.2	0.4 ± 0.1	6.0 ± 1.2	12	0.0306

Estimated Systematic Errors

Table 5: Counting experiment results for M_H values considered in this analysis. A 2–3 σ excess is evident for each mass.

CDF Run I Preliminary

	Cross Section 95% CL Limit(pb)			
	A priori Limit (pb)		Data Results	
M_H	No Systematics	With Estimated Systematics	σ_{WH}	$\sigma_{VH}*$ BR$(H \to b\bar{b})$
100	9.5	11.3	17.8	22.5
110	8.4	9.9	19.9	24.1
120	8.4	10.0	21.8	23.4
130	9.3	10.9	21.4	18.0
140	13.5	15.6	33.3	18.5
150	24.3	28.5	55.2	17.9

Table 6: The 95% CL limit on the WH production cross section as a function of M_H with *a priori* results for comparison.

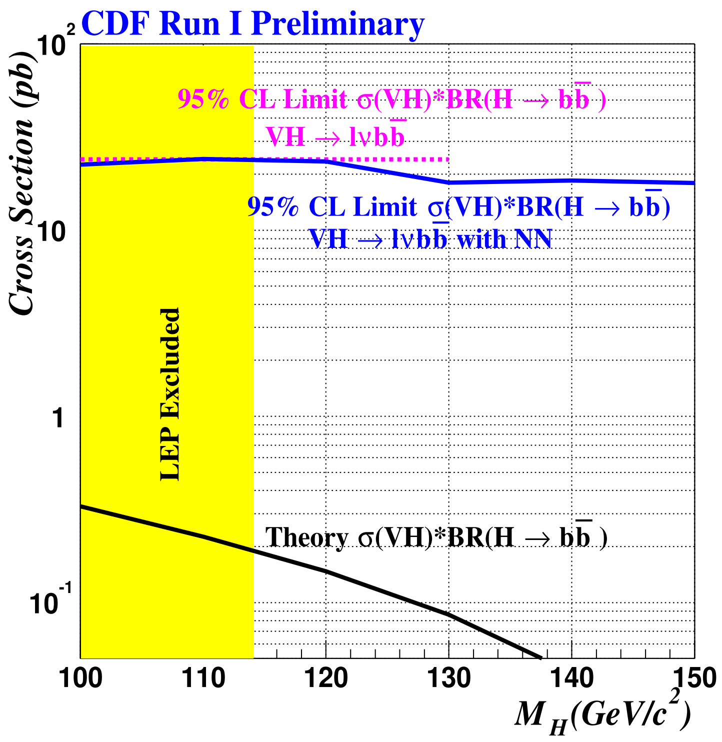

Figure 6: The 95% CL limit on the WH production cross section as a function of M_H.

5 Connection to Other Analyses

It is of interest to see how the advanced selection employed in this analysis treats events from other lepton+jet analyses that found similar excesses in the W+2 jet bin. One such analysis is the latest $t\bar{t}$ cross section measurement [5], which saw an excess in both the single- and double-SECVTX-tagged Run 1 samples (herein we denote "ST" as meaning exactly one SECVTX tag and "DT" meaning exactly two SECVTX tags). Table 7 compares the background expectation and result from the WH search described above. In the W+2 jet bin, the $t\bar{t}$ cross section analysis sees 35 single tag events with an expectation of 29.6 ± 2.7 and 5 DT events with an expectation of 2.4 ± 0.6. We see a similar excess in the ST bin, but limited statistics make it difficult to say much of anything about the DT bin

M_H (GeV)	N^B_{exp}(Total)	Data	N^B_{exp}(ST)	Data	N^B_{exp}(DT)	Data
100	12.6 ± 2.6	19	11.7 ± 2.4	17	0.92 ± 0.19	2
110	12.0 ± 2.4	22	11.1 ± 2.2	20	0.88 ± 0.18	2
120	10.6 ± 2.1	21	9.8 ± 1.9	20	0.79 ± 0.16	1
130	9.2 ± 1.8	17	8.5 ± 1.7	16	0.71 ± 0.14	1
140	7.2 ± 1.4	15	6.6 ± 1.3	14	0.58 ± 0.11	1
150	6.0 ± 1.2	12	5.5 ± 1.1	11	0.48 ± 0.10	1

Table 7: Breakdown of the Run 1 events passing our advanced selection into the 1 tag (ST) and 2 tag (DT) exclusive bins.

Another analysis that saw an excess in the lepton+jets final state is the superjets analysis [6], which studied the soft-lepton tag rate in the W+2,3 jet bin. A superjet is defined as a jet which possesses both a SECVTX and SLT tag. The superjets analysis found an excess of events containing a superjet, identifying 13 such events despite a SM prediction of 4.4 ±0.6. Eight of these 13 superjet events are in the W+2 jet bin that is included in this analysis. Since we employ here an advanced selection designed to be sensitive to $WH \to \ell\nu b\bar{b}$, it is interesting to see if this analysis considers these events to be consistent with WH signal or background.

Table 8 contains a description of the fate of the superjet events when confronted with our advanced selection. We see that one of the superjet events fails our dilepton veto. The dilepton veto is imposed via two criteria:

- Standard dilepton veto: an event is vetoed if it possesses 2 oppositely charged high p_T leptons, $\not\!\!E_T$ > 25 and two $E_T > 20$ jets
- Extended dilepton veto: an event is vetoed if it possesses a primary lepton and a $p_T > 15$, isolated oppositely charged track

In [6] a similar – though less stringent – extended dilepton veto is imposed for the superjets analysis. There they demand only that the isolated track have $p_T > 10\,GeV$. The extended dilepton veto employed here is the standard implementation from the Run 1 top group [7]; other similar analyses vetoed this event [4], [7].

Beyond this difference, one sees that the NN selection employed here cannot supply a clear verdict on these superjet events. In the seven such events that pass our baseline criteria, four are retained by the NN selection while three are rejected. The di-jet mass cut differs for each M_H hypothesis considered, so we simply list each superjet event's $M_{j_1 j_2}$ value in Table 8 for reference.

Run	Event	Pass Basic Selection	Pass NN Selection	$M_{j_1 j_2}$
46935	266805	Y	Y	100.3
41540	127085	N	—	—
41627	87219	Y	Y	98.1
46357	511399	Y	Y	97.8
61167	338226	Y	N	183.8
65384	266051	Y	N	142.0
69520	136405	Y	N	75.6
65741	654870	Y	Y	129.7

Table 8: The eight Run 1 W+2 jet superjet events, and how they fare in the selection employed in this analysis. One event fails the baseline selection(the dilepton veto) in agreement with ??.

Another Run 1 lepton+jets analysis that identified an excess in the W+2 jet bin is the latest Run 1 single-top search [4] In this analysis, 41 W+2 jet events were identified with an expectation of $\sim$ 30. Because of equivalent selection, the W+2 jet data sample constructed for this single-top analysis should exactly match the W+2 jet sample in this analysis, prior to any advanced selection. Yet there is a one event discrepancy between these two analyses, the origin of which is to be determined. It should be noted however that both the superjets analysis and the previous Run 1 single top search each exploit similar baseline event selections and each arrive at a different Run 1 W+2 jet data sample.

In [4] a 3-output NN was used to distinguish single top ($W*$ and W-*gluon* combined) from the dominant backgrounds, $t\bar{t}$ and W+QCD. A subset of the W+2 jet events was found to be more consistent with single top than background; the events in which the single-top probability was > 50%, along with their signal probabilities from the NN single-top search are listed in Table 9, along with their NN output values from this analysis. Recall that here we employ a 5-output NN; the value for each output node can be considered the probability that each event belongs to signal(Output Node 1) or the four background classes(Nodes 2-5).From Table 9 we see that only a few candidate signal events from NN single-top search are also determined to be most likely from single-top here in this analysis. It should be noted that in the NN single top analysis, WH events were not considered to be a significant portion of the background; thus one would not expect the NN used in that analysis to be able to discriminate between WH and single top, two very similar final states.

There are several Run 1 lepton+jets analyses that identified an excess of events. One can argue that these events are single top, scalar quarks, WH production or plain, old W+QCD background. It is evident that something is not well-understood in this final state, and such analyses deserve much attention in Run 2.

6 Summary

We have performed a new Run 1 $WH \to \ell\nu b\bar{b}$ search. This search goes beyond the standard W+jet and tagging requirements by employing in the event a neural network that was designed to be sensitive to WH production. An $M_{j_1 j_2}$ cut was also applied after the NN selection to reduce background levels in the selected sample. An excess of events was found over expectation. The 95% CL limit on the WH production cross section was determined, and the limit is in the range of 18-20 $pb$for M_H< 130 GeV.

References

[1] CDF 6304, “Acceptance Calculation for $WH \to \ell\nu b\bar{b}$ Search”

[2] CDF 6309, “Neural Network Implementation for a $WH \to \ell\nu b\bar{b}$ Search”

[3] CDF 6414, “Systematic Errors in the Run 1 Neural Network $WH \to \ell\nu b\bar{b}$ Search”

[4] C. Ciobanu, “Using A Neural Network to Identify Single Top in Run 1 Data”, CDF 5742

[5] T. Affolder *et al.* [CDF Collaboration], Phys. Rev. D **64**, 032002 (2001) [arXiv:hep-ex/0101036].

[6] P. Giromini, *et al.*, “Evidence for a non-Standard Model signal...”, CDF 4322

[7] S. Wolinski, P. Savard, “An Upper Limit on Standard-Model Single Top...”, CDF 5199

Run	Event	CDF 5742 Single Top Prob	Five-class Probabilities: Signal	$t\bar{t}$	$W+b\ \bar{b}$, $W+c\ \bar{c}$, etc.	Single-top	Diboson, Z+X	CDF 6468 Most Likely
40190	98182	0.642	0.159	0.092	0.169	0.212	0.272	Diboson
41627	87219	0.667	0.291	0.173	0.121	0.356	0.123	Single Top
60766	299452	0.591	0.370	0.029	0.209	0.184	0.211	WH
61167	368226	0.563	0.064	0.472	0.056	0.252	0.110	$t\bar{t}$
61377	114526	0.534	0.127	0.026	0.296	0.155	0.421	Diboson
63883	935	0.582	0.312	0.315	0.102	0.116	0.123	$t\bar{t}$
64126	52063	0.628	0.305	0.144	0.114	0.203	0.230	WH
64997	46557	0.593	0.169	0.183	0.087	0.116	0.273	Diboson
65384	266051	0.614	0.195	0.470	0.103	0.213	0.073	$t\bar{t}$
65470	4390	0.544	0.022	0.056	0.424	0.210	0.302	$W+b\ \bar{b}$,$W+c\ \bar{c}$ ...
65750	106257	0.636	0.342	0.089	0.169	0.326	0.183	WH
66103	743101	0.799	0.259	0.225	0.086	0.430	0.118	Single Top
67692	420568	0.766	0.308	0.148	0.107	0.282	0.141	WH
68044	53510	0.746	0.409	0.051	0.135	0.275	0.225	WH
68423	3326	0.658	0.030	0.581	0.063	0.117	0.125	$t\bar{t}$
68593	37659	0.698	0.441	0.060	0.190	0.223	0.174	WH
68774	150313	0.614	0.350	0.115	0.146	0.318	0.153	WH
69683	21986	0.815	0.165	0.241	0.106	0.323	0.059	Single Top

Table 9: Events from [?] that were determined to be consistent with single top, and how they are classified in this analysis.